A typical QA/QC program includes qualification testing of constituent materials (e.g., cement, pozzolan, water, aggregates, admixtures, etc.), proportioning of a concrete mixture, and testing and inspection during pre-placement, placement, and post-placement phases of the construction. The qualification testing and selection of constituent materials is extremely important because selection of unsuitable constituent materials could have lasting consequences due to the harsh environmental and exposure conditions of offshore and marine structures and the difficulty they present in accessibility during their service life. For example, selection of reactive aggregates and cements with high alkali content could lead to alkali-silica reactions (ASR) that is difficult to mitigate once the structure is placed in service (Figure 5).

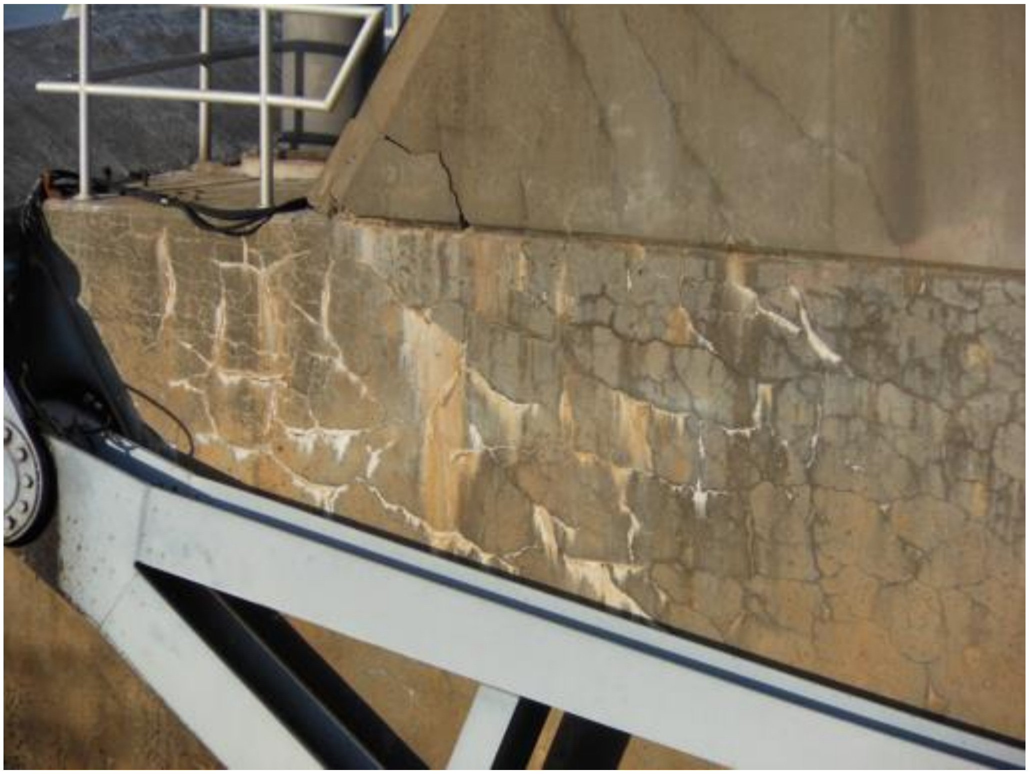

Figure 5— ASR Damage in a Dam Pier at David Terry Lock and Dam in Pine Bluff, Arkansas (*Source: U.S. Army Corps of Engineers*)

ACI Committee 211, Proportioning Concrete Mixtures, has a number of documents that provide guidance on proportioning concrete mixtures that meet project specifications. Trial batches in real field conditions help ensure that concrete mixtures with required properties will be delivered on the project site as designed. Before the concrete placement, there are a number of factors that need to be observed and verified. These include base preparation (soil/rock foundation), formwork, joints, embedded items, reinforcing steel, cleanliness of placement equipment, weather conditions, and consolidation. After-placement observations include finishing, curing, repair of placement defects, and form removal. The tests performed during the placement of concrete include slump (ASTM C143/143M), entrained air content (ASTM C231/231M and ASTM C173/C173M), concrete temperature, unit weight and yield (ASTM C138/138M), and compressive strength (ASTM C39/39M) [3]. Other testing may be added to the QA/QC program specific to the nature and sensitivity of the project, for example, rapid chloride permeability testing (ASTM C1202/AASHTO T-277).

Temperature monitoring and control in offshore and marine structures during placement is very important as they are generally classified as mass concrete due to their large volumes. Large thermal gradients can develop in these structures during placement and initial stages after placement if appropriate measures are not taken to control the temperature. The temperature control measures include the use of low heat generating cements, supplementary cementitious materials, aggregates with low coefficient of thermal expansion, cooling of constituent materials before placement, chilled mixing water, and surface insulation [6]. Wireless sensors are available that can be attached to the reinforcing steel or formwork and the temperatures can be monitored remotely as the concrete is placed, hardens, and cures.

