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Chapter 5 - Concrete Basics

5.1 Concrete Overview

Concrete is a composite material that uses cement to bind together crushed stone, rock, and sand (i.e., aggregate). Cement acts as a binder filling the space among the aggregate particles and glues them together. The exact proportions of aggregate, cement, and water vary depending on the type of concrete being made. The aggregate and cement are mixed thoroughly with water, which starts the chemical reaction causing the cement to harden and set. This chemical reaction is called hydration.

Quality concrete should have the following characteristics:

- It should be constructible. This means concrete mix should be workable, and placed and consolidated with no difficulties. It should flow sluggishly without segregation of the ingredients.
- It should gain the required strength after it is cured.
- It should be durable. This means during the service life, concrete should not develop premature deterioration.

Certain properties may be required, depending on the type of environment, to resist the following types of deterioration:

- Surface cracking (shrinkage cracks) caused by improper curing
- Surface scaling caused by wetting and repeated freeze/thaw action
- Surface scaling caused by deicing salts
- Chemical reaction caused by sulfate action or certain types of aggregate
- Abrasion caused by traffic
- Penetration of water and deicing salts and subsequent corrosion of the reinforcing steel

The most popular type of concrete is hydraulic cement concrete. Polymer concrete is very popular for bridge maintenance repairs, but there are also many other types of concrete including high performance, self-consolidating and lightweight which will be explained in the following sections.

One of the more confusing aspects of concrete is the amount of terminology. Simple definitions of some of the more confusing terms used in this chapter are provided below.

Pozzolan: A material that can be substituted for cement. A pozzolan is a siliceous or siliceous and aluminous material which, in itself, possesses little or no cementitious value, but which will, in finely divided form and in the presence of water, react chemically with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties. Examples are slag, silica fume, or fly ash.

Blended Cement: A cement that also contains pozzolans (supplementary cementing materials) such as slag, silica fume, or fly ash.

Admixture: A chemical material that is added to the concrete mix to enhance its properties.

Aggregate: The material in concrete that is rock-like

Plastic Concrete: Concrete state before it hardens, it can flow

Air-entraining: The ability to insert tiny air bubbles into concrete

High early strength: The ability for concrete to gain strength quickly

5.2 Components and Properties of Hydraulic Cement Concrete

5.2.1 Cement

Cement is a very fine powder made of limestone calcium, silicon, iron, and aluminum, among other ingredients, which absorbs water and acts as a binder to hold the aggregates together. The raw ingredients of cement are heated in large kilns to about 2,700 °F to form a product known as clinkers, which roughly resemble marbles. These are ground into a powder and gypsum is added, creating the gray flour-like substance known as cement. When water is added to cement, it triggers a chemical reaction called hydration which allows it to harden. Cement typically makes up from 10 percent to 15 percent of the total mass of concrete.

When to Call the Engineer

Concrete mix design and selection should be performed by an engineer or technician properly trained in concrete mix design and knowledgeable with the exposure environment, placement conditions and desired properties.

5.2.1.1 Types of Cements

There are many different types of cement, but the type most commonly used in construction is Portland cement. The word "Portland" is not a proprietary term; it indicates the type of cement much like the word "stainless" is used to describe a type of steel. Portland cement is a type of hydraulic cement. Different types of Portland cement are manufactured to meet different physical and chemical requirements for specific purposes, such as durability and high-early strength (i.e., quick setting, typically achieved by addition of an accelerating admixture). Air entraining agents are sometimes added to intentionally create tiny air bubbles in the concrete. The addition of tiny air bubbles can increase the durability of the hardened concrete and also increase workability of the concrete while in a plastic state.

Eight types of cement and a brief description of their uses are listed in Table 5.1.

*Table 5.1 Portland Cement Types and Their Uses**

Cement Type	Use
I	General purpose cement, when there are no extenuating conditions. Cements that simultaneously meet requirements of Type I and Type II are also widely available.
II	Aids in providing moderate resistance to sulfate attack. Type II low alkali (total alkali as Na_2O < 0.6 percent) is often specified in regions where aggregates susceptible to alkali-silica reactivity are employed.
III	When high-early strength is required (high strength at early time period).
IV	When a low heat of hydration is desired (in massive structures). Type IV cements are only available on special request.
V	When high sulfate resistance is required. These cements are in limited production and not widely available.
IA	A Type I cement containing an integral air-entraining agent. These cements are in limited production and not widely available.
IIA	A Type II cement containing an integral air-entraining agent. These cements are in limited production and not widely available.
IIIA	A Type III cement containing an integral air-entraining agent. These cements are in limited production and not widely available.

* American Society for Testing and Materials (ASTM) Standard Specification for Portland Cement: ASTM C150

More than 92 percent of Portland cement produced in the United States is Type I and II (or Type I/II); Type III accounts for about 3.5 percent of cement production (U.S. Department of the Interior, 1989). Type IV cement is only available on special request, and Type V may also be difficult to obtain (less than 0.5 percent of production).

Although Type IA, IIA, and IIIA (air entraining cements) are available as options, concrete producers prefer to use an air entraining admixture during concrete production, where they can get better control in obtaining the desired air content. In general, air entraining agent is added at the plant and if necessary adjusted in the field. However, caution is advised as the quality control is poor, particularly when no means of measuring the air content of fresh concrete is available. Entrained air content can be determined in accordance with the requirements of ASTM standards, i.e., ASTM C231 or ASTM C173.

If a given type of cement is not available, comparable results can frequently be obtained by using modifications of available types. High-early strength concrete, for example, can be made by using a higher content of Type I cement when Type III cement is not available (National

Materials Advisory Board, 1987), or by using admixtures such as chemical accelerators or High-Range Water Reducers (HRWR). The availability of Portland cements will be affected for years to come by energy and pollution requirements. In fact, the increased attention to pollution abatement and energy conservation has already greatly influenced the cement industry, especially in the production of low-alkali cements.

Three types of cement are commonly used in the repair of highway structures.

- Type I, or "Normal" cement, is general purpose cement.
- Type II cement is used when concrete is to resist moderate sulfate attack from sources such as ground water. Also, since Type II hydrates at a slower rate than Type I, there is generally less heat generated. As a result, it may be used in structures of considerable mass, such as large piers, heavy abutments, and heavy retaining walls to reduce rise in the temperature of the concrete mass. If the temperature rise is not controlled, concrete can crack upon cooling since it will shrink substantially. For the same reason, Type II cement is also a desirable cement to be used for concrete to be placed in warm weather.
- Type III is a high-early-strength cement which develops higher strength at an earlier age. This is the desirable cement to be used for concrete patches where early use of the roadway is important. However, unlike Type II cement, Type III will generate more heat of hydration than Type I. Therefore the use of Type III cement is not desirable in large structures and in warm weather construction, since thermal shrinkage cracks can occur after curing.

5.2.1.2 Physical Properties of Cement

ASTM has specified certain physical requirements for each type of cement. These properties include 1) fineness, 2) soundness, 3) consistency, 4) setting time, 5) compressive strength, 6) heat of hydration, 7) specific gravity, and 8) loss of ignition. Each one of these properties has an influence on the performance of cement in concrete. The fineness of the cement, for example, affects the rate of hydration. Greater fineness increases the surface available for hydration, causing greater early strength and more rapid generation of heat (the fineness of Type III is higher than that of Type I cement) (U.S. Department of Transportation, 1990).

5.2.2 Aggregates

Aggregates make up more than 60 percent of a concrete mix — and up to 80 percent in some cases. Aggregate is also less expensive than cement, so a higher percentage can lower the cost. Thus, the concrete mix designer can often save money by selecting the maximum aggregate size allowable. Using larger coarse aggregate typically lowers the cost of a concrete mix by reducing cement requirements, the most costly ingredient. Less cement (within reasonable limits for durability) will mean less water if the water-cement (w/c) ratio is kept constant. A lower water content will reduce the potential for shrinkage and for cracking associated with restrained volume change. Generally speaking, a good aggregate has a combination of rocks of many different sizes, graded, with a specific average and maximum size; the aggregate must be clean and durable, and should not contain clay or other minerals that can absorb water.

The high rock content of concrete makes concrete extremely durable, and it often is used in roadways, bridges, and airport runways. The ingredients in both concrete and cement are among the most abundant on earth, and both can be recycled. Cement production does require a large amount of energy, however, because of the high temperatures required.

The characteristics of aggregates strongly influence the properties of the concrete. To produce high quality concrete, the aggregate should consist of clean, hard, strong, and durable particles free of chemicals, coatings of clay, or any other fine materials that may affect the hydration and the final bond of the cement paste. Weak, pliable, or laminated aggregate particles are undesirable. Aggregates containing natural shale or shale particles, soft and porous particles, and certain types of chert (a form of microcrystallite quartz) should be especially avoided since they have poor resistances to weathering.

Generally, the following characteristics are expected of aggregate:

- Freeze-Thaw Resistance
- Chemical Compatibility with Cement
- Particle Shape and Surface Texture
- Gradation and Size

Each of these characteristics is further described below.

In exposed concrete, aggregate should be resistant to repeated cycles of freezing and thawing. In the presence of absorbed water, repeated cycles of freezing and thawing can deteriorate the aggregate and reduce the strength of concrete with time. Standard tests, such as American Association of State Highway and Transportation Officials (AASHTO) Designation TP17, are available to determine the freeze-thaw resistance of aggregate.

Aggregate should chemically be compatible with cement. Some aggregate may react chemically with cement and cause expansion of concrete and subsequent severe cracking of concrete. This is called "alkali-aggregate" reaction, and the aggregate is called "alkali-reactive" aggregate. Tests are available to identify alkali-reactive aggregates. If alkali-reactive aggregate is the only aggregate available, cements with certain chemical composition or admixtures may be selected to prevent the alkali-aggregate reaction.

These characteristics of an aggregate mainly affect the properties of the plastic or formable (prior to hardened) concrete. Aggregates with rough texture or flat and elongated particles require more water to produce workable concrete than round or cubical aggregates. In turn this can result in a higher water-cement ratio and lower strength. However, aggregates with rough and irregular shapes tend to lock together to produce a stronger matrix than smooth rounded shapes.

Generally, an aggregate gradation with minimum void content is desirable, since the cement paste requirement for concrete increases as the void content in the aggregate is increased. Aggregate with uniform particle size increases void content. To provide the minimum void content, coarse and fine aggregate are combined. Coarse aggregates are particles that generally range between 3/8 and 1.5 inches in diameter, and fine aggregates generally consist of natural sand or crushed stone with most particles passing through a 3/8-inch sieve. Gradation limits for coarse and fine aggregate are specified to ensure minimum void content.

The maximum size of coarse aggregate in the mix depends on the size of the concrete member or size of repair, and on the spacing of the reinforcing steel. The maximum size of coarse aggregate should be small enough to place the mix in the form and in the spaces between the reinforcing steel with no difficulties. Specifications give the maximum size of aggregate on the basis of the minimum dimension of the form and clear space between the reinforcing bars. Also, the smaller the maximum size of aggregate, the greater will be the amount of mixing water required to produce the same workability. Therefore, it is advantageous to use the largest practicable maximum size of coarse aggregate.

5.2.3 Water

Certain levels of chemicals and impurities in mix water can reduce the strength of concrete and cause its deterioration in time. Water that is suitable for drinking is generally preferred as mixing water for making or curing concrete. Conversely, water that is suitable for making concrete may not necessarily be fit for drinking. Therefore, if it comes from a source other than drinking water, the water should be tested to determine that it has the right chemical makeup for making concrete. Examples of components of concern include chlorides (rebar corrosion concern) or alkali carbonates and bicarbonates sometimes occurring in some natural mineral water (alkali-silica reaction concern).

5.2.4 Admixtures

Admixtures are ingredients other than water, aggregates, hydraulic cement, and fibers (sometimes added to reinforce concrete) that are added to the concrete batch immediately before or during mixing. A proper use of admixtures offers certain beneficial effects to concrete, including improved quality, acceleration or retardation of setting time, enhanced frost-freeze-thaw and sulfate resistance, control of strength development, improved workability, and enhanced finishing. It is estimated that 80 percent of concrete produced in North America these days contains one or more types of admixtures. According to a survey by the National Ready Mix Concrete Association, 39 percent of all ready-mixed concrete producers use fly ash, and at least 70 percent of produced concrete contains a water-reducer admixture.

Admixtures vary widely in chemical composition, and many perform more than one function. Two basic types of admixtures are available: chemical and mineral. Mineral admixtures are also called Cementitious Admixtures. Chemical admixtures are generally added to concrete in very small amounts while mineral admixtures are added in larger amounts. All admixtures to be used in concrete construction should meet specifications; tests should be made to evaluate how the admixture will affect the properties of the concrete to be made with the specified job materials, under the anticipated ambient conditions, and by the anticipated construction procedures.

Admixtures are added to concrete with water before mixing the concrete, or during mixing cement, aggregate, and water. Admixtures are generally classified as follows:

- Air-Entraining Admixture
- Water-Reducing Admixture
- High-Range-Water-Reducing Admixture (Superplasticizer)
- Retarding Admixture
- Accelerating Admixture
- Cementitious Admixtures
- Corrosion Inhibitor Admixtures

Admixtures may be used to improve the properties of concrete; however, they should never be used as a substitute for proper design of the concrete mix or proper construction procedures. Also, some admixtures may not be compatible with the other materials used in the concrete. Loss of workability, loss of strength, and excessive shrinkage causing cracking may result. Therefore, it is important that concrete trial mixes are made with the admixture and at temperatures anticipated on the job. In this way, the effects of the admixture can be observed. The amount of admixture is recommended by the manufacturer and verified through tests. Following is a discussion of the concrete admixtures and the reasons for using each.

5.2.4.1 Air-Entraining Admixtures

Recommendation

An air-entrained admixture is recommended for use in all concrete used in structures that are exposed to freezing temperatures

An air-entrained admixture is recommended for use in all concrete used in structures that are exposed to freezing temperatures because it improves the hardened concrete's resistance to surface scaling caused by freezing/thawing action and deicing salts. When the water in the concrete surface freezes, it expands and ruptures the surface layer causing scaling. The entrained air voids act as reservoirs for excess water forced into them. As a result the pressure on the concrete is relieved and damage is prevented. However, air-entrained admixtures have other beneficial effects in both plastic and hardened concrete.

These beneficial effects are:

- Workability of concrete is improved, especially in lean mixes (those with low cement content) because air bubbles act as rollers. Air entrained concrete is cohesive, concrete flows sluggishly, and its segregation is reduced.
- Impermeability of concrete is improved. This is because air entrained concrete uses lower amounts of water in the mix for the same workability. Thus, the voids caused by the evaporation of the excess water, which is not used for hydration, will be minimal.
- Resistance of concrete to erosion caused by sulfate attack is improved. Air-entraining agents protect against sulfate attack in the same manner as they protect against freezing and thawing. The air voids provide microscopic expansion chambers for relief of the pressure that is built up in the concrete by the growth of the sulfate crystals. Air entrainment does not provide permanent protection, but it does delay the deterioration for a period of time depending upon factors such as the concentration of soluble sulfate and the cycles of wetting and drying, which promote the crystal growth.

An air-entrainment admixture is introduced into the batch of concrete with water before mixing the concrete. Air-entrained concrete contains microscopic air bubbles that are distributed, but not interconnected, through the cement paste. Hence, these voids do not act as capillaries and do not affect the permeability adversely. The bubbles are small and invisible to the naked eye. The entrained air is typically from 5 to 8 percent of the volume of concrete. Generally as the maximum aggregate size increases, the amount of entrained air required decreases.

5.2.4.2 Water-Reducing Admixtures

Addition of a water-reducing admixture to concrete mix will reduce the quantity of mixing water required to produce concrete of a given workability. An increase in strength can be obtained with a water-reducing admixture when the water content is reduced and the cement content is kept the same.

Water-reducing admixtures increase the workability of concrete if the same quantity of water is used in the mix. Many water-reducing admixtures also retard the setting time of concrete. However, the time duration of increased workability is short.

A significant increase in drying shrinkage of concrete can result from the use of some of these admixtures. Drying shrinkage takes place after the concrete has gained strength and the excess water has left the voids. The shrinkage in turn can cause cracking of the concrete. It is, therefore, recommended that trial batch tests be made with the job materials and tested for shrinkage.

Recommendation

Make trial batch tests with the job materials and test for shrinkage.

5.2.4.3 High-Range-Water-Reducing-Admixtures

These admixtures are commonly known as super-plasticizers. Basically, they perform similar to water-reducing admixtures. The difference is that their addition to the mix will allow a significant reduction in the quantity of the mixing water required to produce concrete of a given workability. This will permit producing concretes with extremely low water-cement ratio (water-cement ratio lower than 0.4) and very high strengths. Superplasticizers may have adverse effects on concrete drying shrinkage; therefore shrinkage tests on trial mixes should be conducted.

5.2.4.4 Retarding Admixtures

A retarding admixture is a chemical that is used to delay the setting time of concrete. This allows time for the finishing of concrete when, as in hot weather, the set time is reduced. It also provides time to place concrete in difficult places or allows time for finishing of such items as bridge decks or large piers. Most retarders also function as water reducers. The effects of retarding admixtures on concrete drying shrinkage may not be predicted, and shrinkage tests of retarders should be conducted.

5.2.4.5 Accelerating Admixtures

An accelerating admixture is used to decrease the set time and allow for early strength development of the concrete. There are benefits of accelerated setting and early strength gain. In cold weather, cement hydrates slowly, and concrete sets and gains strength slowly. Concrete protection is necessary during the curing to avoid damage by freezing. This protection can be in the form of heating the concrete. Accelerating admixtures can significantly reduce the duration of this costly protection against cold weather. Also, in cold weather, forms can be removed earlier by using accelerating admixtures. Accelerating admixtures are also useful in bridge deck repair, where is desirable to reopen repaired areas to traffic as soon as possible.

In the past, calcium chloride was one of the most commonly used accelerating admixtures. It has been determined, however, that chlorides can cause corrosion of the reinforcing steel and spalling of concrete. Thus, most highway agencies, if not all, have discontinued its use. With the elimination of calcium chloride as an accelerating admixture, the use of Type III cement (high-early-strength cement) has become more common. Another alternative is the use of additional cement in the mix, or the use of different methods of curing and protection such as heating concrete. A substitute for heating concrete may be heating the water and aggregates prior-to-mixing. However, in many cases the use of an accelerator is the most economical and convenient method of obtaining the desired results.

5.2.4.6 Mineral (Cementitious) Admixtures

Cementitious materials, such as fly ash, slag, and microsilica are used both as an admixture and as a partial substitute for cement in concrete.

These admixtures are used to:

- Reduce permeability
- Reduce heat of hydration
- Reduce or eliminate potential expansion from alkali-reactive aggregates and the subsequent cracking of concrete
- Add to the strength
- Most importantly, they are cheaper than cement

The advantages to using mineral admixtures added at the batch plant:

- Mineral admixture replacement levels can be modified on a day-to-day and job-to-job basis to suit project specifications and needs.
- Cost can be decreased substantially, while performance is increased, when taking into consideration that the price of blended cement (defined as a mixture of Portland cement and other pozzolans such as Ground Granulated Blast-Furnace Slag (GGBFS), hydrated lime, etc., combined either during or after the finish grinding of the cement at the mill) is at least 10 percent lower than that of Type I/II cement.
- Ground Granulated Blast Furnace Slag (GGBFS) can be ground to its optimum fineness.
- Concrete producers can provide specialty concretes in the concrete product markets.

At the same time, precautions must be considered when mineral admixtures are added at the batch plant. One example includes the possibilities of cross-contamination or batching errors are increased as the number of materials that must be stocked and controlled is increased.

Fly Ash

Fly ash is a pozzolanic material, which means that when in small particle form and under the right conditions, it reacts with calcium hydroxide and water at ordinary temperatures to form a cementitious material. Fly ash may be added either as a replacement for a portion of the Portland cement or as an addition to the usual amount of cement. Fly ash content is generally between 15 to 20 percent of the weight of cement. Fly ash improves the workability of concrete. The permeability of concrete with fly ash generally decreases with time and its strength increases because of the pozzolanic reactions that occur during and also after the curing period. The pozzolanic reactions depend on the temperature. Those reactions are slow in cold temperatures. If fly ash is replacing the cement in concrete, in cold temperatures, curing periods longer than those required for conventional concrete may be needed to obtain the required strength.

Slag

Ground slag may be used as a replacement for a portion of cement in concrete. The slag content is generally between 40 to 50 percent of the cement weight. A properly used good quality slag reduces concrete permeability in time and adds to the strength. Ground slag also improves the workability of concrete.

Microsilica

Microsilica (silica fume) is a highly effective pozzolanic material. It is obtained as a by-product of the manufacture of silicon. Microsilica admixtures for concrete are furnished either in the dry compacted form or as water-based slurry that are made from dry material. The water in the slurry shall be counted as mixing water for the purpose of determining the water-cement ratio of the concrete.

Addition of microsilica to concrete reduces the permeability significantly. In many cases, the permeability is so low that existing equipment is not suitable for measuring permeability of microsilica concrete. Addition of microsilica substantially increases the strength; however, achieving low permeability is the primary reason for its use in bridge components. Adequate impermeability and resistance to chloride penetration for concrete used in highway applications may be attained with microsilica dosages between 5 to 10 percent of cement weight.

Adding microsilica to concrete reduces slump and adversely affects workability. This is because extremely fine microsilica particles increase water demand. Thus, the use of microsilica in concrete mix almost always makes it mandatory to use HRWRs. The HRWR will compensate for the increased water demand and will allow placement of the concrete at reasonable field slump. Some states have had issues with microsilica concrete overlays bonding to the underlying concrete, so microsilica overlays should be carefully designed and placed for successful performance.

Concrete containing microsilica are highly susceptible to plastic shrinkage cracks during the curing process. Special concrete curing procedures must be set up to ensure proper curing of concrete.

5.2.4.7 Corrosion Inhibiting Admixtures

Recommendation

Perform strength testing on concrete containing inhibitor to ensure that the inhibitor does not adversely affect the concrete strength.

Corrosion inhibiting admixtures provide protection for steel embedded in concrete by reducing the corrosion rate in the presence of chloride ions. Inhibitors act at the steel surface to limit corrosion reactions. Traditionally, inhibitors were inorganic. More recently, inorganic inhibitors have become available. To ensure that the inhibitor does not affect the basic properties of the concrete, concrete containing the inhibitor should be tested for strength.

Inorganic Corrosion Inhibitor

The active ingredient in inorganic corrosion inhibitors is calcium nitrite. The calcium nitrite inhibitor can be added at varying amounts to provide different levels of protection. Calcium nitrite is typically added at a rate of 3 to 5 gallons per cubic yard depending on the severity of deicer salt application. The water in the calcium nitrite should be counted as mixing water for the purpose of determining the water-cement ratio of the concrete.

Calcium nitrite may act as an accelerator, depending on type used, and adjustment in quantities of other admixtures to produce acceptable workability and setting time may be required. The calcium nitrite solution shall be added immediately after the other admixtures have been incorporated into the mixture. However, if High-Range Water Reducer (HRWR) is added at the site, the calcium nitrite shall be thoroughly mixed before the HRWR is added.

Organic Corrosion Inhibitor

Organic corrosion inhibitors are relatively new products. The admixture functions by a twofold mechanism that involves the formation of a protective film at the steel surface against corrosion and a reduction in the permeability of concrete to chloride penetration. The organic corrosion inhibitor will not accelerate the rate of setting of concrete and has no effect on slump, thereby allowing normal placing and finishing operations.

5.3 Polymer Concrete

Polymer concrete as a repair material for highway infrastructures is relatively new. While traditional concrete uses cement as a paste to bind the aggregates together, polymer concrete uses non-Portland Cement based chemical compounds, called polymers, to bind the aggregates together.

Polymer concrete offers several distinct advantages over traditional concrete. It is quick curing, versatile, and is able to expand and contract over time to accommodate temperature changes. The adhesive properties of polymer concrete allow patching of both polymer and conventional cement-based concretes. The low permeability and corrosive resistance of polymer concrete allows it to be used in bridge repairs, culverts, and roadways.

Polymer concrete has historically not been widely adopted due to the high costs and difficulty associated with traditional manufacturing techniques. Uses have been limited to small placements or when reopening the structure as soon as possible is critical. However, recent progress has led to significant reductions in cost, meaning that the use of polymer concrete is gradually becoming more widespread. While these historically high costs have limited the overall thickness of the polymer repair, there is no set limit on the thickness. However, as the compressive strength is typically less than that of Portland cement concrete, deep patches of polymer may be more susceptible to rutting and debonding due to differences in thermal expansion. Even though polymer concretes can be formulated to 12,000 psi, typically lower strength polymer concretes are used (1,500 to 2,500 psi) to facilitate field mixing and application of polymer concretes for maintenance repairs and patching.

Polymer concretes used in bridge repair are “elastomeric polymers”, meaning the material has elastic properties. As defined by ASTM, an elastomer is "a polymeric material which at room temperature can be stretched to at least twice its original length and upon immediate release of the stress will return quickly to approximately its original length".

Elastomers are rubbery material composed of long chainlike molecules, or polymers, that are capable of recovering their original shape after being stretched to great extents. Under normal conditions the long molecules making up an elastomeric polymer are irregularly coiled. With the application of force, however, the molecules straighten out in the direction in which they are being pulled. Upon release, the molecules spontaneously return to their normal compact, random shape. Elastomers are hydrocarbon polymeric materials similar in structure to plastic resins. The difference between plastics and elastomers is based on the property of extensibility or stretching. Elastomers have long been praised for being very strong when struck, hard if scratched, resistant to corrosion from various chemicals, and resilient in the face of humidity or water submersion. Since they do not conduct current, they are good electronic insulators.

Another beneficial property is its ability to be compounded, or mixed, with other materials to strengthen certain characteristics. Other kinds of polymers may make them less likely to soften at high temperatures or break down around ozone gas. Elastomers can easily be installed next to various other materials, such as metal and concrete, with excellent adherence.

5.3.1 Advantages and Disadvantages of Polymer Concrete

5.3.1.1 Advantages of Polymer Concrete

There are many advantages of polymer concrete, including:

- Rapid cure times. Polymer concrete has a liquid working temperature between 60 °F and 85 °F. The maximum workable temperature of this type of concrete is 150 °F. However, at higher temperatures, these materials can set in minutes and be hardened in the mixer.
- High tensile and flexural strengths. These materials can bend and twist more than traditional concretes.
- Good adhesion to most surfaces. Polymers are sticky and will develop strong bonds to properly prepared surfaces, such as concrete and steel.
- Good long term durability with respect to freeze-thaw cycles. The material is very dense so it does not allow water into the pours as it can with Portland-based materials. Polymer concrete does not need to be sealed.
- Low permeability to water and aggressive solutions such as de-icing salts.

- Good resistance against corrosion.

5.3.1.2 Disadvantages of Polymer Concrete

Polymer concrete must be mixed very precisely and very thoroughly. It cannot be mixed beforehand and simply kept turning to avoid curing because the chemical reaction will happen no matter what. Also, the chemicals that this type of concrete uses can be dangerous and everyone nearby must wear masks and skin protection.

Additional disadvantages of polymer concrete include:

- Cost. Polymer concrete is expensive. Too expensive for use in large placements.
- Lower compressive strength. Though polymers can be formulated to 12,000 pounds of pressure per square inch, or psi, the elastomeric concretes used in maintenance repairs are typically of lower strengths, typically 1,500 to 2,500 psi.
- Polymer concretes are sticky and hard to manipulate with conventional tools shovels and trowels.
- Not compatible with water. Most polymers are negatively affected by water. Both the substrate and the aggregate should be free of any water. Some polymers are affected by high humidity.
- Safety. Some polymers are relatively safe to use, others can create hazardous conditions if mixed improperly.
- Training. Crews should receive specific training and review the Material Safety Data Sheet (MSDS) before mixing and placing polymer materials.
- Temperature limitations. Most, but not all polymers, cannot be used in below freezing temperatures. Also, at high temperatures, the material may set too quickly.
- Surface Preparation. Proper surface preparation is critical for quality repair.

5.3.2 Components of Polymer Concrete

5.3.2.1 Polymers

Polymers are typically made up of two chemical compounds. One is termed a resin and the other a hardener. When the two components are mixed together, a chemical reaction occurs and the material begins to cure and harden, thereby, becoming the binder and binding the aggregates together. Some polymers include a third component called an initiator (or accelerator) that helps the polymerization reaction to begin.

Manufacturers have also developed single component systems called monomers that are added to cement to create polymer-impregnated concretes and polymer-Portland cement concrete.

Many different types of polymers can be used to make up polymer concrete, each with specific properties and characteristics. Acrylic, polyesters, polyureas, and epoxies are most often used, but polymer concrete can be made with many kinds of polymer resins that allow the repair material to be pumped, poured, or troweled and then hardened. Polymer concrete offers different benefits depending on the resin used to make it.

Acrylic binders set very quickly and offer resistance to weathering, while epoxies create a very strong material that shrinks very little as it cures. Furan resins can withstand high temperatures, and polyurea resins can replace phenolics or formaldehydes in many construction projects.

Single component monomers, such as latex, have been used in place of water to make latex modified concrete.

5.3.2.2 Aggregates

Polymer concrete is composed of aggregates that include silica, quartz, granite, limestone, and other high quality material. The aggregate must be of good quality, free of dust and other debris, and dry. Failure to fulfill these criteria, especially for a dry aggregate, will reduce the bond strength between the polymer binder and the aggregate.

5.3.3 Material Properties of Polymer Concrete

5.3.3.1 Compression Strength

Strength is an important characteristic of concrete, as it is often used as a structural foundation material. The compressive strength of elastomeric polymer concrete can range from 1,500 to 12,000 psi. Exact compression strength varies depending upon the brand of polymer concrete and what type of material is used as a binder. Compressive strength increases over time. Polymer Methyl Methacrylate Concrete can gain compressive strengths of 8,000 psi after one hour of setting and 12,000 psi after seven days of setting.

5.3.3.2 Corrosion Resistance

A main advantage of polymer concrete is resistance to a wide range of solvents and oils; it is also resistant to acids (pH level ranging from 0 to 7). Polymer concrete is resistant to a variety of acids that can eat away concrete over time, de-icing salts, hydrochloric acid, formic acid, and ammonium sulfate. Polymer concrete does not corrode in the presence of hydrocarbons, such as acetone, gasoline, ethane, methanol, petroleum, diesel and vegetable oils. This type of concrete offers excellent resistance against water.

5.3.3.3 Flexibility

Traditional concrete is vulnerable to shearing forces that can cause cracks and a decline in structural integrity. Resistance to these forces is known as flexural and tensile splitting strengths.

Recommendation

When using polymer concrete, it is important to follow the manufacturer's recommendations. Product representatives may be available to provide training and assist with the proper use.

Polymer concrete offers greater resistance to cracking. Polymer concrete has a flexural strength of around 3,500 psi after eight hours compared to less than 1,000 psi for normal concrete. Tensile strength is around 2,000 psi after the material has been allowed to set for seven days, whereas normal concrete typically has just a few hundred psi. Alternatively, for patching, there are numerous proprietary brands of quick-setting cement. These can be used for patching, but a normal requirement is that they be placed in relatively thin layers because of the heat they generate. The manufacturer instructions should be followed.

5.3.3.4 Using Polymer Concrete

Choose a liquid or dry redispersible polymer option, depending on your needs and preferences. Liquid polymers usually come in a jug with instructions for how much to add to a bag of dry mix containing sand, cement, and other ingredients. It will also include instructions for avoiding freezing temperatures; this affects the integrity of the polymer. Dry polymers are usually added to the dry mortar mix in advance, so the contractor only needs to add water to a bag of dry mix.

Follow the instructions on the label: Cutting corners, like using too little polymer from the jug or using a product in an application for which it was not designed will likely lead to a failed repair.

The use of polymer concrete in concrete replacement is covered in Section 5.7.6.

5.4 Other Types of Concrete

The two previous sections focused on the most popular types of concrete used in bridge maintenance (hydraulic cement concrete and polymer concrete). Other types include:

- High Performance Concrete
- Self-Consolidating Concrete
- Lightweight Concrete

High performance concrete is a specialized series of concretes designed for better performance, cost, extended life cycle and most importantly reduced maintenance. Performance benefits applicable to bridge maintenance include early high strength, toughness, ease of placement and longer life in severe environments. Examples types include Very Early Strength Concrete, which can achieve a compressive strength of 2,000 psi in only 6 hours, to Very High Strength Concrete, which can achieve a compressive strength of 10,000 psi in 28 days. Some mixes include special admixtures such as fiber reinforcement to enhance strength and durability.

Self-Consolidating concrete is highly flowable, resistant to segregation, and requires no vibration. This is an excellent choice for bridge maintenance repairs where there is no effective way to vibrate the concrete. It is also an excellent choice where there is significant rebar congestion that might lead to voids and honeycombing of the repair. Self-Consolidating concrete uses new generation admixtures and for that reason is more expensive than normal concrete. It has some drawbacks, such as sensitivity to water ratio changes in the mix. An example of a slump test, used to determine the workability of fresh concrete, is shown in Figure 5.1. The slump test for self-consolidating concrete is very different from normal concrete. Because the mix is so flowable, the spread of the mix is measured instead of the slump height. The spread of the mix is measured by measuring the diameter of the poured concrete cone

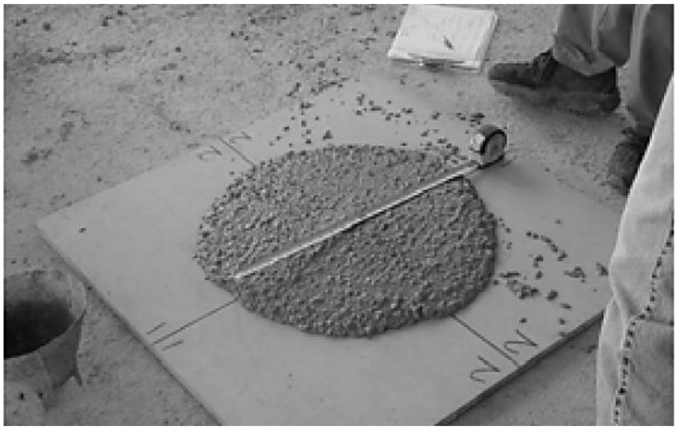


Figure 5.1 Self Consolidating Concrete Slump Flow Test

Lightweight concrete uses a lighter weight aggregate and can reduce overall concrete weight by 20 percent. It could be considered for a concrete repair where the weight of the normal concrete repair could be damaging to the bridge element. Lightweight concrete has been used in many decks. Due to the different types of aggregates used in lightweight concretes and the need for compatibility of the repair with the original design/materials (e.g., weight, electric potential, etc.), an engineer should be consulted if a repair to a lightweight concrete bridge member is to be made.

When to Call the Engineer

Call the Engineer when a repair to a lightweight concrete bridge member is going to be made.

5.5 Identification of Deteriorated Concrete

Concrete is a cost effective building material, i.e., relatively cheap but strong (in compression) and fairly chemically resistant. But eventually concrete will crack and deteriorate. There are many reasons why deterioration occurs, such as:

- Adverse chemical reactions between the cement and the aggregate
- Improper mix design
- Lack of concrete cover
- Problems with delivery to the site
- Temperature extremes on the day of the pour
- Poor curing

While these issues are all important, even a quality mix design placed in perfect conditions can still have problems down the road.

The culprit in concrete degradation typically is not the concrete itself, but the steel reinforcement (rebar) that is embedded in the concrete. When water has access to the rebar, either through a crack in the concrete or through pores in the concrete itself, the rebar is then exposed to water, oxygen, and potentially chlorides. These ingredients, in physical contact with the steel rebar, will begin the corrosion process. Once steel starts to corrode, it expands to many times its original cross section due to the formation of corrosion product at the rebar surface. The corrosion product exerts pressure onto the concrete, a tension force, and since concrete is weak in tension, it will further crack. These new cracks will allow more water, oxygen and salt to further corrode the rebar in a vicious cycle. Soon the concrete will delaminate or debond from the steel, and a spall develops. See Figure 5.2 that depicts the typical concrete deterioration process.