CONCRETE DETERIORATION MECHANISMS

There are a number of ACI documents and numerous publications that describe various concrete deterioration mechanisms, which constructed facilities experience in different environmental and exposure conditions. ACI 201.2R-16—Guide to Durable Concrete [7] and ACI 222R-01—Protection of Metals in Concrete Against Corrosion [8] are good sources of such information. Some of the concrete deterioration mechanisms commonly encountered in offshore and marine structures are briefly described below:

Freezing and Thawing

Freezing and thawing damage is caused by freezing of the internal moisture in concrete, which may be available as part of the microstructure of concrete or may enter concrete from external sources. Freezing within the concrete is accompanied with an about 9% increase in volume, which exerts tensile stresses in the concrete pore structure and if these tensile stresses exceed the tensile strength of concrete, the concrete cracks. Offshore and marine structures, by nature, are exposed to a large body of water and there is no shortage of water entering the concrete externally, even if there is not sufficient freezable moisture in the concrete microstructure initially. A low water-to-cementitious materials ratio (*w/cm*), along with good curing, helps control the amount of freezable water in the concrete microstructure. A low *w/cm* is a starting point for any good quality strong and durable concrete. In order to protect concrete from freezing and thawing damage due to moisture entering from external sources, concrete must be produced with aggregates that are not susceptible to freezing and thawing and a paste that has uniformly dispersed air voids serving as stress relieving sites during freezing of moisture in the concrete. Concrete in its early age, before it has developed sufficient strength, must be protected from the cycles of freezing and thawing by controlling excessive drying and maintaining adequate temperature (curing). The development of a compressive strength of at least 3,500 psi (25 MPa) and 4,500 psi (32 MPa), if exposed to deicing salts, is generally recommended if concrete is expected to experience repeated cycles of freezing and thawing [7]. Surface scaling, which is the loss of mortar from the concrete surface, is the most visible manifestation of freezing and thawing damage. However, freezing and thawing can also cause internal deterioration of concrete compromising its structural integrity.

Alkali-Aggregate Reaction

Alkali-aggregate reaction (AAR) is a reaction between aggregates of certain mineralogical compositions and alkalis in the cement, in the presence of moisture, creating expansive stresses in the concrete which concrete cannot withstand. Depending upon the type and mineralogical composition of the aggregate, this reaction can be classified as an alkali-carbonate reaction (ACR) or alkali-silica reaction (ASR). Of these two reactions, ASR is much more common and widespread than ACR. In ACR, some argillaceous dolomitic limestones, characterized by a matrix of fine calcite and clay minerals with scattered dolomite rhombohedra, react with the sodium or potassium hydroxide of concrete in a manner that dolomite crystals of composition $Ca \bullet Mg(CO_3)_2$ are converted to magnesium hydroxide (brucite), calcium carbonate, and alkali carbonate, as represented by the following equation (R represents Na_+ or K_+):

$$Ca \bullet Mg(CO_3)_2 + 2ROH \rightarrow CaCO_3 + Mg(OH)_2 + R_2CO_3$$

This reaction, often referred to as dedolomitization, causes the affected aggregates to expand and crack, with the cracks extending to the cement paste. The alkali carbonate produced in the dedolomitization process may react with calcium hydroxide in the cement paste to regenerate alkalis for further continued reaction.

ASR is an expansive chemical reaction involving alkalis contained in the cement paste and certain reactive forms of silica within the aggregates. Hydroxyl ions in the concrete pore solution attack siliceous constituents of certain aggregates and liberate silica in the concrete pore solution, ready for reaction with alkali ions Na_+ and K_+. A reaction between silica and these alkali ions produces an alkali-silica gel, which absorbs moisture and expands, leading to the cracking of the aggregates, cement paste, and ultimately the concrete matrix. Cements with Na_2O equivalent of more than 0.6% are susceptible to ASR when used with reactive aggregates. Na_2O equivalent is defined as $Na_2O + 0.658\ K_2O$, and is a term used to express the total amount of sodium and potassium alkalis in the cement. Portland cement is generally the source of alkalis in concrete, however, alkalis can also enter the concrete from external sources, such as seawater. The types of aggregates that are susceptible to ASR include shale, sandstone, siliceous carbonate rock, chert, flint, quartzite, quartz-arenite, gneiss, argillite, granite, greywacke, siltstone, arenite, arkose, and hornfels. Reactive minerals susceptible to ASR include opal, tridymite, cristobalite, volcanic glass, cryptocrystalline quartz, and strained quartz [7].

Sulfate Attack

Sulfate reactions in concrete could occur due to both internal and external sources of sulfates. However, it is believed that deleterious sulfate reactions generally occur from sulfates entering the concrete from external sources. Seawater, to which most offshore and marine structures are exposed to, is a rich source of such external sulfates. Ancient seabed deposits are known to be one of the original sources of these sulfates. Sulfates considered to be deleterious to concrete are generally the sulfates of sodium, potassium, calcium, and magnesium. Calcium sulfate, also known as gypsum, is part of the cement and intentionally added during the cement manufacturing process to control rapid or flash setting of concrete. It is also believed to improve strength development and control drying shrinkage during the initial placement of concrete. When cement is mixed with water, the calcium sulfate ($CaSO_4 \bullet 2H_2O$) reacts with tricalcium aluminate ($3CaO \bullet Al_2O_3$, also denoted in as "C3A") to form a product ettringite ($3CaO \bullet Al_2O_3 \bullet 3CaSO_4 \bullet 32H_2O$), as represented by the equation below.

$$3CaO \bullet Al_2O_3 + 3(CaSO_4 \bullet 2H_2O) + 26H_2O \rightarrow 3CaO \bullet Al_2O_3 \bullet 3CaSO_4 \bullet 32H_2O$$

Most of the gypsum present in cement is generally consumed in the formation of the initial ettringite. The ettringite formed in the initial stages of mixing and placement of concrete is normal and not considered to be deleterious. However, all the C3A may not be consumed in this reaction and the remaining available C3A reacts with the previously formed ettringite to create the following compound, known as calcium monosulfoaluminate:

$$3CaO \bullet Al_2O_3 \bullet CaSO_4 \bullet 12H_2O$$

Even this calcium monosulfoaluminate is not considered destructive if it forms at the time of placement of concrete, when it can move and position itself in the concrete matrix. However, during the service life of concrete, the calcium monosulfoaluminate can react with sulfates entering the concrete from external sources, and when it reacts with external sulfates, it regenerates ettringite. The formation of ettringite in hardened concrete is detrimental because ettringite crystals at this stage do not have an available space to reside, resulting in expansive forces.

In addition to deleterious chemical sulfate reactions, sulfate attack could cause physical attack. When concrete is exposed to a sulfate rich aqueous environment and water evaporates from the concrete surface, such as in splash zones, an accumulation of sulfate salts can occur, resulting in physical salt attack or salt weathering [7].

Corrosion of Reinforcing Steel

Normally, concrete is a highly alkaline material, with a pH of more than 12.5, and this high alkalinity provides protection against corrosion of embedded steel by forming a passive iron oxide film on the steel surface. The formation of this passive film is in itself a corrosion reaction, which occurs at the time of construction when the bare reinforcing steel comes in contact with wet concrete [8]. However, once this passive film is formed on the steel surface and as long as the high alkalinity of the concrete ($pH > 12.5$) is maintained, further corrosion reactions practically stop. Thus, beneficial corrosion reactions at the steel-concrete interface, at the time of concrete placement, are needed to prevent deleterious corrosion reactions later during the service life of concrete.

There are two commonly recognized mechanisms that destroy the passive film and make the steel susceptible to corrosion; one is chloride ion attack and the other is carbonation. Chloride ions attack and destroy the passive film even in the presence of high alkalinity. These chloride ion attacks on the passive film regardless of whether they are localized or widespread, facilitate the onset of corrosion. Carbonation is a reaction between atmospheric CO_2 and the cement paste in concrete, which converts the $Ca(OH)_2$ of the paste to $Ca(CO)_3$. This reaction lowers the alkalinity of concrete from more than 12.5 to less than 9, and thus destroys the passive film on the reinforcing steel. Once the passivity of the reinforcing steel is destroyed, an electrochemical corrosion cell sets up with the formation of anodic and cathodic sites and corrosion initiates and propagates in the presence of moisture and oxygen. The locations where the passivity of the reinforcing steel is destroyed act as anodic sites and the locations where the passivity is still intact act as cathodic sites. The following equations represent the corrosion reactions at the anodic and cathodic sites, respectively:

$$Fe \rightarrow Fe^{++} + 2e^{-}$$
$$2H_2O + O_2 + 4e^{-} \rightarrow 4(OH)^{-}$$

The pore solution of concrete serves as an electrolyte in this electrochemical corrosion process. A porous concrete pore structure, with low electrical resistivity, is conducive to corrosion reactions as opposed to a dense concrete matrix with high electrical resistivity. The ferrous ions combine with oxygen or hydroxyl ions and produce various forms of corrosion products. These corrosion products are larger in volume than the original volume of ferrous from which they are formed, causing an expansion at the steel-concrete interface, which leads to cracking and spalling of the concrete cover [7-9].

Interactive Effect of Different Concrete Deterioration Mechanisms

From the foregoing discussion of various concrete deterioration mechanisms, it is apparent that alkalinity of the concrete plays an important role in the onset and progress of several of these deterioration mechanisms. For example, a high alkaline environment, represented by a Na_2O equivalent of more than 0.6%, is not desirable from the standpoint of alkali-aggregate reactions. The alkalinity of concrete is primarily controlled by the alkalinity level of cement. However, alkalis can enter the concrete from the surrounding seawater. Thus, it is important that the aggregates used in offshore and marine structures are not susceptible to either ACR or ASR. On the other hand, high alkalinity of concrete is desirable from the standpoint of reinforcing steel corrosion. High alkalinity is required for the formation and maintenance of a passive film on the steel surface. However, it is almost impossible to protect offshore and marine structures from chloride ion attack, which break the passive film, as most of these structures are exposed to an aqueous environment rich in chloride ions. The quality and thickness of the concrete cover over reinforcing steel, a dense and impermeable concrete, is the primary protection against chloride ion attack in offshore and marine structures. However, there is an element of nature that comes to the rescue of offshore and marine structures in protecting them from reinforcing steel corrosion. Oxygen, along with moisture, is needed for the onset and propagation of any corrosion reactions. The availability of oxygen in completely submerged conditions is severely diminished. Thus, corrosion of reinforcing steel in submerged portions of offshore and marine structures is not much of a concern. However, it is still a serious concern for portions of the structures in the splash zone and those completely above water.

Sulfate attack and corrosion of reinforcing steel are two different concrete deterioration mechanisms, but when chlorides and sulfates are present in large amounts together, such as in seawater, their deteriorating effects are not necessarily mutually exclusive. The reaction of tricalcium aluminate (C3A) in cement and external sulfates entering the concrete is involved in the sulfate attack of concrete. Thus, generally, a low C3A cement is recommended for controlling sulfate attack. For example, for ASTM V sulfate-resistant cement, a maximum C3A content of 5% is permitted. However, C3A is beneficial in controlling the corrosion of reinforcing steel in concrete as it has the capability to bind the chlorides present in different constituents of the concrete and also the chlorides entering the concrete from external sources. C3A contents as high as 10% are recommended for concrete completely submerged in seawater if *w/cm* is maintained below 0.45. The chloride binding attributes of C3A are also helpful in controlling sulfate attack. C3A bound with chlorides is not available for participating in reactions associated with sulfate attack. Thus, in deeply submerged portions of offshore and marine structures, the deterioration induced by both reinforcing steel corrosion and sulfate attack are reduced to a great extent with an optimum level of C3A [7,8].