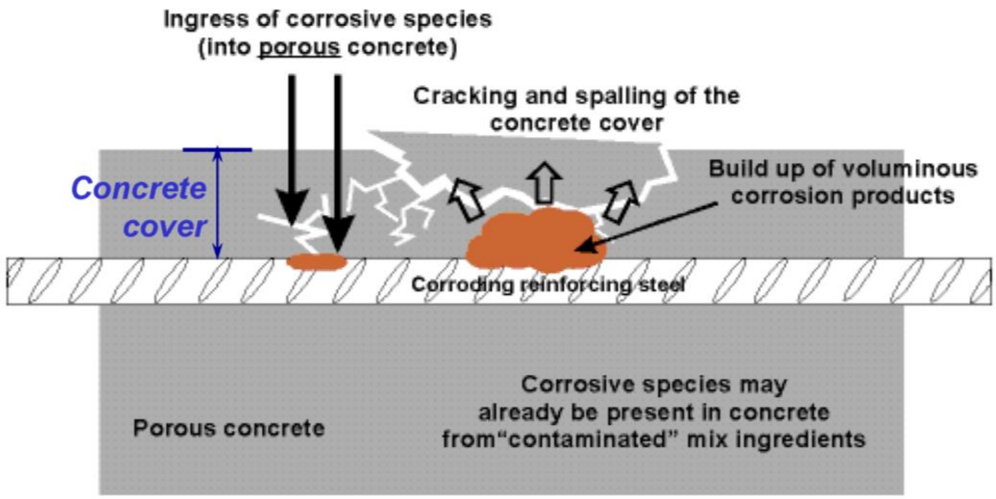


Figure 5.2 Concrete Deterioration Process

Engineers have tried many kinds of potential solutions to this problem. A summary of potential strategies for preventing concrete deterioration is presented in Table 5.2.

Table 5.2 Potential Solutions to Prevent Concrete Deterioration

Potential Solution	How is the Solution Working?
Eliminate one of the ingredients that cause rebar corrosion. Do not salt the concrete roads and bridges.	Salt (chloride) is excellent at melting ice and snow. Some states use sand, but when the sand pile freezes, they add salt to melt. Don't introduce chloride-containing salts to concrete.
Protect the steel rebar by coating	This has been used with some success, epoxy, galvanized, stainless steel, stainless clad rebars, etc. Caution needed when rebar coating is damaged, particularly during on site storage and placement during bridge construction (e.g., there are stories of trucks driving over the rebar).
Replace steel rebar altogether with smart materials	Rebar made of fiber reinforced composites (FRP) has been used in many bridges with promising results.
Make concrete more dense	Low permeability concrete has helped deter the corrosion process by reducing the water access to the rebar.
Preventive Maintenance, fill cracks as soon as they appear, apply protective membranes	BINGO!

Failure of concrete is a complex phenomenon because more than one mechanism of damage occurs at the same time, and it is difficult to determine which problem caused the initial damage. It is important to have an understanding of the basic underlying causes of damage in concrete and the maintenance problems that develop. The most common cause for failure of reinforced concrete is corrosion of the reinforcing steel, but concrete can deteriorate by other means as well.

Some common construction related defects in concrete include voids and inclusions (also known as honeycombing, due to incomplete vibration), poor surface finish or cracked surface (due to plastic shrinkage), damage and cracking from residual stresses (due to thermal effects), surface weakness, weak bonds between steel and concrete due to bleeding and cracking at cold joints.

In-place concrete can deteriorate from load-related causes, such as fatigue, impact, residual stresses due to overloading, and creep. Or, deterioration can be environment-related, such as corrosion, chemical attack (alkali-silica reaction), creep and shrinkage, carbonation, freezing and thawing, de-icing salts, and scaling. Improper maintenance or repair could also be classified as a service-induced damage.

5.5.1 Condition Assessment

Assessing the condition of concrete members is categorized into Non-Destructive Testing (NDT), semi-destructive testing, and destructive testing. NDT (also called Non-Destructive Evaluation or NDE) is a class of evaluation techniques that do not damage the existing concrete. Semi-destructive tests require removal of a piece of the material for evaluation. Destructive tests are performed to failure. Destructive tests, such as those done on concrete cores, result in some minor damage to the concrete, but the damage can be repaired. A brief summary of NDE is provided in this section, with a more comprehensive summary provided in Appendix 2 References.

The first step in performing a condition assessment is to get details of the structure with respect to its design, features, and past performance. An initial visual inspection of the structure can reveal useful information about areas that need a closer look. There are many causes for the deterioration of structures, so it is difficult to exactly pinpoint the type of damage that has led to the deterioration. However, all types of damage, whether they be load related, environment related, or earthquake related, lead to similar signs of concrete deterioration, cracking, spalls, delaminations, and corrosion.

Traditional methods for locating unsound or deteriorated concrete include visual assessments (including cameras), sounding (chain drag and hammer sounding), and half-cell potential measurements (copper-copper-sulfate). Specialized equipment can also be brought in to help determine the specific mode of deterioration. These methods are discussed further in Section 5.5.3, Chapter 20, and Appendix B.

5.5.2 Types of Reinforced Concrete Deterioration and Detection

The main categories of reinforced concrete deterioration are shown below:

Cracking

Cracking can be found in almost all concrete bridge elements. The cracks may be vertically oriented such as the column cracks shown in Figure 5.3, horizontally oriented following the rebar spacing, and they can be full depth or partial depth such as deck cracks due to concrete plastic shrinkage or restraint. Cracking can also be random based on the material deterioration as described below.

Delamination

Detection of delaminations (or the debonding of concrete from the reinforcing steel) includes detection of predominantly horizontally-oriented cracks, although substructure members may exhibit delamination on vertical surfaces. Delamination occurs as a result of rebar corrosion, overloading, or other type of deterioration. Delaminated concrete needs to be detected and restored to original conditions. Delaminations are detected by sounding.

Spalls

Spalls (concrete pieces that are flaking or breaking away from the surface) are detected during a visual review.

Corrosion

Detection of rebar corrosion is directed towards two main objectives: detection and evaluation of intensity of active corrosion, and detection and evaluation of the severity of existing corrosion.

Figure 5.3 Vertical Crack on a Pier Column

Concrete Material Deterioration

Detection of concrete deterioration involves measurement of a change or variability of material properties regardless of what is the cause of concrete deterioration: corrosion, alkali-silica reaction (ASR), carbonation, and mechanical or thermal stresses.

Alkali Silica Reactivity

ASR is a widespread problem, affecting concrete structures in almost every area of the U.S. It occurs when silica in aggregate and alkali in cement react in the presence of water. This reaction creates a gel in the hardened concrete. Over time this gel expands causing cracks and disintegration of the bond between the concrete ingredients. An example of ASR cracking is shown in Figure 5.4.

The *SHRP Handbook for the Identification of Alkali-Silica Reactivity in Highway Structures*, http://www.fhwa.dot.gov/pavement/concrete/asr/pubs/hif12022.pdf, describes a test that treats concrete core samples with a uranium acetate solution before viewing under ultra violet (UV) light. Any ASR gel present in the treated concrete will then appear to fluoresce under UV light. An example of ASR cracking viewed by this method is shown in Figure 5.5.

Figure 5.4 ASR Cracks in a Concrete Column

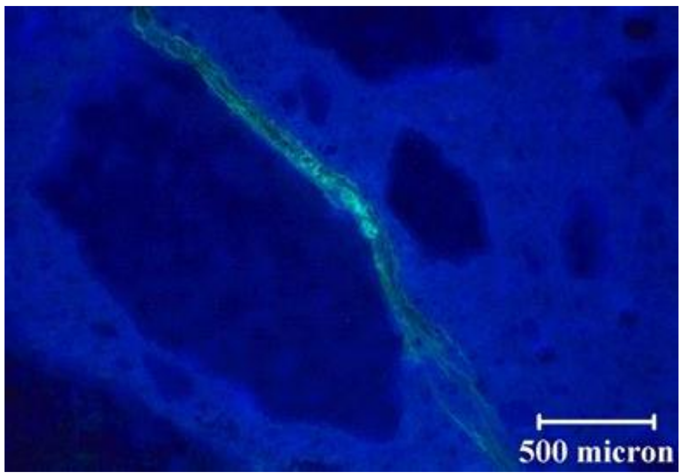


Figure 5.5 Microscopic Image of ASR Crack

Reactive aggregates should be avoided if possible in future construction and repairs. However, solutions to prevent or mitigate this problem on existing bridges are limited. The most practical solution appears to be drying concrete (artificially if possible) and sealing with a low viscosity polymeric material (such as high-density methacrylate) which could penetrate deep into hairline cracks. The application of this method is limited to the elevated members, such as bridge decks. In that case, sand is spread on the sealer for friction. In members in contact with earth the drying method may not be effective because of the ready access of moisture from the earth. For bridge columns, it has been suggested that ASR expansion may be restrained by cylindrical wrapping of the column.

For each of the main deterioration types, several technologies have shown potential for detection and evaluation. However, there is not a single technology that has shown potential in evaluation of all deterioration types.

For additional information, please refer to Chapter 20 Concrete Deck Decision Aid Matrices and Appendix B References.

5.5.3 Non-Destructive Evaluation (NDE) Techniques

Non-destructive evaluation techniques range in sophistication from simple methods where the quality of sound obtained by striking the surface of the material with a hammer to complicated techniques where the ultrasonic signals traveling through the material are analyzed mathematically.

Good NDE methods possess the following qualities:

- Sensitivity to small flaws
- Reliability
- Simplicity
- Cheap
- Portable
- Easy to use

NDE methods provide information but are not 100 percent accurate. Some factors that affect the reliability of NDE techniques are:

- The location and the orientation of subsurface cracks
- Difficult access for the equipment
- Selection of the proper technique
- Correct application – proper training of technician and proper calibration of equipment
- Environmental factors – weather, live traffic, and material property
- Human factors – the location of the test, operator fatigue, time constraints, bias, and experience

5.5.3.1 Visual Assessment

Visual assessment is the most commonly used non-destructive evaluation method for determining concrete condition. A detailed visual inspection makes it possible to focus on the critical areas in a structure that may benefit from further investigation using more sophisticated techniques. Areas that show cracking, discoloration, rust stains, etc. should be investigated closely with the help of visual aids such as magnifying lens and crack comparators. Visual inspections can identify areas of deterioration that could be investigated further using more sophisticated techniques. Concrete scaling, such as that shown in Figure 5.6, is one of the forms of deterioration readily identifiable during a visual inspection.

Visual inspections can be aided by a number of tools such as:

- Telescopes / Binoculars
- Camera
- Magnifying lenses
- Real-time video
- Ruler, measuring tape
- Crack width gauge comparator
- Light hammer, chipping / scraping tools

Figure 5.6 Scaling on a Bridge Deck (Courtesy of Iowa State University)

Table 5.3 provides a visual observation of concrete deterioration and corresponding probable cause.

Table 5.3 Likely Causes of Various Types of Deterioration

Visual Observation	Deterioration Type and Probable Cause
Rust staining, cracks run in straight parallel lines at uniform intervals as per the reinforcement position. Spalling of concrete cover	Reinforcement corrosion: Exposure to normal atmospheric conditions, Cyclic wetting and drying
Cracks mostly on horizontal surfaces, parallel to each other, 3 to 6 feet apart, relatively shallow 1/2 to 1 inch in depth and vary in length from 1 inch to 10 feet (see Figure 5.7)	Plastic shrinkage: Caused by surface tension forces, environmental effects of temperature (concrete and ambient), wind velocity in excess of 5 mph and low relative humidity while curing
Cracks characterized by their fineness and absence of any indication of movement, shallow (a few inches) in depth, typically orthogonal or blocky	Drying shrinkage and creep: Placement of a footing on a rough foundation, or chemical bonding of new concrete to earlier placements; the combination of shrinkage and restraints cause tensile stresses that can ultimately lead to cracking
Cracks are regularly spaced (restrained contraction) and perpendicular to larger dimensions of concrete, spalling (restrained expansion), shallow and isolated (internal restraint), extend to full depth (external restraint), surface discoloration (fire damage) (see Figure 5.8)	Thermal effects: Induced by exothermal chemical reaction in mass concretes. If volume change is restrained during cooling of the mass, by the foundation, the previously placed concrete, or exterior surfaces, sufficient tensile strain can develop to cause cracking
Spalling and scaling of the surface, exposing of aggregate which is un-cracked, surface parallel cracking and gaps around aggregate (see Figure 5.6)	Freeze-thaw deterioration: Alternate cycles of freezing and thawing, use of deicing chemicals
Absence of calcium hydroxide in cement paste and surface dissolution of cement paste exposing aggregates	Acid attack: Acid smoke, rain, exhaust gases
Rough surface, presence of sand grains (resembles a coarse sand paper)	Aggressive water attack: Causes serious effects in hydraulic structures due to a continuous water supply resulting in the washing away of aggregate particles due to leaching of cement paste
Map or pattern cracking, general appearance of swelling of concrete (see Figure 5.9)	Alkali-carbonate reaction: Chemical reactions between alkali in cement with certain dolomitic aggregates, Expansion due to dedolomitisation and subsequent crystallization of brucite
Map or pattern cracking, expands freely, silica gel leaches from cracks, calcium hydroxide depleted paste.	Alkali-silica reaction: Chemical reactions between alkali ions (Na^+ and K^+) in cement with silica in aggregates
Map and pattern cracking, general disintegration of concrete	Sulphate attack: Formation of gypsum, thaumasite and ettringite which have higher volumes than the reactants
Single or multiple long diagonal cracks (usually larger than 0.25 inch in width) accompanying misalignment and displacements	Structural damage: Induced by improper construction and maintenance throughout the lifetime of a structure.
Spalling or cracking of concrete, complete collapse of structure	Accidental loadings: Generates stresses higher than strength of concrete resulting in localized or complete failure of the structure
Honey combing, bug holes (Small holes less than about 0.25 inch in diameter), cold joints, cracking in concrete	Construction errors: Improper mix design, consolidation, curing etc., inexperienced labor work, incorrect position of reinforcement.
Surface is generally smooth with localized depressions, long shallow grooves, spalling along monolith joints (abrasion). Severely pitted and extremely rough surface (Cavitation)	Erosion: Rolling and grinding of debris (abrasion), sub atmospheric pressure, turbulent flow and impact energy (cavitation)
Cracking or spalling of concrete, complete deterioration of the structure. (see Figure 5.10)	Design errors: Abrupt changes in design, insufficient reinforcement, inadequate provision for deflection and drainage

The following forms of deterioration may be observed by visual inspection and apply to concrete construction:

- Crack type, classified as:
  - Hairline – barely visible
  - Fine – 1/32 inch to 1/16 inch
  - Medium – 1/16 inch to 1/8 inch
  - Wide – Greater than 1/8 inch
- Patterns, location, and orientation of cracks (whether stress related or not)
- Scaling, classified as:
  - Light – does not expose coarse aggregate
  - Medium – involves loss of surface mortar to 1/8 inch to 3/8 inch in depth and exposure of coarse aggregate
  - Severe – involves loss of surface mortar to 1/8 inch to 3/8 inch in depth with some loss of mortar surrounding aggregate particles 3/8 inch to 5/8 inch in depth
  - Very Severe – involves loss of coarse aggregate particles as well as mortar generally to a depth greater than 5/8 inch
- Spalling, classified as:
  - Small – involves a roughly circular depression not greater than 5/8 inch in depth and 6 inch in any dimension
  - Large – may be roughly circular or oval or in some cases elongate; more than 5/8 inch in depth and 6 inches in greatest dimension
- Exposed reinforcement

Other general defects that can be identified by visual observation are:

- Surface distress: Disintegration of the surface, surface honeycombing.
- Water leakage: Surface dampness, efflorescence, seepage or leakage through joints or cracks.
- Movements: Deflection, heaving, settlement.
- Metal corrosion: Rust staining, exposed post-tension cable strands.
- Miscellaneous: Blistering membranes and coatings, ponding of water, discoloration.

Figure 5.7 Plastic Shrinkage

Figure 5.8 Cracking from Thermal Effects

Figure 5.9 Map Cracking

Figure 5.10 Spalls and Cracking

Concrete Cracks

Cracks in reinforced concrete do not necessarily mean the presence of unsound concrete. Regardless of the crack type, water seeps in and causes the reinforcement to corrode. The corroded reinforcement expands and exerts pressure on the concrete. This pressure can cause delaminations and spalls. The presence of rust stains or efflorescence are evidence of possible reinforcement corrosion and section loss.

Exercise care in distinguishing between nonstructural cracks and structural cracks. An example of spalled concrete and efflorescence is shown in Figure 5.11.

Figure 5.11 Spalled Concrete and Efflorescence on the Underside of a Bridge Deck

Crack widths in reinforced concrete bridges exceeding 0.006 inches to 0.012 inches reflect the lower limit of moderate cracking. The American Concrete Institute Committee Report 224R-01 presents guidance for what could be considered reasonable or tolerable crack widths at the tensile face of reinforced concrete structures for typical conditions. These range from 0.006 inches for marine or seawater spray environments to 0.007 inches for structures exposed to de-icing chemicals, to 0.012 inches for structures in a humid, moist environment. A crack comparator used for determining crack widths is shown in Figure 5.12.

In prestressed concrete bridge structural elements, cracking is generally more problematic than cracking in reinforced concrete elements. This is because prestressing is designed to control or prevent cracking in the member while normal steel reinforcement is intended to structurally bridge cracks. Thus, cracking in prestressed elements may indicate a design or fabrication flaw or that an overload of the structural element has occurred. A determination of the exact cause of the cracking, as well as an assessment of possible structural damage to the element and/or its prestressing steel, is needed before arriving at a repair method.

Figure 5.12 Crack Comparator for Determining Crack Width

5.5.3.2 Sounding

Hammer Sounding

A good evaluation of concrete can be easily obtained by just sounding it (i.e., tapping it) with a hammer. When the hammer is struck on good concrete, a ringing sound is created. Where delaminations occur, the striking of the hammer produces a drum-like, or thud. A schematic is presented in the left side of Figure 5.13. Because sounding is a manual method, several factors can affect accuracy of the investigation. Exposure to constant sounding may lead to temporary or permanent operator desensitization to high-pitched tones. It can also be difficult to hear when sounding near live traffic. The feel of the rebound of the hammer will help an experienced technician determine the condition of the concrete. The hammer will seem to bounce off sound concrete but tend to “lay-into” punky concrete. The limitation of sounding is that it cannot detect defects that exist deep in the member. Also, defects lying under overlays are also difficult to find. Operator fatigue can also be a problem.

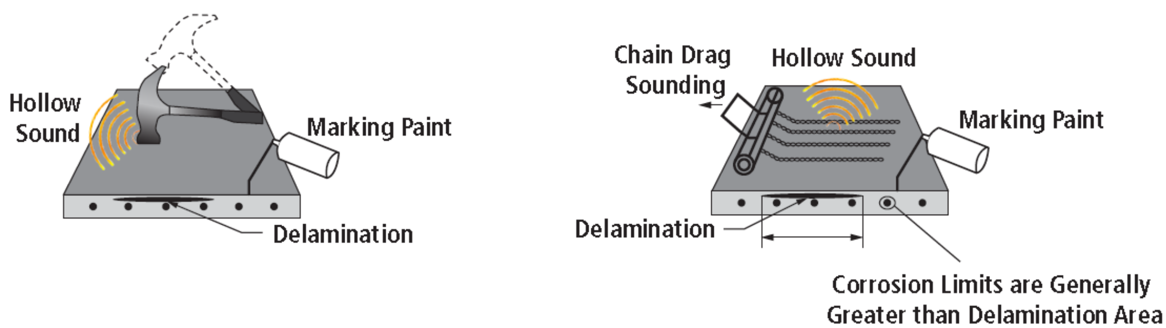


Figure 5.13 Sounding Tests: Hammer (left) and Chain Drag (right)

Recommendation

The sounding method should not be used on asphalt overlaid concrete decks.

Chain Drag Sounding

Chain drag is another way of finding delaminations and voids. Compared to sounding with a hammer, chain drag can cover more area in a given time. In this method, the operator passes a heavy chain on the surface of the concrete. The quality of sound generated is picked up using microphones and can be characterized by wavelengths. A schematic of chain drag was shown in the right side of Figure 5.13.

To conduct a sounding test, a grid is first laid on the concrete surface. Then the surface is sounded; the areas where delaminations are heard are recorded. A delamination map is then drawn and the amount of delamination is computed as a percentage of the total surface area. Spalls are not included. For bridge decks, 5-foot grid may be used. For substructure and/or superstructure members, the grid size may be 2.5-foot.

Suggested Procedure

Sound Testing

1. A grid is first laid on the concrete surface.
2. Then the surface is sounded; the areas where delaminations are heard are recorded.
3. A delamination map is then drawn and the amount of delamination is computed as a percentage of the total surface area. Spalls are not included. For bridge decks, 5-foot grid may be used. For substructure and/or superstructure members, the grid size may be 2.5-foot.

When the method is used on decks overlaid with cement concrete mixtures, it will detect both debonding of the overlay and delamination of the underlying concrete; but the method cannot distinguish debonding from delamination. A supplementary corrosion detection test may be used to delineate debonding from delamination. Note that delamination will be associated with bar corrosion, whereas debonding will not. The sounding method is considerably less accurate when used on decks overlaid with asphalt concrete and should not be used on decks overlaid with asphalt concrete. For more information, see ASTM D4580 *Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding*, 2012.

5.5.3.3 Corrosion Survey

Corrosion Potential

This procedure determines the potential for the existence of reinforcing steel corrosion through measuring the electrical potential of the reinforcing steel. The electrical measurements are made by placing a half-cell probe on the deck surface at predetermined grid points. The electrode may be attached to a hand-held voltmeter or it may be in the wheel of a rolling device that stores data for transfer to a laptop computer. Either way, the probe is attached to a rebar in the deck, which is in contact with the rebar mat being tested. A schematic of half-cell equipment for measuring corrosion potential is shown in Figure 5.14.

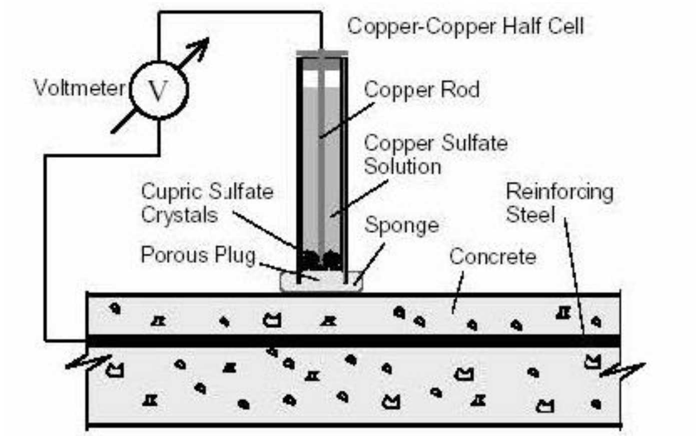


Figure 5.14 Schematic of Half-Cell Potential Test

An example of half-cell test equipment applied on a bridge deck is shown in Figure 5.15.

Figure 5.15 Example of Half-Cell Potential Test

The magnitude of the voltage measured determines the state of the steel with respect to corrosion. Laboratory tests have found that steel is corroding if the electrical potential is numerically greater than 0.35 Volts (relative to copper/copper sulfate reference cell) and steel is not corroding if the potential is numerically less than 0.20 Volts. For potential in the range of 0.20 to 0.35 Volts, the corrosion activity of steel was found to be uncertain. Electrical potential test results may be used for repair of reinforced concrete bridge elements. To do this, the deteriorated areas as well as all areas with a corrosion potential numerically more than 0.25 Volts (relative to copper/copper sulfate half-cell) are removed and replaced.

The half-cell corrosion detection test cannot be conducted when a dielectric material, such as a waterproofing membrane or polymer, is applied on the concrete surface, unless the material is punctured at the test location. Also, the test is not recommended for epoxy-coated reinforcement. This is because epoxy-coated bars are electrically insulated from each other. Older decks in which the epoxy coating is more deteriorated may be an exception; in that situation, half-cell testing may provide value.

Recommendation

Half-cell corrosion detection should not be used if the following conditions are present:

- The concrete surface is protected with polymer or waterproofing membrane
- Epoxy Coated reinforcement is present in the concrete member to be evaluated

Depth of Cover Meter (Pachometer)

The less concrete over the rebar, the less protection there is against salt penetration, since moisture can access the rebar more quickly. Cover depth may be measured by a cover meter (pachometer), which is a magnetic flux device. This device uses a magnetic field to detect reinforcing steel within concrete. It can determine the location, orientation, size, and depth of the bar. For a meaningful evaluation, a number of locations should be tested. An example of an appropriate number of tests is the greater of (1) 40 locations per member or (2) 40 locations per every 5,000 square feet of deck. Examples of a cover meter (pachometer) are shown in Figure 5.16 and Figure 5.17.

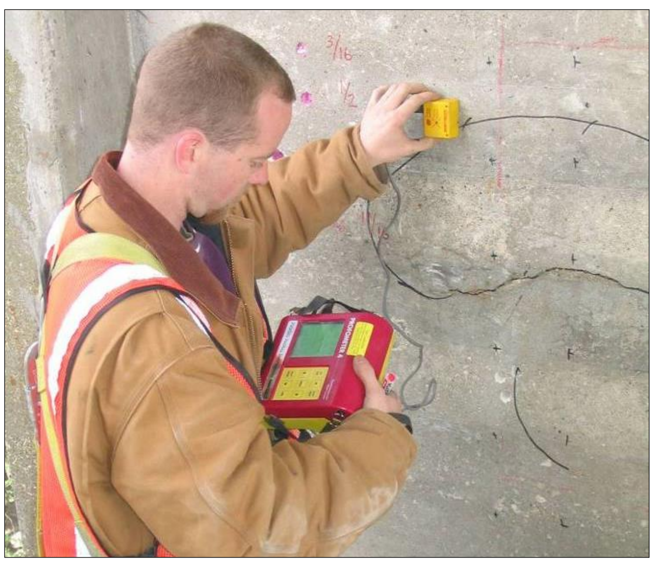


Figure 5.16 Pachometer in Use

Figure 5.17 Examples of Pachometer Equipment

The accuracy of the device in measuring the depth of cover decreases as the depth of cover increases. Magnetic particles in the concrete can influence the measurements. Thus, a correction factor should be obtained by exposing the bar at one location and measuring the actual depth. Usually, the correction factor is obtained at a location which can later serve as the half-cell test bar ground connection.

If the bar size is not known, due to equipment limitations using magnetic field measurements, the depth cannot be read directly from the scale. Therefore, the following procedure is suggested:

Suggested Procedure

Using a Pachometer

1. Locate the bar in the test area.
2. Place a two-by-four, or other non-metallic spacer, between the probe and the concrete surface.
3. Record possible bar size and depth combinations.
4. Correct readings for the thickness of the spacer by subtracting its thickness.
5. Place the probe directly on the concrete surface and record possible reading.

The bar size for which the same cover depth is obtained in Steps 4 and 5 is the correct result.

Cover depth may also be determined using Ground Penetrating Radar (GPR).

Corrosion Rate Measurement

Since concrete deck deterioration from salt contamination is one of the most expensive bridge maintenance problems, there are ongoing advancements in detecting and predicting the problem. Examples of newer, and perhaps more precise, methods of predicting corrosion damage are devices that measure the rate of corrosion and the permeability of concrete.

The corrosion rate device determines the rate of corrosion of reinforcing steel, or stated differently, the thickness of the rebar section loss every year. Corrosion current is expressed in terms of milliamperes per square foot of reinforcing steel area, which can be converted to section loss per year. These types of measurements may be performed using a field machine, together with appropriate probes and electrodes. An example field machine is shown in Figure 5.18. Also shown is a schematic of a typical probe and electrode set-up. Wire cable connections between field corrosion rate device and electrodes are not shown. Similar to a half-cell potential test, corrosion rate tests cannot be carried out where epoxy-coated or galvanized reinforcement is used or where there is a dielectric overlay or coating on the concrete.

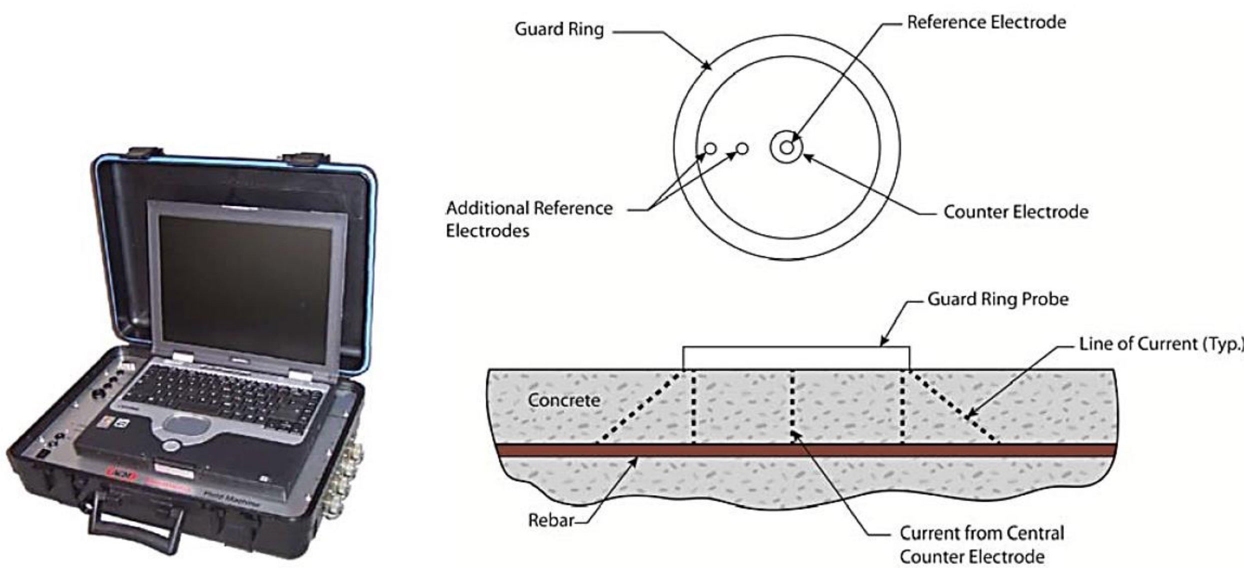


Figure 5.18 Example of a Corrosion Rate Device and Associated Electrode Schematic

5.5.3.4 Swiss Hammer for Approximate Compressive Strength

A hand held, spring loaded, device known as a Swiss Hammer (also called a Schmidt Hammer) can be used to gauge concrete compressive strength. Striking the spring tip against a concrete surface produces a gauge reading on the hammer that indicates the compressive strength. It is best to try this several times and take an average reading. The hammer is less accurate than laboratory compressive testing, but may be useful as a triage device in deciding whether to take cores and send them to a lab. A photo of a Swiss Hammer, or Schmidt Hammer device, is presented in Figure 5.19.

Figure 5.19 Swiss (Schmidt) Hammer

5.5.3.5 Portable Surface-Air Flow Device for Relative Permeability

Strategic Highway Research Program (SHRP) has developed a test procedure to measure relative concrete permeability non-destructively in the field. Using a portable surface-air flow device, the permeability measuring method creates a vacuum and measures the rate of air flow through the top half an inch of concrete. The higher the air flow rate, the higher will be the permeability. The SHRP method saves time by making on-site, non-destructive testing possible. The SHRP test method, *Method for Field Measurement of Concrete Permeability*, is documented in SHRP Report No. SHRP-S/FR-92-109, Strategic Highway Research Program, National Research Council, 1992.

5.5.3.6 Advanced NDT Techniques

Unlike a visual or hammer sounding where the assessment is a subjective determination, these techniques use data recorders and sensors to generate numbers.

Some of the more specialized methods appropriate for the evaluation of highway structures include: Impact echo (IE), Ultrasonic pulse echo (UPE), Ultrasonic surface waves (USW), Ground penetrating radar (GPR) and Infrared thermography (IT).

Non-destructive testing (NDT) of concrete is complicated because concrete is composed of aggregates, cement, rebar, and small air voids. It becomes difficult to distinguish between defects and an indication (a defect within tolerance is called an indication) in normally occurring situations within the concrete. In addition, a uniform pass/fail defect criteria for good concrete is not available.

Detailed information on the following advanced NDT Techniques is provided at:
http://www.ndtoolbox.org/

Impact Echo (IE)

The IE method is based on the reflection measurement of mechanical stress waves, i.e., the time it takes for the stress wave generated by an impact to be received by the receiver. This method was originally developed to determine the thickness of concrete slabs and to detect defects such as delamination and void within concrete structures and has been standardized under ASTM C1383. The method has also been used for detection of debonding beneath Asphalt Concrete (AC) and Portland Cement Concrete (PCC) overlays. An example of the IE method is shown in Figure 5.20.

Recent advances in IE technology include the development of scanning systems and advanced signal processing approaches to speed up field testing and facilitate the interpretation of IE data. The IE method, with both point-by-point and scanning devices, can be used for characterizing delamination, overlay debonding, and for evaluation of vertical cracks.

Figure 5.20 Impact Echo Testing

Ultrasonic Pulse Echo (UPE)

A UPE test involves measuring the time it takes a high frequency ultrasonic wave to travel through a material between two or more points. Based on the time or velocity, this technique can also be used to detect the presence of internal flaws such as cracks, voids, delamination and other damage. Examples of ultrasonic pulse echo equipment are shown in Figure 5.21 and Figure 5.22.

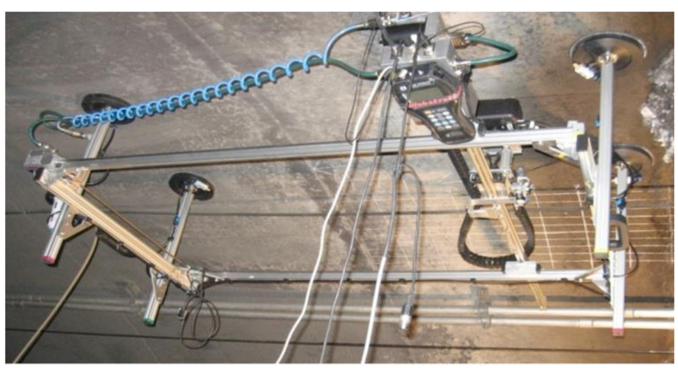


Figure 5.21 Ultrasonic Echo Control Unit Mounted on Automated Scanning Device

Figure 5.22 Ultrasonic Echo Control Unit and Sensor Array

Ultrasonic Surface Wave (USW)

With suitable equipment and processing software, an USW test can be rapidly performed to assess the properties of concrete including the changes in modulus caused by mix design, compaction, curing, stress-related cracking and concrete deterioration. For concrete deck deteriorations such as debonding and delamination, the USW method can play a supplemental role. Examples of USW equipment are shown in Figure 5.23 and Figure 5.24.

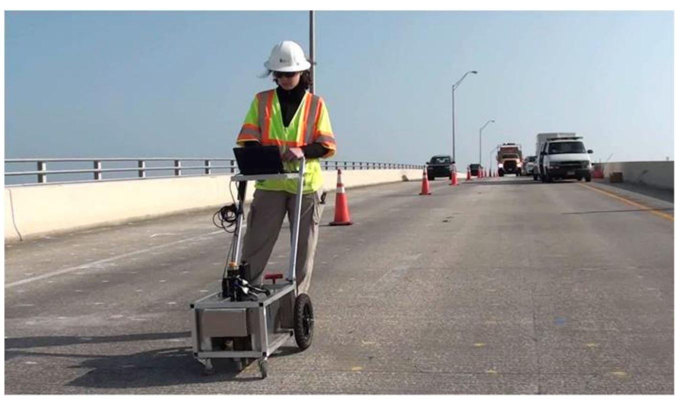


Figure 5.23 USW on Bridge Deck

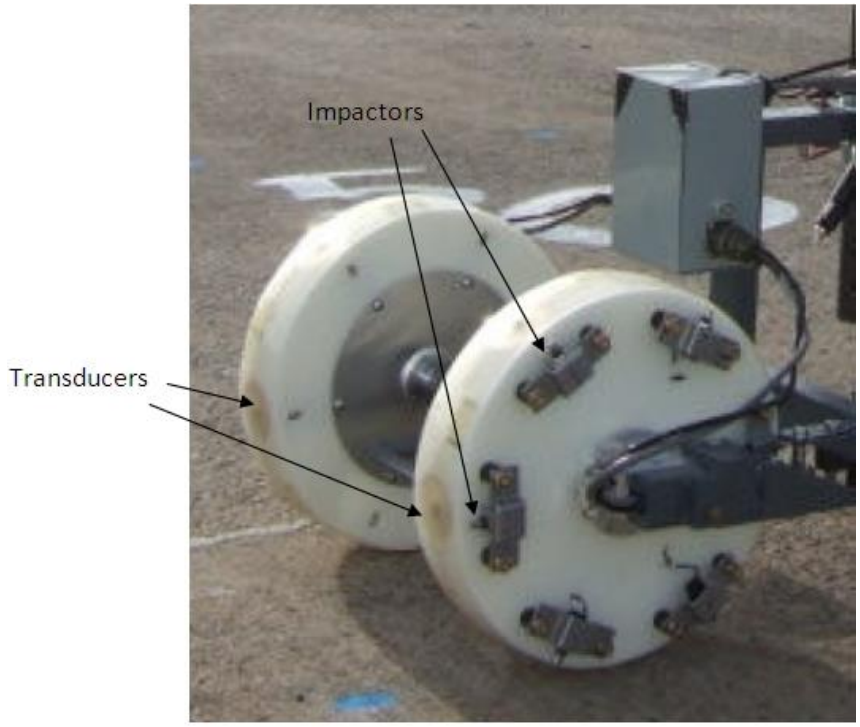


Figure 5.24 Bridge Deck Scanner Device has Two Identical Transducer Wheels

Ground Penetrating Radar (GPR)

The Ground Penetrating Radar (GPR) method is an electromagnetic-based reflection method that can provide graphical images of subsurface features. The images are useful for interpreting subsurface structure and layout. Application of this technique is good for detecting rebar location, pavement thickness, asphalt overlay thickness, and voids beneath pavements. A photo of a worker performing GPR testing is shown in Figure 5.25.