With these interactive effects of different concrete deterioration mechanisms, the following practices can help protect offshore and marine structures from different deterioration mechanisms:

- Use of a low *w/cm* concrete mixture.
- Use of adequate concrete cover over reinforcing steel.
- Use of aggregates that are not susceptible to freezing and thawing damage, alkali-carbonate reaction (ACR), and alkali-silica reaction (ASR).
- Use of a cement with a C3A content that is optimum for protection against both sulfate attack and reinforcing steel corrosion. This optimum C3A content may be 6% to 8%.

TESTING AND INSPECTION OF OFFSHORE AND MARINE STRUCTURES

The diversity of offshore and marine structures and the difficulty in accessing their components, particularly those in submerged conditions, presents special testing and inspection challenges compared to above-ground structures. The testing and inspection of the portions of the offshore and marine structures above water, including in the splash zone, can be treated like any other structure, and, thus, the testing and inspection techniques used in general structures will be briefly described here. However, underwater testing and inspection techniques are specific to offshore and marine structures, including bridges, docks, nearshore terminals, wharfs, dams, locks, levees, and offshore oil platforms. The application and limitations of such techniques are highlighted in this section.

Above-Water Testing and Inspection Techniques

Visual Surveys

A good visual survey is the starting point of any testing and inspection program of an in-service structure. In many cases, a visual survey is needed to define the scope of a testing and inspection program. A visual survey is a detailed observation and documentation of the deterioration visible on the concrete surface, along with photographic documentation. A good understanding of various concrete deterioration mechanisms and their interactive effects is needed to perform a visual survey, which may be sufficient on its own or help formulate an economical qualitative and quantitative testing and inspection program. A visual survey soon after construction and then at periodic intervals during the service life of the structure can provide the most meaningful information on changes in the condition of the structure and the need for timely and appropriate remedial actions. The collection of records and specifications related to materials, construction, and maintenance are part of the visual survey. ACI 201.1R-08—Guide for Conducting a Visual Inspection of Concrete in Service [10], as the name implies, provides good guidelines for the visual survey of in-service concrete structures. It describes different types of cracks and distresses that concrete may experience during its service life. Some of the observations that need to be made during a visual survey are briefly discussed below.

Discoloration and Deposits: Discolorations and deposits on the concrete surface are generally good indicators of the reactions occurring within the concrete (Figure 6). For example, rust stains on the concrete surface are obvious signs of reinforcing steel corrosion, and the cracking and spalling associated with these rust stains should be carefully documented. If there is any exposed corroded reinforcing steel, the cross-sectional loss of the reinforcing steel should be physically measured. Another example is leaching and efflorescence, which appear on the concrete surface as a white deposit. These deposits are generally sulfate and carbonate compounds of sodium, potassium, and calcium, which are created by dissolution of some parts of the hydrated concrete by water, their movement to the concrete surface, and then their eventual evaporation and precipitation. Excessive leaching and efflorescence may weaken the pore structure of concrete. More importantly, they are indicators of a porous concrete where water can easily flow in and flow out, facilitating other concrete deterioration mechanisms.