Figure 5.25 Worker Performing GPR Testing

GPR has a distinct advantage over other NDE methods since it is able to be used fairly quickly and easily for a variety of bridge decks and other reinforced concrete applications. The GPR condition assessment reaches the top rebar mat and can be performed at highway speeds. An example of GPR results is shown in Figure 5.26.

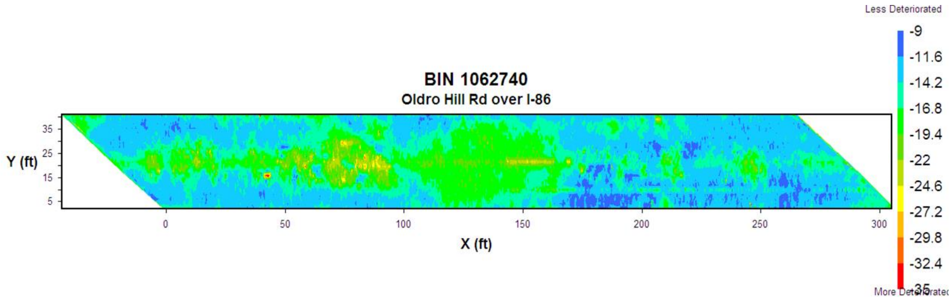


Figure 5.26. Map of GPR Results

Infrared Thermography (IT)

The detection of heat flow through a body can indicate the presence of flaws or defects. In the Infrared Thermography (IT) technique, heat is passed through the material, and an infrared detector detects the heat patterns flowing in the body. As shown in the schematic in Figure 5.27, when a defect is present in the body, it would show up as a hot spot when heat is flowing inward, and as a cold spot when the heat is flowing outward.

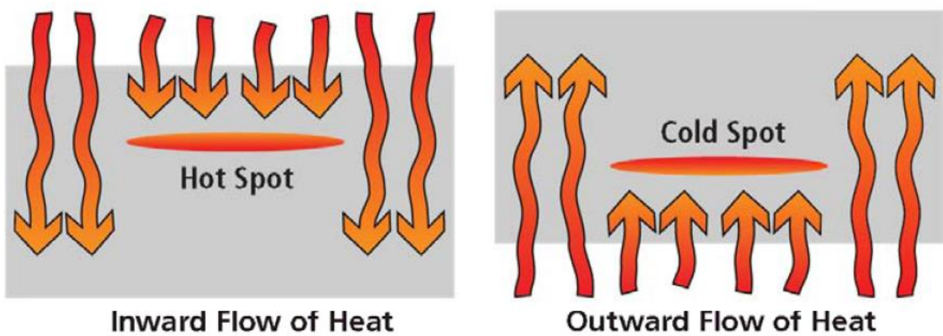
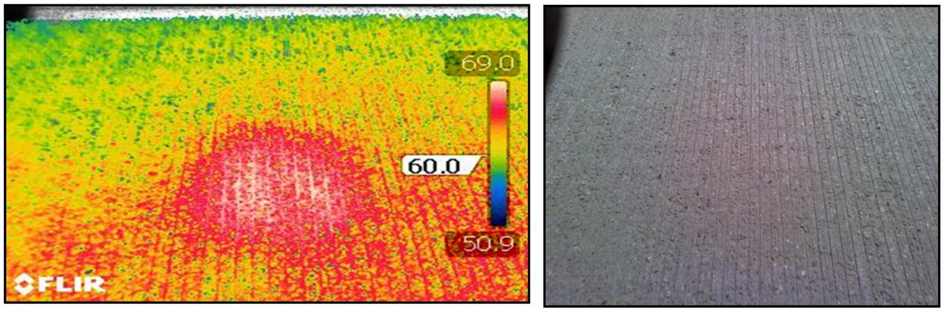


Figure 5.27 Schematic of Flow Direction and Corresponding Defect Appearance During IT

This technique is very useful in detecting delaminations in bridge decks. Complete thermal scan of the bridge deck may be obtained to identify defective areas. The limitations of this technique are that its accuracy is somewhat limited to the near-surface areas, and the application requires the presence of good weather and the suitable time of day. Also, surface conditions might have a bearing on the result. An example of IT results showing a subsurface defect and corresponding photo of the surface is presented in Figure 5.28.



(a) (b)

Figure 5.28 Example of (a) IT Results Showing Subsurface Defect (b) Corresponding Photo

The surface of the concrete over the delaminated area exhibits a temperature gradient (positive during the day and negative at night) with respect to its surrounding intact area. The capability and effectiveness of this method depend on climate conditions, as shown in Table 5.4.

Table 5.4 Environmental Conditions for Deck IT Inspections According to ASTM D 4788-07

Time of Year	Direct Sunlight (hours)	Change in Ambient Temp.	Wind Speed (miles per hour or mph)	Detection Limit (ΔT)	Notes
Summer	3	None specified	< 30 mph	1.8 °F	Dry deck for 24 hours prior to test
Winter	4	20 °F	< 15 mph	1.8 °F	Ambient temp. > 32 °F
Winter, asphalt	6	20 °F	< 15 mph	1.8 °F	Ambient temp. > 32 °F

The advantages of using thermography are:

- Real-time feedback for assessment while crews are mobilized
- No processing software needed; straightforward data analysis, works independently of PC
- Early detection of delaminations possible before visual signs of distress occur
- Hands-on access not required
- Relatively simple to use, essentially the same operation as consumer digital camera, whereas the investigation of very shallow areas in concrete structures often difficult with other NDT methods
- Testing at highway speeds possible

Disadvantages/Limitations:

- Favorable weather conditions are needed, i.e., clear skies, dry and calm winds.
- Generally the imaging is limited of a depth of 2 inches.

The limitations and scope of these techniques must be well understood. The type of test to be carried out and the extent of the investigation (i.e., whether only specific areas are to be selected or the entire structure needs investigation) should be properly detailed.

5.5.4 Destructive Testing

5.5.4.1 Concrete Cores

Cores are taken to provide a sample of the hardened concrete in place. Cores are used to perform microscopic analysis and other laboratory procedures that identify problems related to aggregate quality, air content, materials incompatibility or chemical contamination. Cores can also be tested to measure the compressive strength of the concrete. However, most concrete problems on existing bridges are related to durability rather than strength, so cores are rarely needed for strength.

The core sample technique requires drill equipment and subsequent laboratory testing. The method is destructive in that it causes micro-cracks and leaves holes in the base material, as shown in Figure 5.29. Since coring is moderately expensive and destructive, cores are typically taken only when other evidence indicates that further investigation is warranted. All core holes should be filled upon completion of coring with a suitable patching material. If the cores are taken on bridge decks, the material should gain at least 2000 psi strength or minimum mandated by the highway agency which owns the bridge before being exposed to traffic. Additional coring photos are included in Figure 5.30 and Figure 5.31.

Figure 5.29 Example of Core Removal

Figure 5.30 Core of Repaired Concrete at Perimeter of Patch

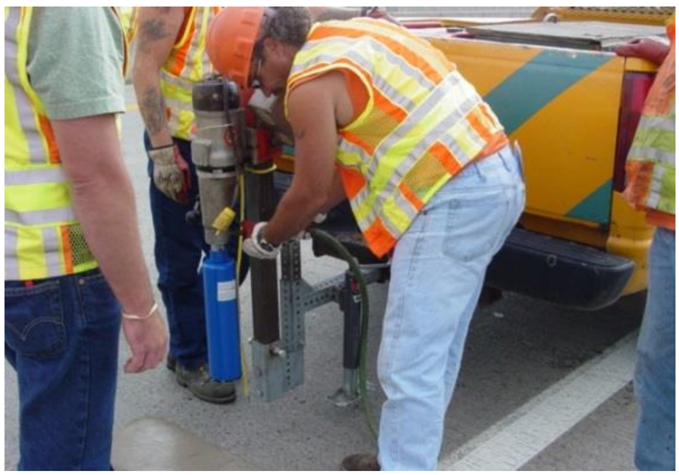


Figure 5.31 Coring Rig Anchored to Trailer Hitch

Petrographic UV Analysis

Once a core is taken to the laboratory it can analyzed for multiple issues including water and soluble chloride content, concrete mix type and concrete deterioration mechanisms such as ASR. From the core, a specimen is cut using a table saw, chemically cleaned, polish, etched, and placed under a microscope. An ultraviolet (UV) lamp is used to illuminate the surface of the sample and built in cameras record results. Under the UV light, the presence of the swelling gel associated with ASR can be easily seen, as shown in Figure 5.5.

Permeability

The durability of concrete is related to its permeability. Low permeability concrete is less susceptible to deterioration caused by environmental factors such as deicer corrosion, freezing-thawing, or alkali-silica reactivity. Permeability testing is performed on concrete core samples and determines the relative permeability of the concrete (or concrete overlay). Many highway agencies are currently using "Rapid Determination of the Chloride Permeability of Concrete," (AASHTO T277 / ASTM C1202) which requires coring a 4-inch diameter, 2-inch thick concrete and conducting a relatively simple laboratory test. The permeability is indicated by the electrical charge passed through the cored concrete. The electrical charge is expressed in terms of coulombs. The higher the electrical charge passed, the higher is the permeability. Electrical charges less than 2000 coulombs represent low permeability. Those between 2000 and 4000 coulombs represent moderate permeability, and charges more than 4000 coulombs are indication of high permeability.

Performing field permeability testing was discussed in Section 5.5.3.5. An advantage of field testing is that no cores are taken, i.e., the test is performed on the concrete surface. However, field trials have shown that while an indicator of relative permeability, cores should be obtained and lab tested if more accurate values are needed.

Chloride Profile

This test determines the chloride (salt) content of concrete. Chlorides in concrete are the main reason for corrosion of the rebar and delamination and spalling of concrete. If water soluble chloride content of concrete exceeds 1.5 pounds/cubic yard, the potential for corrosion of the rebar exists.

Concrete samples are taken from the dust produced directly from the concrete by means of a rotary hammer and collected with a vacuum bit. The same hole is used to collect samples at different depths. Each time a sample is collected, the remaining residue is cleaned out before drilling can continue. For a meaningful evaluation a number of location should be sampled. An example of an appropriate number of test locations is the greater of 10 locations per element or 10 locations per every 5,000 square feet of deck.

Each of the powder samples is analyzed and the chloride content is graphed. Typically, the chloride content is higher near the surface and diminishes with depth. Examples of a chloride profile and chloride profile sampling equipment are shown in **Figure** 5.32 and Figure 5.33.

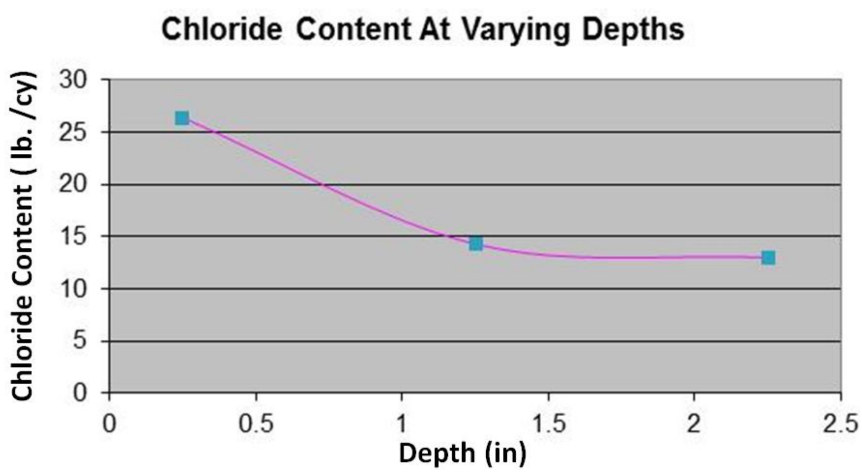


Figure 5.32 Example Graph of Chloride Content in Concrete Core

Figure 5.33 Chloride Profile Sample Collection

5.5.4.2 Endoscopes/Borescopes

Endoscopes (also known as borescopes) are viewing tubes that can be inserted into drilled holes for the inspection of hollow members such as concrete box girders and post-tensioning ducts. This could be considered a destructive test because it involves destroying a small portion of the member in order to insert the scope. The portable video endoscope/borescope provides high-resolution video images that are rich in detail and quality. They allow the user to capture images and video files of remote visual inspections for future reference. They are an excellent tool for inspection of difficult to see areas of a bridge such as behind bearings or anchorages, inside closed structural elements, etc. Figure 5.34 is a photograph of a typical endoscope/borescope with video capability.

Figure 5.34 Typical Endoscope/Borescope

5.6 Removal of Deteriorated Concrete

5.6.1 Introduction

Concrete can fail for a variety of reasons, such as from exposure conditions, excessive loads, infiltration of deleterious chemicals (de-icing salts, improper placement, and improper mix design). Lack of quality control and quality assurance procedures, inadequate training, limited knowledge of the materials, and poor aggregate are additional factors. An example of a severely deteriorated concrete pier is presented in Figure 5.35.

Figure 5.35 Severely Deteriorated Concrete Pier

The extent of deteriorated concrete removal operations on a given bridge component can vary from large regular areas covering most of the component to small irregular areas in random locations. Bridge decks present large surface areas that are exposed almost uniformly to deicing chemicals and water. This means that deteriorated areas and contaminated areas with potential for deterioration are more likely to occur on decks with almost a systematic pattern. Other bridge elements normally present smaller and irregular deteriorated surface areas. For example, concrete pier caps below leaking joints are also frequently deteriorated by drainage from above. Additionally, deterioration of bridge pier columns located near roadways is typically more prominent on the side subjected to salt laden spray from passing vehicles.

The depth of concrete removed has a profound effect on the method and cost of concrete removal. The necessary depth of concrete removal is tied to the extent of deterioration. Well bonded but stained concrete or concrete preparation to receive a sealer are situations that require only surface removal, such as sand or shot blasting. In contrast, spalled or delaminated concrete needs to be removed to a deeper level. This typically would require concrete removal from around the total perimeter of the rebar to obtain a good bond between the replacement concrete and reinforcement steel. If the rebars are corroded, then the rebars must be sandblasted from behind to arrest the corrosion.

5.6.2 Surface Abrasion and Cleaning

Often it is necessary to remove concrete surface contaminants, such as dirt, oil, and rubber on bridge decks, to provide a durable bond between the concrete surface and certain types of protective layer, such as a sealers and coatings, applied on the surface. The objective is to clean and provide a rough texture for bonding rather than to remove material. The two most frequently used methods for concrete surface removal and cleaning are sandblasting (abrasive blast cleaning) and shotblasting. Other options, such as sponge blasting and water blasting (either with abrasives or without abrasives in the water) are also effective in abrading concrete surfaces.

5.6.3 Abrasive Blast Cleaning

Abrasive blast cleaning uses compressed air to propel particles at high velocity onto the surface. The impact of particles produces a very abrasive action which cleans and roughens the exposed concrete. Sand and coal slag (e.g., Black Beauty) are commonly used to abrade the concrete surface. As the blast particles break down contaminates are released into the air and can be inhaled by workers and residents in the area. Recycled glass and very hard aggregates such as garnet do not break down as completely and are safer to use as abrasives, are more environmentally friendly, and perform as well or better than sand or coal slag. Examples of abrasive blast cleaning are shown in Figure 5.36 and Figure 5.37.

Figure 5.36 Abrasive Blast Cleaning Along the Curb Line

Figure 5.37 Abrasive Blast Cleaning a Concrete Barrier

As the concrete surface is abrasive blast cleaned, dust is created. The dust contains silica and very small particles that can cause respiratory and other health related problems. Workers should always wear proper respiratory protection.

Recommendation

Always wear proper respiratory protection when abrasive blast cleaning.

5.6.4 Shotblasting

Shotblasters propel steel shot at high velocity against the concrete surface. The impact is capable of removing concrete to depths up to 1/4 inch. The rate at which the machine moves across the surface effects the amount of concrete removed. Machines vary from ride-on types to walk-behind and vary in widths of cut. Shotblasting can also be performed manually. Shotblasting is typically used to prepare the bridge deck surface for a rigid concrete or polymer overlay. An example of shotblasting is shown in Figure 5.38.

Figure 5.38 Shotblasting a Bridge Deck

A collection chamber collects debris and concrete dust and steel shot. The shot is separated from the debris and recycled. The debris should be disposed of as an industrial waste. A schematic describing the shotblasting process is presented in Figure 5.39.

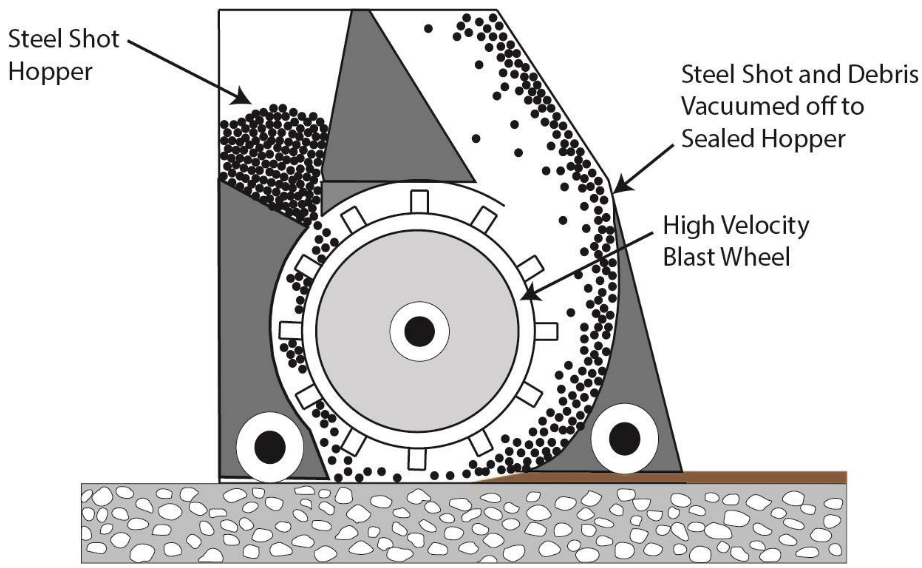


Figure 5.39 Typical Shotblasting Blast Wheel

5.6.5 Cover Removal

Certain types of protective layer, such as bridge deck concrete overlays, require substantial roughening of the surfaces for bond. This and the fact that these systems add to the deadload substantially require partial removal of concrete cover to reduce the dead load and maintain the live load carrying capacity of the structure at the pre-repair level. The work involves removal to a depth less than the cover depth of the steel and thus no work between, around, or under the reinforcing mat is included. Cover removal is normally done by a milling machine, also known as a scarifier, or hydrodemolition, or a combination of both. The machines remove concrete by the impact of numerous teeth mounted on a rotating drum (milling) or pressurized water (hydrodemolition. These techniques are typically used for concrete removal on horizontal surfaces. Refer to Section 5.6.7.2 for additional information on hydrodemolition. Severe damage to reinforcement can occur when milling teeth cut or snag the reinforcement.

Therefore, the teeth should be kept clear from the reinforcement or other metallic objects on the surface. The final step is blast cleaning of the concrete surface (e.g., shotblast, abrasive blast, or waterblast) to remove loose particles.

5.6.6 Saw Cutting

The recommended procedure to prepare the patch area is to saw cut the perimeter of the patch approximately 1/2 inch to 1 inch deep. Make square cuts. If a concrete overlay is to be applied monolithic with the repair, saw cutting is unnecessary and the edge of the areas of removal should be chipped at about 45 degrees to prevent pockets of entrapped air when placing the overlay. Feather-edging the patching material should always be avoided. Sharp edges, at least 1 inch deep should be formed by jackhammers (not preferred) or, preferably, by saw cutting. When saw cutting, it is advantageous to tilt the saw blade to key in the patch by making it wider at the bottom than at the deck surface. This can be done by running one wheel of the saw on a plank placed on the deck. This angled portion would be made below the 1/2 inch to 1 inch deep vertical surface saw cut. An example of saw cutting and removal of deck cover concrete is shown in Figure 5.40.

Figure 5.40 Saw cut and Removal of Deck Cover Concrete

5.6.7 Removal around Reinforcing Steel

When spalls, delaminations, and contamination have progressed into the concrete that surrounds the reinforcing steel, it is necessary to remove concrete from between and below the reinforcing steel in addition to removing the cover. An example of saw cut removal around reinforcing steel is shown in Figure 5.41. The work must be done such that the steel is not damaged. Also, in the adjacent areas where the concrete is not removed, the bond between steel and concrete must not be destroyed, and the substrate concrete must not be cracked.

Figure 5.41 Saw cut Around Reinforcing Steel with Concrete Removed on an Angle

The two common methods to remove concrete without damaging the rebar are pneumatic breakers (jack-hammers) and hydrodemolition (a form of water blasting). Both of these systems can be used to remove concrete cover and concrete from between and below reinforcing steel. They could also be used to remove concrete from between and below reinforcing steel after a more high production method, such as milling, has been used to remove the cover concrete . If concrete has an asphalt overlay, it should be milled prior to hydrodemolition. Hydrodemolition can be used without milling if delaminations or spalls are present.

Jack hammers are suited for small jobs. However, improper handling of the hammer can destroy good concrete. Hydrodemolition is better for large jobs. It also does not cause any of the damage discussed above. Estimating the quantity of concrete to be removed prior to repairs is not an easy task, especially if it is intended that only unsound concrete be removed. Substantial overruns have not been uncommon. Estimating errors can be minimized by a thorough concrete condition survey as close as possible to the time the work is executed.

When the survey is done years prior to the repair, it is common to increase the estimated quantities by an arbitrary amount, usually 25 percent, to account for continued deterioration. Before concrete removal is started on a structural member, the member should be analyzed to determine whether shoring or formwork is required. After the concrete is removed, the remaining section must support its weight, any superimposed dead load, live load if the bridge is to be repaired under traffic, formwork, equipment, and the weight of plastic concrete. On a flexural member the final dead load deflection must be compatible with the other members in the unit.

When to Call the Engineer

When removing concrete around reinforcing steel, the Engineer should be contacted to determine if shoring or temporary support is necessary.

5.6.7.1 Pneumatic Breakers (Jack-Hammers)

The pneumatic breaker (commonly known as a jack-hammer) is the most prevalent method for removing concrete from between and below reinforcing steel. An example of a worker jack hammering concrete is shown in Figure 5.42. It is a hand-held tool and powered by compressed air to deliver a series of high frequency blows that fracture concrete in a small, controlled area. The production depends on the size of the hammer and the skill of the operator.

Figure 5.42 Hammering Concrete

It is common practice to restrict the size of hammers used in concrete removal to prevent damage to otherwise sound concrete. A typical restriction is the use of a 30 pound maximum size jackhammer above the top reinforcing steel and a 15 pound maximum size chipping hammer between and below the reinforcing steel. The existing concrete is removed to sound concrete. Pneumatic hammers should be worked at an angle of 45 to 60 degrees to the plane of the surface being removed.

Some states require removal to below the top mat of reinforcing steel to ensure the new concrete is “locked-in” by the rebar, but practices vary widely. The concrete directly below the top mat (i.e., the “shadow area”) may be in good condition and care must be taken not to hit the rebar with the hammer as this will damage the rebar and may cause cracking in the concrete that is to remain. Figure 5.43 shows the top mat of reinforcement exposed and ready to be patched.

Figure 5.43 Extensive Patching on a Bridge Deck

Where it is necessary to chip below the bar, a clear space of 1/4 inch plus the maximum size of the aggregate to be used in the repair concrete must be provided. This space is typically 1 inch beyond the reinforcing bar. It is also usual to expose bars that are heavily rusted or where there are heavy rust deposits in the concrete adjacent to the bar. The final step in preparing the existing concrete surface is blast cleaning of the concrete and the exposed steel. If the cause of deterioration is chloride-induced corrosion of the reinforcing steel, it is essential to remove all salt and chlorides from the reinforcement. Abrasive blast cleaning is typically done to remove rust and abrade the surface for the new concrete. After completion of this operation, the concrete should be carefully inspected and aggregate particles that have been cracked or fractured during chipping should be removed to a sound surface.

In areas of very badly deteriorated concrete decks, full-depth removal may be necessary. In such cases, forms must be attached to the soffit of the deck.

5.6.7.2 Hydrodemolition

Hydrodemolition is a high-production method for concrete removal. An extremely high-pressure water jet is used to destroy the cement matrix and liberate aggregate. The hydrodemolition equipment is expensive and complex. This method of concrete removal needs special skills to produce the desired results. Although hydrodemolition work is mainly used to remove concrete from between and below the reinforcing steel, the equipment can be calibrated to remove concrete to almost any depth. The hydrodemolition process is such that the system self-adjusts the depth of concrete removal depending on the soundness of the material encountered. An example of an area treated by hydrodemolition is shown in Figure 5.44.

Figure 5.44 Hydrodemolition Test Section

Hydrodemolition is mainly used on horizontal surfaces such as bridge decks and for large-scale concrete removal to minimize cost. However, the method can be used on inclined, vertical, and overhead surfaces but cost effectiveness is reduced by the excessive cost of the specialized equipment needed to safely direct the jet and contain the debris.

Hydrodemolition works well on decks with uniform concrete. Decks that have a variety of patches of differing strength or hardness of concrete may not yield uniform removal depths when hydrodemolition is used.

5.6.8 Concrete Removal on Pier Caps and Columns

Because of leaky joints, bridge piers may have significant amounts of concrete deterioration which would require extensive concrete removal. It is imperative that the structural integrity of the piers be maintained during the repair process. Guidelines limiting the amount of concrete removal that can be completed at any one time on the pier/bent cap, beams and columns should be adhered. Techniques for concrete removal on pier caps and columns are very similar to those discussed above for bridge decks.

When to Call the Engineer

A structural engineer should be consulted to ensure that a sufficient number of rebars remain encased or in contact with the existing concrete during the rehab process. If so much of the concrete around reinforcement is deteriorated and has to come out, the structural engineer can design temporary supports until the repairs can be made.

The single bottom mat of reinforcing steel in the pier caps provide the majority of the tensile strength in the pier caps between the columns. In the columns, the reinforcing steel provides resistance to axial loads and bending and shear stability for the concrete.

5.7 Replacement of Deteriorated Concrete

Once the unsound concrete is removed, the replacement concrete can be placed. A term used in bridge maintenance to replace unsound concrete in an existing structure is to ‘patch’ the concrete. A patch is often thought of as a temporary fix, but that can be subjective and dependent on the quality of the patch. If most of the procedures in this manual are followed, many owners consider the patch as a permanent repair. Examples of a temporary patch include ones where saw cutting or hammering was not used, or asphalt or a concrete of non-similar quality of the original material was used. Some owners consider any localized patch as temporary, but a larger repair like a deck overlay as permanent.

The following sections address Estimating, Purchasing, Delivering, and Storing Concrete Repair Materials. Specific references are provided at the end of this chapter.

5.7.1 Estimating

To estimate the quantity of concrete repair material required for a job, calculate the volume of the cavity to be filled in cubic feet. Divide the calculated volume by the yield in cubic feet of one unit (sometime called kits) of concrete repair material to calculate how many units will be needed. Add 5 percent to 10 percent for waste and spillage. Estimate the waste higher for smaller jobs.

The most common cavity shape encountered in repair operations is a rectangle. When the shape of the area to be repaired is irregular or uneven in depth, the average length, width, and depth must be determined by measurement or by estimate. Consider that an irregular shape should be squared off to help make a more durable repair.

To find the volume (V) of a rectangle in cubic feet (for example a pothole) multiply the length (L) in inches times the width (W) also in inches times the depth (D) also in inches.

$$V = L \text{ x } W \text{ x } D$$

The calculated volume will be in cubic inches. As most repair products are sold in cubic feet, it is necessary to divide the cubic inches by 1728. This is because 1728 is the number of cubic inches in one cubic foot. Alternatively, if the estimation is performed in yards, divide the cubic feet by 27.

5.7.2 Purchasing

To compare the cost of a concrete repair material needed for a job, determine the cost per cubic foot for each material under consideration. Because concrete repair materials are sold in different sized bags or pails, or may yield different volumes when extended, it is necessary to compare cost on volume. Following this procedure will provide a basis for cost comparison. Comparing the number of units is not an accurate method.

5.7.3 Delivery

Concrete repair materials should be delivered, premeasured, and packaged in sealed, dry containers, and on shrink-wrapped pallets to prevent shipping damage. Repair material may also be delivered in ready mix trucks.

5.7.4 Storage

Concrete repair materials should be stored in a dry location at a temperature near 70 °F degrees, but never below 40 °F or above 90 °F. Concrete repair materials that become damp or otherwise defective should not be used and should be removed from the job site. Concrete repair materials that are beyond the manufacturer expiration date should not be used unless the manufacturer has requalified them by actual laboratory testing.

Recommendation

Do not use concrete repair materials that are beyond the manufacturer expiration date unless the manufacturer has requalified them by laboratory testing.

5.7.5 Preparation of Reinforcement

Prior to replacing concrete, exposed reinforcing steel in the removal areas needs to be prepared for the repair. It is important that loose bars be tied at each intersection point, as shown Figure 5.45. Tying the reinforcing bars prevents relative movement of the bars and the concrete in the repair under the action of traffic in adjacent lanes during the curing period.

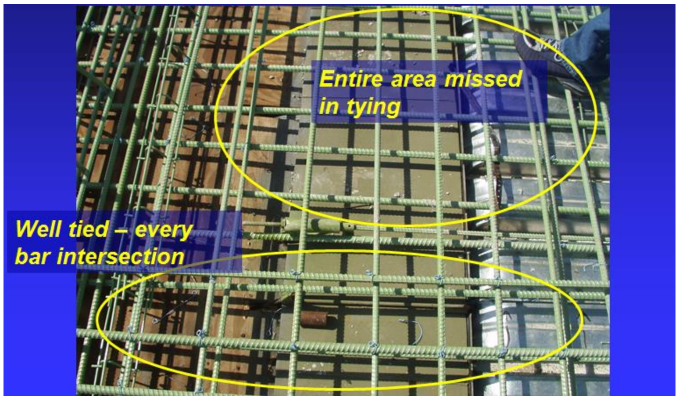


Figure 5.45 Reinforcement Bars Should be Tied at Intersection Points

If corrosion has reduced the cross-sectional area of the reinforcement by more than 20 percent, extra reinforcement is usually added. The typical method of adding reinforcement is to lap the weakened bars with additional bars to restore the cross-sectional area to its original value. The lap lengths over the undamaged parts of the bar should be the same as those required for new construction (typically 30 times the bar diameter). The lapped bars should be tied at both ends, as a minimum. If lapping is not possible, holes are drilled in the existing concrete and dowels or anchors installed. Mechanical splicers may also be used. The preparation of plain (not epoxy coated) reinforcing steel prior to replacement may include a calcium nitrate rust inhibitor coating of the reinforcement or use of sacrificial anodes (see Figure 5.46) to prevent further corrosion. The preparation of reinforcing steel prior to placement of repair material should include abrasive blast cleaning.

Figure 5.46 Sacrificial Anode Secured to Rebar

5.7.6 Types of Concrete Replacement

Areas of concrete removal can be repaired in several different ways, including:

- Form and Pour (Recasting) with concrete
- Prepacking dry aggregates and grouting
- Patching with cementitious, or polymer-based materials
- Shotcrete

On overview of each of these four methods will be presented in this chapter. Additionally, there are numerous American Concrete Institute (ACI) publications on repair techniques. The following repair manuals are available for free at the online bookstore for the American Concrete Institute http://www.concrete.org/Store.

RAP-1 Structural Crack Repair by Epoxy Injection
RAP-2 Crack Repair by Gravity Feed with Resin
RAP-3 Spall Repair by Low-Pressure Spraying
RAP-4 Surface Repair Using Form-and-Pour Techniques
RAP-5 Surface Repair Using Form-and-Pump Techniques
RAP-6 Vertical and Overhead Spall Repair by Hand Application
RAP-7 Spall Repair of Horizontal Concrete Surfaces
RAP-8 Installation of Embedded Galvanic Anodes
RAP-9 Spall Repair by the Preplaced Aggregate Method
RAP-10 Leveling and Reprofiling of Vertical and Overhead Surfaces
RAP-11 Slabjacking
RAP-12 Concrete Repair by Shotcrete Application
RAP-13 Methacrylate Flood Coat
RAP-14 Concrete Removal Using Hydrodemolition

Preparing Old Concrete for Repair with Cementitious Materials

To ensure an adequate bond and to reduce shrinkage of the new cementitious concrete, the existing concrete needs to be prepared. The first step, after the deteriorated concrete is removed, is to remove all loose particles, oil, grease, laitance, or any other material that would prevent the bonding to the concrete surface. The existing surface should be cleaned by light sand-blasting or other surface abrasion methods.

After cleaning, the concrete surface should be saturated with water spray, for 24 hours, if possible to create a saturated surface-dry condition. If a 24 hour saturation is not practical, the concrete should receive a water spray for as long as possible. A quick "blessing" of sprinkled water just before the pour will not pre-soak the existing concrete sufficiently. The mix water in the new concrete will be soaked up by the existing concrete. The result will lead to increased shrinkage cracks and poor bond.

Suggested Procedure

Steps for Achieving a Saturated Surface Dry (SSD) Condition

1. Clean concrete surface
2. Saturate repair area with water
3. Remove any standing water

Prior to the pour, any water remaining in the hole will need to be removed by waiting out or air blasting. If standing water remains, the quality of the new concrete will be affected. The compressive strength and durability of the repair will be compromised.

Next, a bonding agent (usually a cement grout or epoxy bonding agent) is well worked onto the concrete surface just before the installation of formwork. It is very important that the bonding agent does not dry out when the repair concrete is recast. Bonding agents are not always required because if the agent dries out, it can actually become a bond breaker.

5.7.6.1 Form and Pour with Concrete (Recasting)

The form and pour method uses forms to repair bridge elements such as beams, columns, and wingwalls (see Figure 5.47 through Figure 5.50). If the formwork installation is lengthy, the use of bonding grout may not be possible, since it will dry out before the concrete is cast. In this case, specially formulated polymer bonding agents may be used which allow more working time.

Figure 5.47 Forming for a Wingwall Repair

Figure 5.48 Manufactured Forms for Columns

Figure 5.49 Forming for a Pier Cap Repair

Figure 5.50 Forming for Deck Repair

Formwork for recasting should be rigid enough to prevent new concrete from sagging away from the existing concrete under the weight of new concrete. The formwork should with stand forces from pumping of the concrete, if pumping is used to transport the concrete. Also, it should withstand the forces from the external vibrators, if such vibrators are used to consolidate the concrete.

Steel forms have the advantage of being rigid, but they are heavy and not easily handled. Another advantage of steel forms is that they allow heat dissipation of the concrete during the hydration. This will minimize thermal shrinkage and subsequent cracking of the new concrete. Forms are either supported by props or fixed to the structure itself. To repair a vertical patch, a “birds mouth” is built into the forms to allow the placement of concrete, as shown in Figure 5.51. Prior to placing the concrete, the forms should be cleaned, sprayed with a form release agent and wetted to prevent absorption of the water used in the concrete. Concrete for recasting should easily flow and fill all the voids in the form. Since space is limited, use of internal vibrators is usually restricted. Ideally, the mix should be very workable; however use of water is limited to keep drying shrinkage to a minimum.

Figure 5.51 Birds Mouth Examples

Superplasticizers may be used to provide workability without resorting to water. Good compaction is achieved by placing the concrete in small amounts and vibrating effectively as the work proceeds. External vibrators are often used. When recasting deck soffit, sometimes it is possible to drill through the deck and place the concrete from the above. For difficult areas to access or in locations with considerable rebar, self-consolidating concrete could be used.

Consolidation

In some types of construction, the concrete is placed in forms, and then consolidated. Consolidation compacts fresh concrete to mold it within the forms and around embedded items and reinforcement and to eliminate stone pockets, honeycomb, and entrapped air. It should not remove significant amounts of intentionally entrained air. Vibration, either internal or external, is the most widely used method for consolidating concrete (see example in Figure 5.52). When concrete is vibrated, the internal friction between the aggregate particles is temporarily destroyed and the concrete behaves like a liquid; it settles in the forms under the action of gravity and the large entrapped air voids rise more easily to the surface. Internal friction is reestablished as soon as vibration stops.