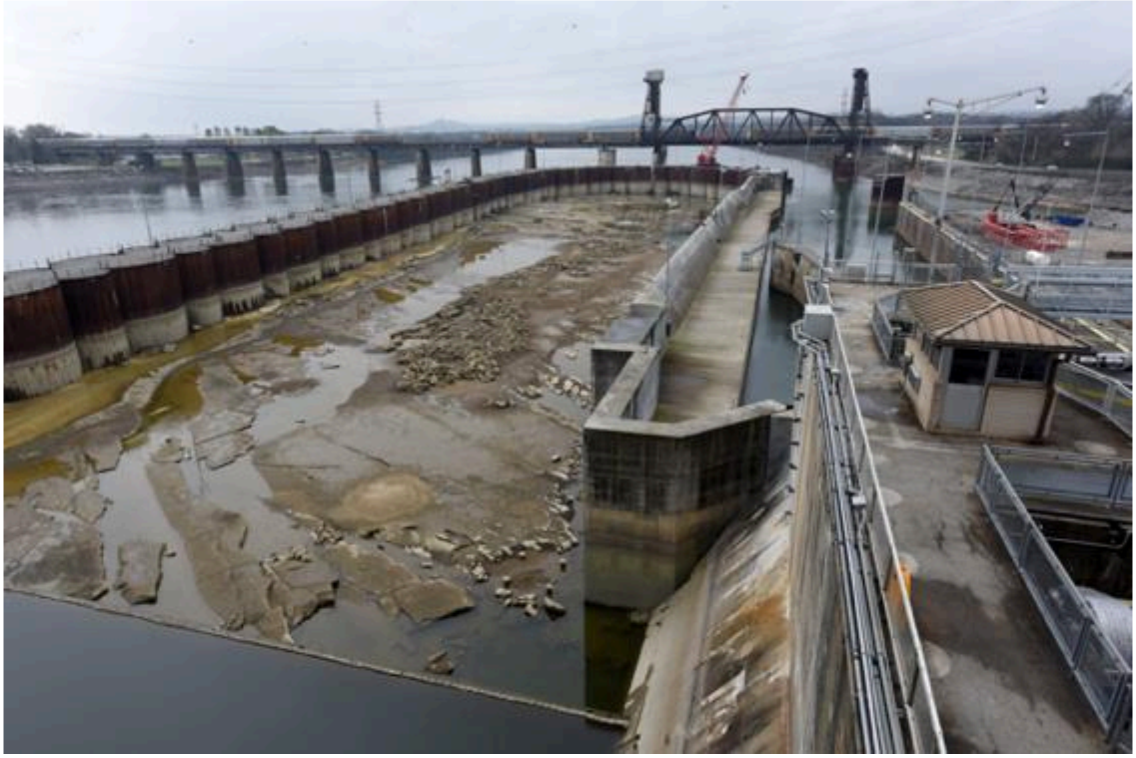

Figure 6—Rust Stains and Efflorescence Visible (Right Side) During the Chickamauga Lock Replacement Project in Tennessee (*Source: U.S. Army Corps of Engineers*)

Cracks: The type, severity (width, depth), and orientation (longitudinal, transverse, diagonal) of all the cracks should be noted. These include map cracking, pattern cracking, shrinkage cracking, random cracking, and temperature cracking. This information helps identify the deterioration mechanisms responsible for these cracks. In some cases, crack patterns alone cannot identify the deterioration mechanism and further testing and inspection may be needed. For example, map cracking could be due to shrinkage or as a result of alkali-aggregate reactions.

Distresses: There are many different types of distresses that can be visually observed and quantified with limited physical measurements. These distresses, which could be both materials and load related, include deflection, deformation, disintegration, exudation, joint damage, leakage, mortar flaking, peeling, pitting, popout, scaling, and spalling. ACI 201.1R-08 provides a checklist of items that need to be included in a visual survey report [10].

Subsurface Delamination and Defect Surveys

Delaminations are subsurface defects in concrete, which are not visible on the concrete surface, and, thus, may not be captured in visual surveys. A delamination is the separation of a concrete layer along a plane parallel to the concrete surface, which may be separation from another concrete layer or from the reinforcing steel. Separation of overlay from base concrete is an example of delamination of different concrete layers. In the case of corrosion-induced delaminations, the expansion of corrosion products exerts tensile stress within the surrounding concrete and causes a loss of bond between reinforcing steel and the concrete. This loss of bond, which creates a gap between reinforcement and concrete, is initially classified as delaminations, but eventually may lead to the spalling of concrete cover over the steel [11]. Some of the commonly used techniques in delamination surveys are described below.

Chain-Drag and Hammer Sounding: Chain-drag is the most common and traditional technique for detecting delaminations in concrete. It involves dragging a chain on the concrete surface under investigation and listening to its acoustic response. An intact concrete element produces a clear ringing sound, whereas delaminated concrete produces a dull or hollow sound. The technique has been standardized in ASTM D 4580 for bridge deck applications, but the principles apply to any concrete structure. On vertical concrete surfaces, a hammer is typically used for sounding, and likewise the type of sound generated from the hammer's impact can identify delaminations. These manual acoustic-based techniques are simple and relatively inexpensive when small test areas are involved. However, for large test areas, other techniques may be more economical. ASTM D 4580 includes two more techniques, which are still acoustic-based, but have some level of automation. One of the techniques is an electro-mechanical sounding device and the other technique is a rotary percussion device [11].

Impact Echo: In the impact-echo technique, a small steel impactor introduces mechanical energy, in the form of stress waves, into a concrete member. These stress waves either travel through the entire thickness of the member or encounter a flaw within the concrete member and then reflect back to its surface. These discovered flaws may be gaps created by a failed surface layer or a failed overlay, inadequately consolidated concrete, settlement of concrete when in its plastic stage, or delamination caused by corrosion of reinforcing steel. A transducer mounted on the surface of the concrete, and close to the impact point, receives the reflected stress waves. Resonant echoes from the member thickness or flaws can be analyzed relatively easily by their acoustic frequencies. Fast Fourier Transform (FFT) analysis is involved in the analytical process, and the resulting amplitude spectra help identify the dominant frequencies present in the echoed waveform. Concrete members without any internal defects are characterized by a single primary frequency peak, which represents the thickness of the member [11]. Zhang et al. [12] used impact echo, along with chain-drag and hammer sounding, to assess the condition and estimate remaining service life of the Ruskin Dam Spillway in British Columbia, Canada.

Infrared Thermography: Thermography takes advantage of the phenomenon that occurs when heat flows through concrete; the presence of any defect in the concrete reduces the diffusion rate and causes localized temperature discontinuities to become detectable on the surface of the concrete. These contrasting discontinuities can be recorded by infrared cameras. In this technique, subsurface defects are located by measuring surface temperature under conditions of heat flow. The solar radiation during daytime causes a heat flow into the concrete and cooling during nighttime causes a heat flow out of the concrete. Sunshine conditions during the daytime and clear skies during the nighttime create ideal conditions for the required heat flow. Also, during the heat flow, a thermal gradient needs to occur for subsurface defects to appear as heat anomalies. The recommended time for infrared thermography surveys is soon after sunrise or one-half to one hour after the sunset as these are the times when a maximum thermal gradient occurs. Also, the concrete should be free from debris and surface moisture. Considering the weather constraints associated with this technique, an artificial source of heating can be used to create the required heat flow and gradient within the concrete, as discussed by ACI 228.2R-13 [13] and Dumoulin et al. [14].

Ground Penetrating Radar: Ground penetrating radar (GPR) technology has been developed over the last three decades, however, its application is still limited. GPR emits electromagnetic energy that is projected in the form of radio frequency pulses into the concrete. When this electromagnetic energy comes in contact with an interface between two materials of different electromagnetic properties, some of the energy is reflected from the interface and the remaining energy propagates through the interface. The amplitude of the signals reflecting from the interface or propagating through the interface depends upon the difference in the dielectric properties of the materials at the interface. The radio frequency reflections are received by the radar antenna, which are processed for detecting delaminations. Accurate data interpretation in GPR is critical to its successful use. Because the images in GPR represent the amplitude of radar-reflected signals from interfaces within a structural element having different electromagnetic properties, the interpretation of subsurface radar feedback requires significant expertise on the part of the interpreter. Thus, research still continues toward a better understanding of reflected GPR signals, for example, recent studies by Raju et al. [15] and Rhee et al. [16].

Reinforcing Steel Corrosion Condition Evaluation

Corrosion of reinforcing steel in concrete is one of the major causes of deterioration in offshore and marine structures. The deterioration starts with the delamination of the concrete at the concrete-steel interface, which can progress to spalling of the entire concrete cover over the reinforcing steel. Rust stains and cracks appear on the concrete surface between the stages of delamination and spalling. Various techniques for detecting corrosion-induced delaminations are described in the preceding section. This section describes several testing and inspection techniques that can be used in detailed corrosion condition evaluation of offshore and marine structures.

Half-Cell Potential Testing: Half-cell potential measurements provide an indication of the presence or absence of the corrosion of steel embedded in concrete. In this test procedure, a high impedance voltmeter is used with the positive terminal of the voltmeter connected to the steel and the negative terminal to a Cu-$CuSO_4$ half-cell placed on the concrete surface. The half-cell potential values obtained are interpreted according to the guidelines of ASTM C-876. Half-cell potential values more negative than -350 mV indicate more than 90% probability that corrosion is occurring at the surface of the steel. On the other hand, half-cell potential values more positive than -200 mV indicate more than 90% probability that corrosion is not occurring at the surface of the steel. Corrosion activity is uncertain for half-cell potential values between -200 mV and -350 mV. If steel is continuous in a structural element, such as a pier cap or pier column, the voltmeter is connected to steel at one location, and half-cell potential values recorded for the entire structural element by placing the half-cell on the concrete surface at different locations, generally on a grid.

Corrosion Rate Measurements: Half-cell potential measurement is a good screening tool for determining the likelihood of corrosion. However, the areas identified as exhibiting active corrosion should be tested for corrosion rate to quantify the corrosion activity. Corrosion rate measurements based on polarization resistance technique are generally used in the evaluation of reinforced concrete. In this technique, the application of a small amount of current on a corroding metal in a conductive solution causes corresponding change in the potential and yields a linear relationship. A three-electrode system is used in these measurements. The reinforcing steel or prestressing strand being tested is referred to as “working electrode.” The electrode through which current is induced in the steel is referred to as “counter electrode.” Finally the electrode used to measure the potential change as a result of the application of current is referred to as “reference electrode.” This reference electrode is generally a Cu-$CuSO_4$ electrode commonly used in half-cell potential measurements. The system is equipped with high precision voltmeter, ammeter, and timer for the application and measurement of current and potential. In general terms, the larger the amount of current required to shift the potential by a given amount, the higher is the corrosion rate [8,17].

Cross-Sectional Loss Measurement of Reinforcing Steel: In situations where corrosion has progressed to an extent that the concrete cover is spalled and the reinforcing steel is exposed, the physical measurement of the cross-sectional loss of the reinforcing steel should be made. This can be done by removing the corrosion products, cleaning the reinforcing steel, measuring the remaining cross-section using a caliper, and then comparing it with the original cross-section. Cross-sectional loss measurements are useful in determining the structural integrity of the reinforced concrete members and the entire structure [8].

Concrete Cover Measurements: A magnetic cover meter is generally used to non-destructively locate reinforcing steel and provide an estimate of the concrete cover over reinforcing steel. Concrete cover measurements, along with other information, are useful in assessing the performance of a structure. If favorable conditions exist for the initiation and propagation of corrosion, inadequate cover usually contributes to the early cracking and spalling of concrete.

Sampling and Analysis for Chloride Ions: As discussed earlier, chloride ions are one of the destroyers of the passivity of reinforcing steel, leading to the corrosion process. Research in the past has established the threshold chloride ion content in concrete that is required for the initiation and propagation of reinforcing steel corrosion. Acid soluble chloride ion content 1.0 to 1.5 lb/yd$_3$ (0.6 to 0.9 kg/m$_3$) of concrete is generally considered as threshold in the United States [8]. Chloride ion content threshold is a matter of on-going debate within ACI Committee 222, Corrosion of Metals in Concrete, and new guidelines may be developed in the future. Concrete powder samples can be retrieved from the structure and then analyzed in the laboratory according to AASHTO T-260, which is a titration based method and includes both water soluble and acid soluble test procedures. AASHTO T-332 offers a rapid acid soluble test procedure, based on specific ion probe, which can also be used for chloride ion analysis of the concrete powder samples. AASHTO T-332 was originally developed as part of the Strategic Highway Research Program and later revised based on the findings of Khan [18].

Carbonation: As discussed earlier, carbonation is a reaction which lowers the alkalinity of concrete to a level at which the passive iron oxide film is no longer stable (pH < 9.5). Carbonation is a slow process, it starts from the surface and progresses through the depth of concrete. Carbonation becomes a concern when it reaches to the level of steel. Depth of carbonation can be measured simply using a phenolphthalein test. A solution of phenolphthalein in ethanol is applied on a freshly cut or drilled concrete surface. A non-carbonated concrete surface turns pink and a carbonated concrete surface remains colorless.