An option to consolidation for these types of repairs has been self-consolidating concrete which was discussed earlier in this chapter. This type of concrete is very flowable and needs no vibration. Excess use of a vibrator can actually damage the composition of the concrete.

Figure 5.52 Pumping with Elephant Trunk and Consolidating with Vibrator

5.7.6.2 Prepacking Dry Aggregates and Grouting

The surface preparation and formwork for this technique is basically the same as those for the form and pour (recasting) method. The only difference is that dry aggregate is packed in the space behind the form so that it fills the space completely. Subsequently, grout is pumped from the lowest to the highest point to fill the space between the aggregate. Typically, a uniform size aggregate is used. An advantage of prepacking dry aggregate and grouting is that the overall shrinkage of the repair is eliminated.

5.7.6.3 Horizontal Patching

Horizontal patching does not require formwork unless the patch is a full depth type patch, for example on a bridge deck. These larger type patches are covered in Chapter 7. Small concrete areas up to 2 inches in depth can be patched with trowel-applied cement mortar regardless of the type of surface. To begin, clean the surface of the existing concrete by abrasive blast cleaning and bring it to a saturated surface dry condition. Subsequently, a conventional bonding agent may be used with caution as it can dry out (or prematurely set-up). Since no formwork is required, patching can be done immediately after the application of the bonding agent, thus preventing the bonding agent from drying out. The patch mortar should be firmly applied into place so that entrapped air is excluded as much as possible. The closer the physical properties of the patch material are to the existing material, the better. It is also important to minimize the shrinkage of the patching material. This can be done by using the exact amount of mixing water and ensuring the cement and water are well mixed. The inclusion of latex in a concrete or mortar will help reduce the amount of water required for workability and also reduce the permeability of the patch. Other performance-proven additives can be used to reduce setting time and increase strength. The aggregate can be adjusted in the mix design for thin patches.

Proper curing is important for all cement concrete. Thin patches present a particularly difficult problem because they dry out or cure quickly. The existing concrete will tend to absorb the moisture in the patching material. If exposed to the sun or wind, the moisture evaporates. It is recommended that thin patches be cured by covering with moist burlap and polyethylene sheet on top. Without the polyethylene sheet on top, the burlap will dry out faster, doing more harm than good.

To protect the rebar from additional corrosion a corrosion inhibitor can be brushed onto the steel. Furthermore, galvanic anodes that contain zinc can be tied onto the rebar, as shown in Figure 5.53. The zinc contained within the anode will protect the steel from further corrosion.

Figure 5.53 Galvanic Anodes Placed into a Patch of a Pier Cap

<u>Non-Portland Based Concretes</u>

In addition to conventional cement based material, there are two types of materials that are used for patching concrete: quick-setting hydraulic cements and polymer materials.

There are a variety of proprietary brands of quick-set hydraulic and polymer material that are designed to gain strength rapidly. Each proprietary material has a number of unique properties favorable for bridge maintenance work. For some materials, the patch may be opened to bridge deck traffic after about one hour. Quick-setting hydraulic cements most commonly used are formed by the reaction between magnesium-oxide and a soluble phosphate. These materials have material properties that exceed those of Portland-based cements, but they are more expensive and require additional care during the mixing and installation. “Mag-Phosphates”, as they are commonly called, can reach a compressive strength of 2,100 psi in less than an hour. Ultimate strengths can reach 10,000 psi. These materials also have good adhesion properties and are marketed for vertical and overhead applications as well.

Care must be taken during the mixing not to deviate from the recommended amount of mixing water. Even a small deviation will severely impact the durability of the cement. An example of a failed rapid-setting mix is shown in Figure 5.54. Aggregates used to make the concrete should not be calcareous (containing limestone) as these aggregates react with the cement to form a gel that deteriorates the concrete in presence of water over time. The rapid hardening process creates considerably more heat during hydration than a Portland-based reaction. Failure to control the heat of hydration will cause severe shrinkage cracking. In order to limit the amount of heat generated, Mag-Phosphate cements should not be placed in lifts greater than 4”. Modified formulations have been developed for repairs done in hot weather.

Figure 5.54 Failure of Rapid-Setting Mix

Polymer Concrete

Several types of polymers, such as epoxy, polyesters, methylacrylates, and ureathanes, have been developed for the repair of concrete. Polymers consist of a resin and a hardener. These two components are proportioned and mixed at the site. Aggregated is added to improve the compressive strength and because polymers are expensive, reduce the amount of material used. The mix solidifies upon a rapid chemical reaction. Priming the existing surface with the polymer material (without aggregate) provides good bond. Polymer materials liberate heat, set, and gain strength very rapidly. Their pot life is very short, especially when they are used in large quantities or in hot weather. This is because more heat is liberated and this in turn expedites setting of the polymer. On the other hand, their strength gain usually slows down substantially when the air temperature is 65 °F or below, and they may not gain sufficient strength.

Each type of polymer has material characteristics that make them unique from cement. Two of the more commonly discussed are viscosity and elongation. Viscosity refers the ability of the material to flow. A very viscous material like molasses has a high viscosity number. Water is a low viscosity material. Polymer materials can be made fluid enough to flow into place by gravity so inaccessible places can be filled with them without compaction.

Aggregates for Polymer Concrete

Polymer materials expand and shrink much greater than concrete when ambient temperature fluctuates. This unfavorable characteristics of polymer materials will cause debonding and separation of the patch from the old concrete in time. The addition of aggregate helps to alleviate this problem.

Aggregates must be dry and free of fine particles. Moisture negatively affects the polymer reaction and additional polymer would be necessary if too many fines are included. A hard durable 3/8 inch sized aggregate is used in extending polymer concrete. A more angular aggregate produces a stronger matrix so that less polymer is needed.

Mixing Polymers

Each of the two parts, the resin and the hardener, should each be stirred separately for about 3 minutes or as per manufacturer recommendation prior to mixing together. This is necessary to re-mix any settled particles. Polymers are mixed in a ratio, typically one part resin to one part hardener, though some polymers may be formulated differently. Care should be taken to ensure the entire amount of resin and hardener are removed from each container. These combined parts should be mixed again for 5 minutes before adding the aggregate. Add the aggregates to the polymer. This helps to ensure the aggregates are coated with the polymer and thereby a more durable patch. Mixing should continue for another 5 minutes. Be sure to closely follow the manufacturer instructions.

Recommendation

Always follow the manufacturer instructions when mixing polymers.

Examples of mixing for smaller patches and for larger patches are presented in Figure 5.55 and Figure 5.56, respectively.

Figure 5.55 Five Gallon Bucket Mixing Method for Small Patches

Figure 5.56 Power Mixers for Larger Patches

Placing Polymers

All surfaces should be dry and free of any contaminates. It is critical the surfaces are dry. Adding a primer, as shown in Figure 5.57, will allow the polymer to bond better to the existing concrete. Unlike cementitious-based repair materials, the bond capability of polymer-based materials is significantly reduced in the presence of water. The surfaces should be clean of loose materials, rust, and oil free. The use of an electric leaf blower to air clean surfaces is recommended, as shown in Figure 5.58. Unlike combustible motors driven air compressor that rely on water and oil filters to provide clean air, the air from electric leaf blowers will not contain these contaminates.

Figure 5.57 Priming a Patch with Polymer

Figure 5.58 Using a Leaf Blower to Clean Surfaces

For a neat looking repair, duct tape is used to protect the perimeter concrete from spilled polymer that becomes difficult to remove once hardened. An example is shown in Figure 5.59.

Figure 5.59 Taping the Perimeter for a Clean Look

As polymers are generally not an electrically conductive material, the use of sacrificial anodes to protect the rebar is ineffective.

5.7.6.4 Shotcrete

Shotcrete, or pneumatic applied mortar, is used to repair and restore the surface of concrete bridge elements. It is conveyed through a hose and nozzle and pneumatically projected at high velocity onto a surface. It contains the same cement, aggregate and water as concrete except that there are no course aggregates in the mix. The mix has high cement content and low water/cement ratio. Addition of silica fume, fly ash and/or slag enhances performance of shotcrete. Shotcrete can contain silica fume at a minimum of 7 percent by weight of cement, fly ash at a maximum of 20 percent and slag at a maximum 50 percent. Steel or synthetic fibers have also been used to increase compressive strength and decrease potential for cracking. When properly applied, mortar is dense, durable and strong. It is also reported to have superior bonding characteristics. A typical shotcrete machine is shown in Figure 5.60.

Figure 5.60 Typical Shotcrete Machine

The applicator controls the quality of the work. The applicator controls the amount of mix water that is added to the dry mix and the amount of material applied to the surface, as shown in Figure 5.61. A field verification jig is commonly used to assess the skill level of the applicator prior to performing the work. Qualification of applicators and test panel should be required.

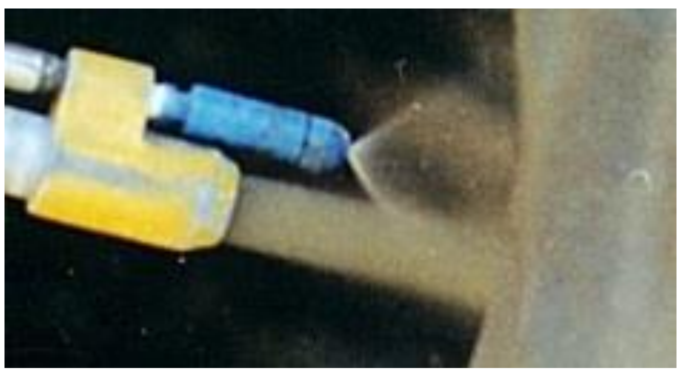


Figure 5.61 Mix Water Added at Nozzle

On vertical and overhead surfaces, since forming is not required, pneumatic mortar can be a useful alternative in bridge restoration. Large surface areas can be repaired in relatively short periods of time. Examples are shown in Figure 5.62 and Figure 5.63.

Figure 5.62 Shotcrete Repair of an Invert of a Corrugated Metal Culvert

Figure 5.63 Shotcrete Repair of a Pier

Preparation of the existing surface is an important part of the repair. All deteriorated concrete should be removed, as previously described in this manual, with the edges sloped about 45° to prevent entrapment of rebound material. Existing concrete and reinforcing steel should be cleaned by abrasive blast cleaning. Reinforcement of the patch with welded wire fabric or small diameter wire mesh is advised for depths exceeding 3 inches. The limits of the existing concrete face should be exceeded, if necessary, to obtain a minimum 2 inches cover on existing reinforcement.

Recommendation

Mortar should not be used in thicknesses of less than 1 inch.

Mortar should not be used in thicknesses of less than 1 inch. The existing surface is wetted as needed so it will not absorb water from the pneumatic mortar. The natural handgun finish is preferred from bond and durability standpoints. Scraping or cutting may be used to remove high points and material that has exceeded the limits of the repair after the mortar has become still enough to withstand the pull of the cutting device. Troweling or other finishing is discouraged as it has a tendency to disturb the bond. Curing is very important for the rich mixes and thin sections used with pneumatic mortar. Seven days of water curing is generally advisable to promote good hydration of the cement, keep the mortar cool in hot weather, and prevent early shrinkage that may disturb the bond. Any defects in the shotcrete, such as the "Bug-holes" shown in Figure 5.64, should be repaired prior to curing.

Figure 5.64 Repair "Bug-Holes" after Placing Shotcrete

Small Volume Pneumatic Concrete

Hand-held machines have been developed for small repairs. These machines are effective in re-pointing laid up stone, re-mortaring granite curbs, and re-mortaring bridge rail post foundations. An example of a small volume shotcrete tool is shown in Figure 5.65.

Figure 5.65 Small Volume Shotcrete Tool

A concrete mix with fine aggregates (mortar sand for instance) is added to a hopper on the tool. Water is added to the dry mix at the nozzle. The success of this application is also dependent on the skill of the applicator. The application, if done properly, provides for a dense concrete with good adhesion. An example of a small volume shotcrete tool application is shown in Figure 5.66.

Some manufacturers offer polymer modified mixes that can be pneumatically applied. These mixes offer the advantages of polymer concretes along with the benefits gained from pneumatically applying concrete to a vertical or overhead surface.

Figure 5.66 Re-Pointing a Laid-Up Stone Parapet With a Small Volume Shotcrete Tool

5.7.7 Finishing

Concrete that will be visible, such as approach slabs, bridge decks, and sidewalks, often needs finishing. Concrete slabs can be finished in many ways depending on the intended service use. Some surfaces may require only strikeoff and screeding (see Figure 5.67) to proper contour and elevation, while for other surfaces a broomed, floated, or troweled finish may be specified (see Figure 5.68). In slab construction, screeding or strikeoff is the process of cutting off excess concrete to bring the top surface of the slab to proper grade. A straight edge is moved across the concrete with a sawing motion and advanced forward a short distance with each movement. A challenge for concrete finishers can be access. Figure 5.69 shows a worker using a bridge to hand finish the concrete.

Figure 5.67 Use of a Screed to Finish Elevation on a Sidewalk

Figure 5.68 Trowel Finish on a Deck Patch

Figure 5.69 Using a Bridge for Concrete Finishing

Bullfloating eliminates high and low spots and embeds large aggregate particles immediately after strikeoff. This looks like a long-handled straight edge pulled across the concrete. Jointing is required to eliminate unsightly random cracks. Contraction joints are made with a hand groover or by inserting strips of plastic, wood, metal, or preformed joint material into the unhardened concrete. Saw cut joints can be made after the concrete is sufficiently hard or strong enough to prevent raveling. After the concrete has been jointed, it should be floated with a wood or metal hand float or with a finishing machine using float blades. This embeds aggregate particles just beneath the surface; removes slight imperfections, humps, and voids; and compacts the mortar at the surface in preparation for additional finishing operations. Where a smooth, hard, dense surface is desired, floating should be followed by steel troweling. Troweling should not be done on a surface that has not been floated; troweling after only bullfloating is not an adequate finish procedure. A slip-resistant surface can be produced by brooming before the concrete has thoroughly hardened, but it should be sufficiently hard to retain the scoring impression.

5.7.8 Curing

Curing plays an important role on strength development and durability of concrete. Curing takes place immediately after concrete placing and finishing, and involves maintenance of desired moisture and temperature conditions, both at depth and near the surface, for extended periods of time. An example of a wet cure for a small deck patch is shown in Figure 5.70. Pre-soaked burlap covered with polyethylene sheets is used to keep the concrete wet. Properly cured concrete has an adequate amount of moisture for continued hydration and development of strength, volume stability, resistance to freezing and thawing, and abrasion and scaling resistance.

Figure 5.70 Wet Cure of a Small Deck Patch Using Pre-Soaked Burlap

The length of adequate curing time is dependent on the following factors:

- The type of cementitious materials used
- Mixture proportions
- Specified strength
- Size and shape of concrete member
- Ambient weather conditions and
- Future exposure conditions

Slabs on ground (e.g. pavements, sidewalks, parking lots, driveways, floors, canal linings) and structural concrete (e.g. bridge decks, piers, columns, beams, slabs, small footings, cast-in-place walls, retaining walls) require a minimum curing period of seven days for ambient temperatures above 40 °F).

The American Concrete Institute (ACI) Committee 301 recommends a minimum curing period corresponding to concrete attaining 70 percent of the specified compressive strength. The often specified 7-day curing commonly corresponds to approximately 70 percent of the specified compressive strengths. The

70 percent strength level can be reached sooner when concrete cures at higher temperatures or when certain cement/admixture combinations are used. Similarly, longer time may be needed for different material combinations and/or lower curing temperatures. For this reason, ACI Committee 308 recommends the following minimum curing periods:

- ASTM C 150 Type I cement: 7 days
- ASTM C 150 Type II cement: 10 days
- ASTM C 150 Type III cement: 3 days
- ASTM C 150 Type IV or V cement: 14 days

There are three main functions of curing:

1. To maintain mixing water in concrete during the early hardening process, which is accomplished by:

    - *Spraying and fogging:* Spraying and fogging are used when the ambient temperatures are well above freezing and the humidity is low. Fogging can minimize plastic shrinkage cracking until the concrete attains final set.
    - *Saturated wet coverings:* Wet coverings saturated with water should be used after concrete has hardened enough to prevent surface damage (see Figure 5.71). They should be kept constantly wet.
    - *Left in Place Forms:* Left in place forms usually provide satisfactory protection against moisture loss for formed concrete surfaces. The forms are usually left in place as long as the construction schedule allows. If the forms are made of wood, they should be kept moist, especially during hot, dry weather.

2. To reduce the loss of mixing water from the surface of the concrete:

    - *Cover concrete with impervious paper or plastic sheets:* Impervious paper and plastic sheets can be applied on thoroughly wetted concrete. The concrete surface should be hard enough to prevent surface damage from placement activities.
    - *Apply membrane-forming curing compounds:* Membrane-forming curing compounds are used to retard or reduce evaporation of moisture from concrete. They can be clear or translucent and white pigmented. White-pigmented compounds are recommended for hot and sunny weather conditions to reflect solar radiation. Curing compounds should be applied immediately after final finishing.

3. Accelerating strength gain using heat and additional moisture:

    - *Live steam:* Live steam at atmospheric pressure and high-pressure steam in autoclaves are the two methods of steam curing. Steam temperature for live steam at atmospheric pressure should be kept at about 140 °F or less until the desired concrete strength is achieved.
    - *Heating coils:* Heating coils are usually used as embedded elements near the surface of concrete elements. Their purpose is to protect concrete from freezing during cold weather concreting.
    - *Electrical heated forms or pads*: Electrical heated forms or pads are primarily used by the precast concrete producers.

- *Concrete blankets:* Concrete insulation blankets are used to cover and insulate concrete surfaces subjected to freezing temperatures during the curing period. The concrete should be hard enough to prevent surface damage when covering with concrete blankets.

Figure 5.71 Preparing for the Cure of the Repair of a Concrete Fascia Beam Repair

Curing in either cold or hot weather requires additional attention. In cold weather, some of the procedures include heated enclosures, evaporation reducers, curing compounds, and insulating blankets. The temperature of fresh concrete shall be above 50 °F. The curing period for cold weather concrete is longer than the standard period due to reduced rate of strength gain. Compressive strength of concrete cured and maintained at 50 °F is expected to gain strength half as quickly as concrete cured at 73 °F. In hot weather, curing and protection are critical due to rapid moisture loss from fresh concrete. The curing actually starts before concrete is placed by wetting substrate surfaces with water. Sunscreens, windscreens, fogging, and evaporation retardants can be used for hot weather concrete placements. Since concrete strength gain in hot weather is faster, curing period may be reduced.