Concrete Property Tests

There are several tests that can be performed to determine the properties of in-place concrete. Two commonly used tests, compressive strength testing and petrographic analysis are discussed here. Compressive strength measurements of cores retrieved from the structure provide an indication of the degradation of the quality of concrete, which could result from harsh exposure conditions and associated deterioration mechanisms. Concrete compressive strength tests are performed in conformance with ASTM C-39. A petrographic analysis is performed to assess the general overall quality of concrete and determine cause(s) of concrete deterioration other than reinforcing steel corrosion, such as freeze-thaw damage, ASR, and sulfate attack. In this analysis, polished concrete and thin sections are studied under microscope and information such as *w/cm*, aggregate content, pozzolans, amount and distribution of entrained air, and presence or absence of different deterioration mechanisms is obtained. Concrete mixture proportions determined from petrographic analysis can be compared with original mixture designs. The petrographic analysis is performed in accordance with ASTM C-856. An air void analysis, generally as supplement and part of petrographic analysis, is performed according to ASTM C-457.

Underwater Testing and Inspection Techniques

The testing and inspection techniques described in this section are the techniques that can be used for the submerged portions of offshore and marine structures. Testing and inspection of the submerged portions of the structures presents special challenges, which include weather, sea current, marine growth, visibility, and accessibility. The depths to which these structures extend below the surface of water, which could be several hundred feet, is probably the biggest challenge. Considering these challenges, a testing and inspection program for offshore and marine structures should be carefully planned, utilizing remote and nondestructive evaluation (NDE) techniques to the extent possible.

Levels of Underwater Inspections

There are some federal agencies which have been involved in the underwater inspection of concrete structures, including the Navy, U.S. Army Corps of Engineers, and the Federal Highway Administration (FHWA). The underwater inspection of bridges is a major issue and the FHWA has developed an underwater bridge inspection manual [19]. Much of the information in this manual is applicable to almost any concrete structure with its foundations in shallow to moderate depths of water. The underwater inspection is generally classified into three levels of inspection, depending upon the complexity of the testing and inspection involved. These include Level I, Level II, and Level III, as described below.

Level I Inspections: These inspections are close visual inspection of the entire submerged portion of concrete structures, which could be aided with handheld lights. The inspections, generally referred to as "swim-by" inspections, are performed by professional divers who could be equipped with waterproof cameras, video equipment, and other lightweight probing and testing devices. The intent of these inspections is to have an understanding of the general overall condition of the structures and identify any suspect deteriorated areas which may need cleaning of the surface and/or detailed testing and evaluation, as described in Level II and Level III inspections below.

Level II Inspections: A Level II inspection is still a visual inspection, but it requires cleaning of the concrete surface, which might be covered with aquatic or marine growth. In fresh water, any aquatic growth can be easily removed by wiping with glove-covered hands. However, the surface cleaning in salt and brackish water is more challenging, time-consuming, and may require the use of a hard bush. The areas selected for cleaning are representative of the suspect deteriorated areas of the structure. After cleaning, a close visual examination may provide important information to assess the condition of the structure or lead to a Level III inspection.

Level III Inspections: The intent of Level III inspections is to identify and quantify deterioration that is not visible on the surface, but is suspected to be occurring internally, as manifested by signs such as cracks and rust stains. A Level III inspection requires the use of some form of semi-destructive or non-destructive testing technique, and, thus, requires extensive cleaning to make the concrete surface accessible and suitable for such testing. Coring, drilling, and sampling may be needed as part of Level III inspections.

Visual Inspections

Underwater visual inspections require technical skills to observe, document, and discern the condition of submerged concrete along with diving skills to move and remain under water for significant amount of time. The divers are exposed to a variety of physiological hazards, including pressure, temperature extremes, oxygen deficiency, and nitrogen narcosis. As the depth of diving increases, the ability of a diver to remain in water with no-decompression decreases. For example, according to U.S. Navy Diving Manual, at a depth of 60 ft (18.3 m), the no-decompression time limit is 60 minutes. Whereas, at a depth of 150 to 190 ft (45.7 to 57.9 m), the no-decompression time limit is 5 minutes. Thus, it appears that at a depth of 150 ft (45.7 m) and beyond, a meaningful underwater visual inspection is not practical. The U.S. Occupational Safety and Health Administration (OSHA) regulations, 29 Code of Federal Regulations, Part 1910 (29 CFR 1910), Subpart T-Commercial Diving Operations, regulate all diving operations [19]. Some of the tools that can be used in underwater visual inspections are briefly described below.

Camera: Photographic documentation of the condition of the concrete structure in underwater inspections is particularly important because if there is a need to go back to the test site to confirm any observation, it might not be possible or it might be too expensive. Thus, it is important to do the things right the first time and in as much detail as possible. Fortunately, cameras are currently available that can be used in underwater inspections. These could be cameras fitted with water housing or waterproof cameras without any attachments. The cameras are digital cameras equipped with a variety of lenses and digital flash units (Figure 7). Also, these cameras are generally calibrated in apparent distances, because in submerged conditions the apparent distances are about three-fourths of the actual distances and objects appear larger than their actual size. In case of extremely turbid waters when the visibility is very low, sometimes clearwater boxes are used to photograph the structural element. These clearwater boxes are rectangular clear acrylic plastic boxes filled with clean water. When pressed against the concrete surface, they displace the dirty water and a camera placed on the opposite face of the box can capture an image of the concrete surface through the clear water [19].