Concrete bridges require a high standard of curing to achieve the low permeability required for protection of steel reinforcement. Standard recommendations for curing bridge decks is moist curing for a minimum of 7 days for concrete mixtures containing only Portland cement and as long as 14 days when supplementary cementing materials are included in the concrete mixture. Some states also require the application of curing compound upon removal of the moist curing methods.

Curing can be problematic for bridge maintenance staff when patching existing concrete decks. Traffic typically needs to be restored in less than 7 days. For this very reason there are specific deck patching products that cure quickly, typically 2 to 4 hours. These patch materials contain special additives or polymers to help in curing. A product popular with many bridge owners allows curing and restored bridge traffic in 45 minutes.

Typical moist curing for bridge decks requires the application of adequate quality water saturated burlap or other approved absorptive material covered with minimum 6 mil plastic covering (see example shown in Figure 5.72). The temperature of the saturated materials should be within 20 °F of the temperature of the in-place concrete. White plastic is used to reflect solar radiation, reducing the temperature rise beneath the plastic, while cold temperatures (less than 50 °F) may allow the use of black plastic to add heat to the system.

Figure 5.72 Wet Cure with Pre-Soaked Burlap for a Large Deck Repair

5.8 Crack Repair

The cause of cracking should be determined before repairs are undertaken. Structural defects should be remedied before filling. A crack caused by settlement, flexural or diagonal tension will recur if the problem is not corrected.

Cracks can be repaired one at a time or done by a flood coat (also called: topical application). Small cracks occurring over large areas can be sealed with a crack filler applied to the entire surface. These materials have very low viscosity and are able to flow deep into the cracks to seal out moisture. If the cracks are full-depth, it will be necessary to seal off the bottom surface. As these cracks cannot be cleaned out, the bond to the existing concrete may be compromised. The sealant is often an epoxy compound. Urethanes, which remain flexible through large temperature variations, have been used successfully. Rapid setting cementitious mortars may also be used.

Large, open cracks that are dormant or not “working” may be treated by injection. Typically an epoxy or urethane based product is used. The injection method is laborious but is effective in treating vertical cracks. Cracks on horizontal surfaces can be packed with mortar sand, and then a low viscosity polymer is fed into the sand. A lower viscosity product, such as a urethane, should be used for this type of repair.

If cracks are open and appear to be “working”, or if a crack has been sealed but has cracked again, a flexible sealant, such as asphalt crack sealer, should be used. This usually requires routing a groove into the crack to act as a reservoir to hold the proper amount of sealant (see example in Figure 5.73). A backer rod may also be necessary.

Figure 5.73 Modified Squeegee to Contain Low Viscosity Polymer

In all cracking operations, the cause of the cracking should be understood and corrected (if practical). The crack surfaces should be clean and dry and the depth of the seal should be less than or equal to the width of the seal.

The following sections present information on the type, application, and effectiveness of sealers and coatings. Generalized information is provided in Table 5.5 .

Table 5.5 Sealer, Coating and Membrane Properties

Material (Coating/Sealer Type)	Bond	Abrasion Resistance	Chemical Resistance	Elongation	Chloride Ion Resistance	Water Absorption Resistance	Vapor Transmission	Penetration	Ultraviolet Resistance	Life Expectancy	Wear Resistance	Cost
Linseed Oil (Penetrating Sealer)					P	P	P	P	P	L	G	low
High Molecular Weight Methacrylate (HMWM) (Penetrating Sealer)					G	E	F	E	V	E	P	high
Silicate (Penetrating Sealer)					F	P	G	F	F	G	G	low
Siloxane (Penetrating Sealer)					E	E	V	G	G	G	V	mid
Silane (Penetrating Sealer)					V	V	E	E	E	E	E	high
Latex (Surface Sealer 0-30 mils or High Build Coating 10-30 mils)	G	F	P	-								
Silicone (Surface Sealer 0-30 mils)	F	P	P	-								
Methacrylate (Surface Sealer 0-30 mils)	G	G	F	-								
Epoxy (Surface Sealer 0-30 mils or High Build Coating 10-30 mils)	E	G	F	-								
"Hard" Urethane (Surface Sealer 0-30 mils or High Build Coating 10-30 mils)	F	E	G	-								
Elastomeric Urethane (Membrane 30+ mils)	F	F	P	E								
Vinylester (Membrane 30+ mils)	E	G	E	-								
Polyester (Membrane 30+ mils)	G	G	E	-								

Rating Definitions: E – Excellent, V – Very Good, G – Good, F – Fair, L – Low, P – Poor

Additional information can be found in the crack repair guide at:
http://www.virginiadot.org/business/resources/const/GuideManCrackRepair.pdf

5.8.1 Routing and Sealing Cracks

Flexible sealing can repair "working" cracks. The technique consists of: 1) Routing the crack (see example routers in Figure 5.74 and Figure 5.75), 2) Cleaning and drying the crack, and 3) Filling the crack with a suitable field-molded flexible sealant (see Figure 5.76).

Routing and sealing may also repair both narrow and wide cracks that are dormant (non-working) cracks. The method involves enlarging crack along its exposed face and filling and sealing it with a suitable joint sealant (see Figure 5.76). This is the simplest and most common technique for crack repair. It can be executed with relatively untrained labor.

Figure 5.74 Crack Router for Preparing Horizontal Cracks

Figure 5.75 Routing Longitudinal Cracks

Figure 5.76 Placing Crack Sealing into "Working Cracks"

The routing operation consists of preparing a groove at the surface that is sufficiently large to receive the sealant. The groove is prepared by using a concrete saw or pneumatic tools. A minimum surface width of 1/4 inch is desirable. Repairing narrow grooves is difficult. The surface of the routed joint should be cleaned with an air jet and permitted to dry before placing the sealant.

5.8.2 Flooding Application of Crack Sealers

Relatively wide, dormant cracks in bridge decks are effectively repaired through gravity fill polymers such as high-molecular-weight methacrylates, ureathanes, and low viscosity epoxies. To fill these cracks the deck is usually flooded with the polymer. The polymer is brushed into the cracks until they are filled. Usually, sand is spread onto the wet, uncured polymer to provide adequate skid resistance (shown in Figure 5.77). Failure to do so will cause slippery conditions when wet. The material remaining on the deck will abrade under traffic. Though the deck may be unsightly during the process, no harm is done to the concrete.

Figure 5.77 Spreading Mortar Sand onto Topical Crack Sealer

Polymers used to repair cracks by gravity fill have a viscosity of less than 100 centipoise (a measure of viscosity). High-molecular-weight methacrylates that have viscosity of less than 25 centipoise (cp) have been shown to be effective in repairing cracks with widths of 0.008 to 0.08

inch. A minimum crack of 0.02 inch is recommended for gravity fill epoxies that usually have a viscosity of about 100 cp.

5.8.3 Sealing Concrete Cracks by Epoxy Injection

Sealing cracks by a process of injecting epoxy into the crack is very effective in bridge maintenance.

The process of determining the feasibility of epoxy injection of cracks includes:

- Consulting with engineer to determine if feasible. For example, if there are so many cracks that the structural integrity of the element is too compromised for this type of repair.
- Determine the size and depth of the cracks.
- Determine if the cracks are active.

Examples of epoxy injection are presented in Figure 5.78 and Figure 5.79. Before a method is identified for repairing a crack, it must be determined if the crack is working (i.e., active or moving) or not. If the crack is working it should be filled with flexible material. If it is passive a bonding material such as an epoxy can be injected into the crack. It is also necessary to determine if the crack is full depth. This may be difficult if the crack is in an abutment.

Figure 5.78 Epoxy Injection Repair (Horizontal Surface)

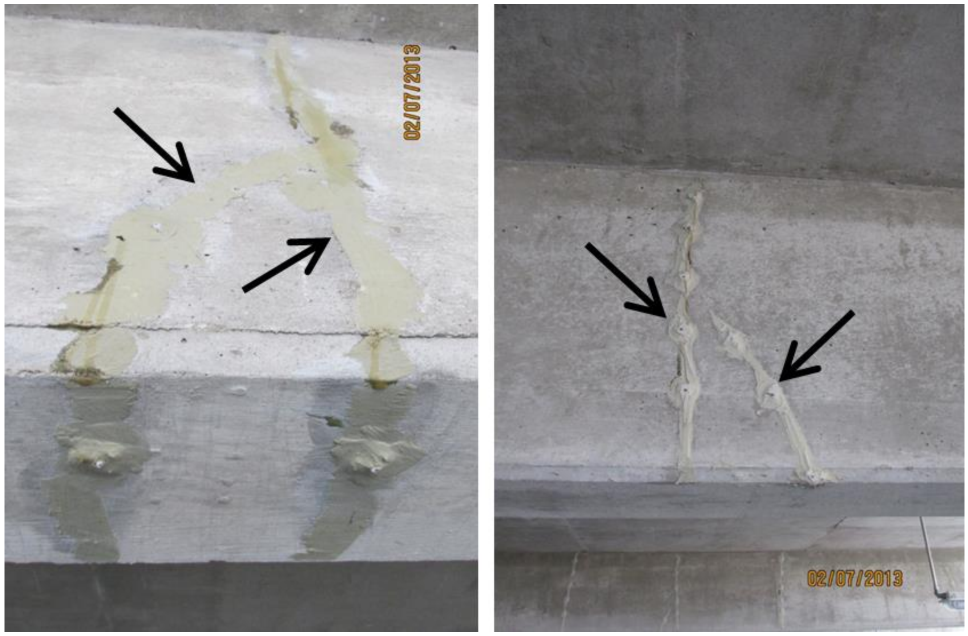


Figure 5.79 Epoxy Injected Cracks (Horizontal and Vertical Surfaces)

Narrow cracks that are dormant (i.e., non-working) may be effectively sealed by epoxy injection. The procedure can be applied to both horizontal and vertical surfaces. Cracks as narrow as 0.002 inch can be sealed and bonded by the epoxy injection. The procedure has potential to provide structural repair (increase stiffness and strength) in addition to sealing the crack.

The technique requires:

1. Cleaning the cracks
2. Sealing of the crack surface
3. Installation of entry and venting ports
4. Preparation of epoxy
5. Injecting the epoxy
6. Removal of surface seal

These procedures are discussed in greater detail below.

1. Cleaning the cracks: Before injection, the interior of the crack should be cleared of all dust, dirt, oil, grease, or fine particles of concrete that could prevent epoxy penetration and bonding. Harsh chemicals or detergents should not be used to clean the cracks because they may compromise the ability of the epoxy to bond to the concrete.

2. Seal the crack surfaces: The exterior of the cracks should be sealed and allowed to harden to prevent the injected epoxy from leaking out of the crack. Cracks can be sealed by applying an epoxy, polyester, or other appropriate sealing material to the surface of the crack. For cracks that extend through the entire member section, the opposite side of the injection should be sealed as well. If the cracks on each side do not connect, epoxy injection should be performed on each side individually. If extremely high injection pressures are needed, the crack can be cut out to a depth of 1/2 inch and width of 3/4 inch in a V-shape, filled with epoxy and struck off flush with the surface.

3. Install the entry and venting ports: There are two general methods that can be used to install the entry and venting ports; surface mounted and socket mounted. Entry ports are typically tube devices that allow the pressurized epoxy resin to be pumped into the crack (see Figure 5.80). The entry port spacing is typically at 8 inches on center but can be increased for wider cracks. Port spacing depends on the crack width and the amount of pressure applied, however the spacing should be limited to the thickness of the repaired member if the cracks pass all the way through. Surface-mounted entry ports are normally adequate for most cracks, but socket-mounted ports are used when cracks are blocked, such as when calcified. In some cases, it may be necessary to drill holes approximately 3/4 inch in diameter and 1/2 to 1 inches below the surface of the crack to place the entry or exhaust port.

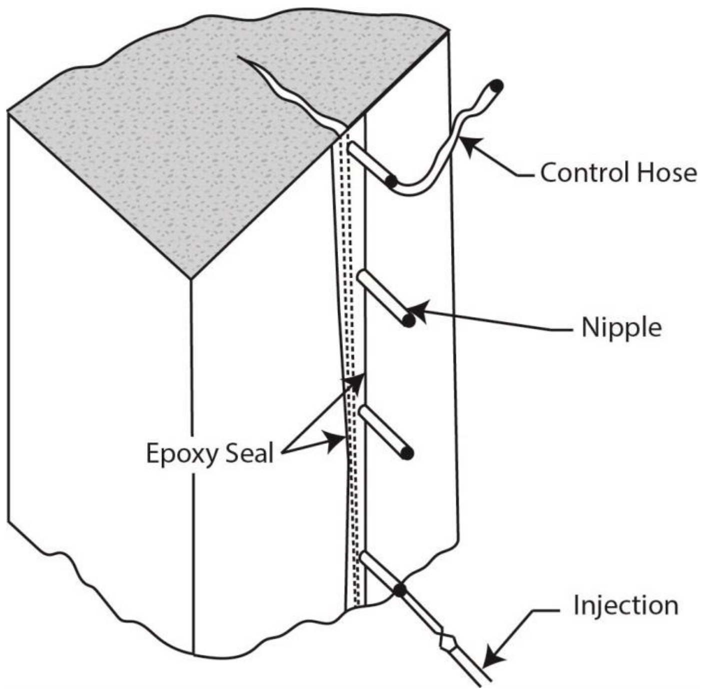


Figure 5.80 Epoxy Injection Schematic (Vertical Surface)

4. Inject Material: The injection progresses from port to port, normally starting at the lowest point, and continuing until epoxy is extruded from the next port. The distance between the ports should not exceed the expected penetration depth. A handgun or pressure pot can be used, but various types of machines are available that assure the proper proportioning, mixing, and temperature of the two part epoxy and the proper injection pressure. This technique may also be used to fill isolated voids or delamination in concrete. In this case, injection pressure must not be too high. This is not, however, considered as permanent as removing and replacing the concrete.

5.8.3.1 Epoxy Repair Safety

Epoxy repairs utilize epoxy resins that are hazardous and appropriate safety precautions should be followed. Safety precautions should include the following:

- Have the Material Safety Data Sheet (MSDS) on site and read it before use
- Wearing protective clothing including rubber gloves and protective eyewear
- Having eye wash kit or facilities available

- Providing ventilation in confined spaces or wear an appropriate air respirators where needed
- Having necessary cleaning materials on hand

Epoxy injection is further addressed in several sections of this document, including:

- 7.2.4.2 Epoxy Crack Injection regarding maintenance of bridge decks and slabs
- 11.4.3 Epoxy Injection Crack Repair regarding maintenance and repair of concrete superstructures
- 13.4.5 Crack Repair regarding repair and rehabilitation of concrete substructures

Additional information can be found in ACI 306.1, *Standard Specification for Cold Weather Concreting*, ACI 306R, *Cold Weather Concreting*, ACI 305.1, *Specification for Hot Weather Concreting*, and ACI 305R, *Hot Weather Concreting*.

5.8.3.2 Quality Control of Epoxy Injection of Cracks

To ensure that the injection has been successful, quality assurance measures may include test cores or NonDestructive Evaluation (NDE).

1. Test cores:

- Core locations should be chosen to avoid cutting reinforcing steel, drilling cores in areas of high stress, or creating core holes below the waterline. The engineer should determine core locations when these types of conditions exist.
- Be sure the epoxy has set before extracting a core.
- Take cores (normally 2 inch diameter) to check that the penetration of the epoxy is adequate.
- Inspect the core visually to determine the penetration of the epoxy into the crack; Cores can be further tested for compressive and split tensile strength per ASTM C 42.
- Subsequently, patch the removed-core area (after proper surface preparation) with an expansive cementitious or epoxy grout compatible with the existing substrate concrete and the surrounding environment.

2. Methods for nondestructive evaluation:

- Impact Echo (IE)
- Ultrasonic Pulse Velocity (UPV)

5.8.3.3 Underwater Epoxy Injection of Cracks

Pressure injection of cracks underwater can be used for underwater applications also. When cracks expose the reinforcing steel to moisture, the stage is set for the corrosion process to begin. In salt water environments corrosion can occur very fast. With the proper selection of a water-compatible adhesive, normally an epoxy resin, dormant (non-moving) cracks saturated with water can be repaired. The procedure can also repair other small voids such as delaminations or honeycombed areas near the surface of the concrete. Pressure injection can be used, within limits, against a hydraulic head provided the injection pressure is adjusted upward to counteract the pressure of the hydraulic head. The material must displace the water as it is injected into the crack to ensure that the crack is properly sealed resulting in a watertight monolithic structural bond.

Epoxies must have certain characteristics to cure and bond the cracked concrete together. Many adverse elements are present inside the concrete crack such as water, contaminants carried by water, dissolved mineral salts, and debris from the rusting reinforcing steel. The typical low surface temperature of concrete underwater eliminates many products due to their inability to properly cure. The epoxy injection resins for cracks are formulated in low viscosity, and they do not shrink appreciably. The surface wettability of epoxy resin is of major importance, because the resin should displace all water in the crack and adhere to a wet surface and then cure in that environment.

The procedure involves cleaning of the crack by a high-pressure water jet system and shaping the surface of the concrete directly above the crack so that it can be sealed with a grout. Injection ports are installed in holes drilled to intersect the crack by a hydraulic or pneumatic drill. Subsequently, the surface of the crack is sealed with a grout material suitable for underwater use such as the cementitious or epoxy mortar described earlier. The purpose of the grout is to retain the adhesive as it is pumped into the crack. The adhesive is pressure-injected into the crack through the ports that are embedded in the grout at regular intervals. The injection sequence begins at the bottom and advances upward. The injection moves up when the adhesive reaches and begins to flow from that port. Epoxy resin is mixed either before or after pumping. Cracks varying in width from 0.002 inch to 0.25 inch may be injected successfully. Epoxy pressure injection has gained widespread acceptance as a cost effective method to bond together and seal cracked structural concrete members.

The following precautions should be noted:

- Contaminants growing inside the crack, especially those found underwater can reduce the successful welding of cracks.
- Corrosion debris can also reduce the effectiveness of pressure injection.
- Time and patience is required for the successful injection project.
- Injection is labor-intensive. (As the temperature drops below 50°F, it becomes more difficult to pump the epoxies into fine cracks).

Experience on the part of the diver in injection and the formulation of the epoxy for injection are very important.

5.9 Chapter 5 Reference List

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