Video: Similar to underwater cameras, currently video devices are available for underwater applications. These video devices can be placed in a water housing or could be waterproof units on their own. The video imaging and recording in visual inspections offer the advantage of voice recording of the inspector which can later be transcribed to a text format. The video devices can be used with an umbilical cable to the surface for real-time viewing and monitoring. With advances in wireless technology, video cameras are currently commercially available that can be connected to WiFi cables, as long as 300 ft (91.4 m). The wet end of these WiFi cables is connected to the video camera and the dry end is connected to a cellular phone above water. These video cameras do not need to be carried underwater by a diver, rather they can be lowered in water from above water. Once the WiFi connection is established, the position of the camera can be controlled from above water and underwater video imaging can be viewed in real-time. These video cameras are fitted with light sources.

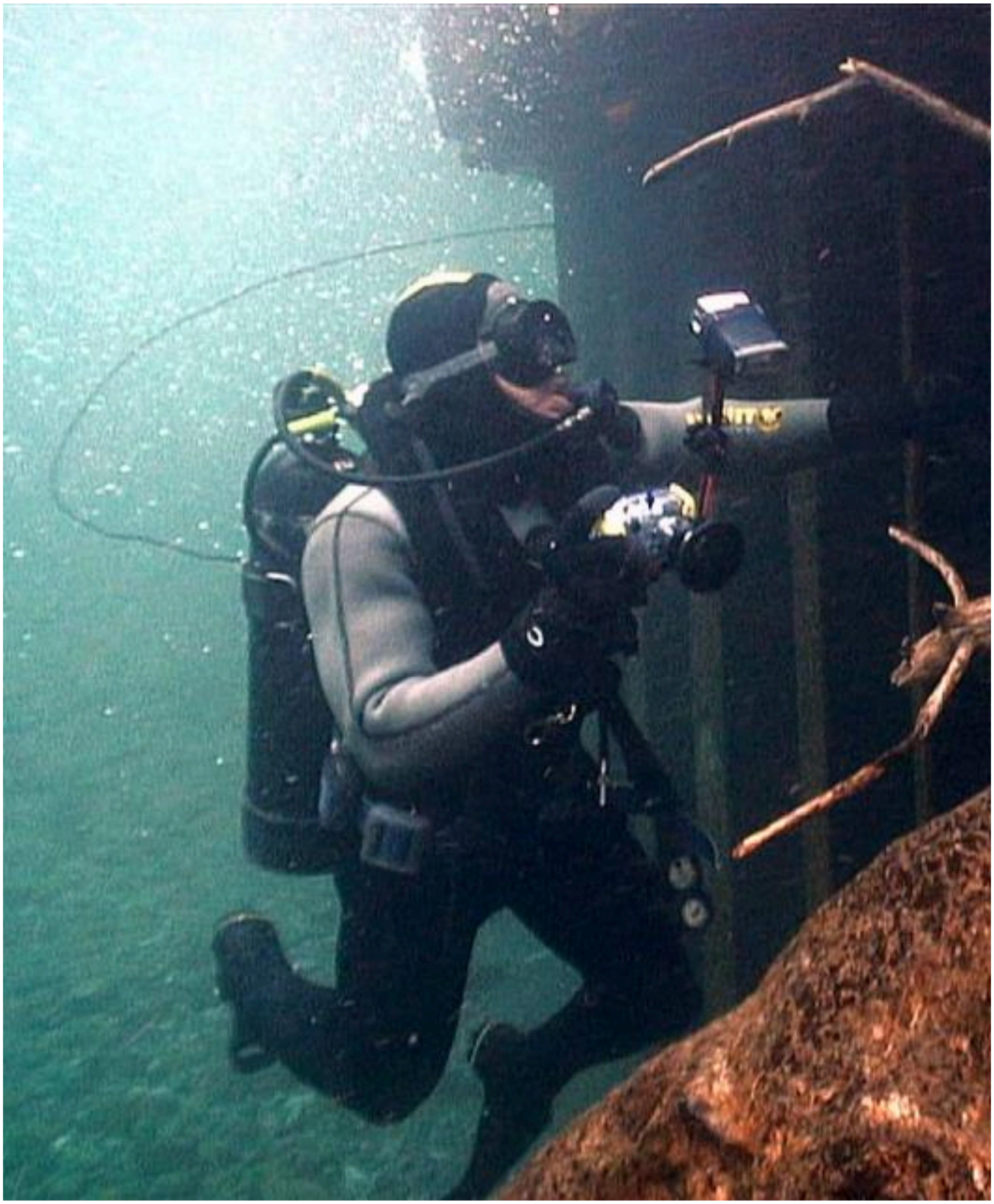

Figure 7—A Diver Taking a Photograph of a Bridge Substructure with a Digital Camera in Waterproof Housing (*Source: Federal Highway Administration [19]*)

Remotely Operated Vehicles: Remotely Operated Vehicles (ROVs) are similar to the remote video imaging, described above. An ROV is a tethered underwater video camera platform, which may also be fitted with some testing equipment which incorporate an electric or electro-hydraulic propulsion system. The ROV is monitored and controlled from above water using a video system and "joystick" type of controls. These ROVs have been in use for several decades and were designed for underwater operations that were either too inaccessible or too hazardous to divers. These include deep polluted, contaminated, or extremely cold waters. The ROVs are not effective in murky waters and high sea currents.