EVALUATION TECHNIQUES FOR CONCRETE BUILDING ENVELOPE COMPONENTS

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1.0 INTRODUCTION

Building facades constructed of exposed concrete framing elements and infill windows are common for many high-rise residential, hotel, and institutional buildings (*Photo 1*). This results in economical construction and allows for free expression of the building structure.

When properly designed and constructed, exposed concrete facade elements can provide a long service life with a reasonable level of maintenance. Design, construction, and material deficiencies, however, can cause premature deterioration of the facade elements, leading to costly repairs.

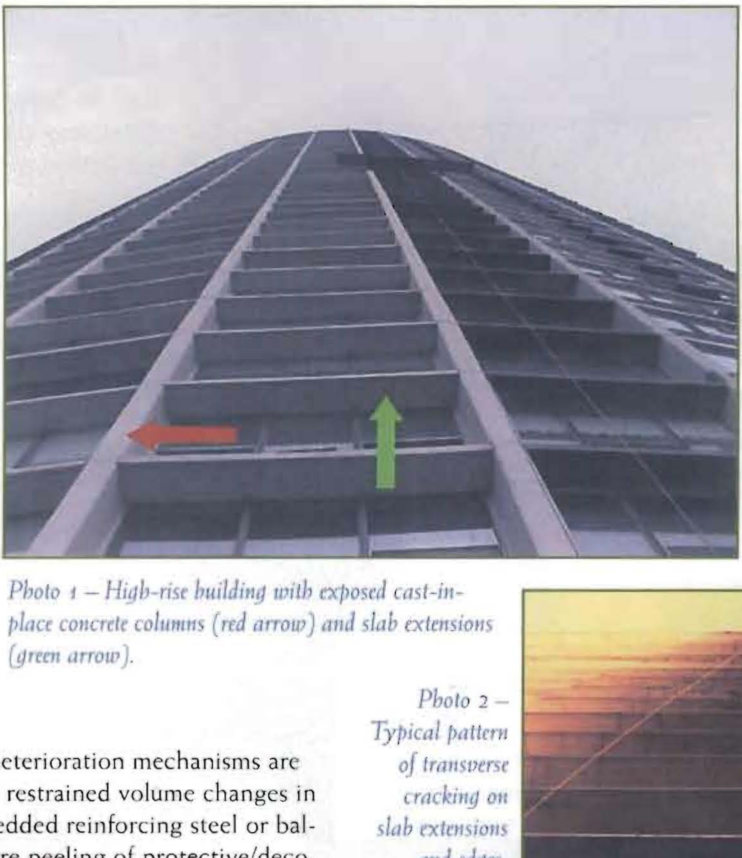

Photo 1 – High-rise building with exposed cast-in-place concrete columns (red arrow) and slab extensions (green arrow).

The most common facade deterioration mechanisms are associated with cracking due to restrained volume changes in the concrete, corrosion of embedded reinforcing steel or balcony railing posts, and premature peeling of protective/decorative coatings. These factors can contribute to water leakage, air infiltration, poor appearance, and safety concerns from falling concrete. If not repaired, severe concrete deterioration can also jeopardize the structural integrity of the building.

Prior to initiating repairs on a concrete building facade, the cause, type, and extent of deterioration should be evaluated thoroughly by proper investigation of the facade components. Repair alternatives and quantities can then be developed to address the underlying causes of the deterioration.

Evaluation of the building facade components requires a thorough understanding of each component's configuration and materials. An understanding of typical modes of deterioration or deficiencies encountered with each materi-

Photo 2 – Typical pattern of transverse cracking on slab extensions and edges. Cracks appear wider since they have been routed and filled with a sealant.

al is also essential in selecting evaluation techniques and approaches.

2.0 TYPICAL DETERIORATION MECHANISMS IN CONCRETE FACADES

2.1 Cracking

Although cracking of structural concrete components is a normally anticipated phenomenon, it is typically the first indication of more serious deterioration in concrete structures. Normally, anticipated cracks are associated with restrained volume changes of concrete associated with drying shrinkage and temperature fluctuations. Such cracks are typically hairline, are oriented perpendicular to the long dimension of the concrete member, and appear at relatively regular intervals (*Photo* 2). Vertical cracks along the exposed edges of floor slabs are common in many buildings and are typically due to drying shrinkage and temperature-induced restrained volume changes.

Photo 3 – Indications of extensive reinforcing-steel corrosion on a high-rise building exterior column.

Photo 4 – Same column shown in Photo 3 after removal of the delaminated concrete.

Cracking may also be load-induced. Hairline cracks in the tension sides of beams and slabs are to be expected. Fine, shear cracks near the supports of beams are also not serious problems, but they should be evaluated by an experienced structural engineer. However, cracks wider than hairline, cracks that show evidence of movement, or cracks in unexpected locations may indicate overloading or inadequate design of the structure and should be investigated further.

Cracks can also indicate corrosion of embedded steel in concrete. As corrosion of embedded reinforcing steel progresses, cracks will extend to the concrete surface. Cracks frequently reflect the location of reinforcing steel. Corrosion of column reinforcing bars usually results in vertical cracks, often at corners, which can run for several feet down the face of the column (*Photos* 3, 4, and 5). Corrosion of column ties will likely lead to horizontal cracking on the face of the column at regularly spaced intervals reflecting the placement of the ties. Similarly, balcony cracking can reflect reinforcing bar placement. In most cases, significant cracks are wide enough to be observed easily. However, wetting the concrete surface reveals finer cracks that may be of interest but are not readily observable when dry.

2.2 Corrosion of Reinforcing Steel

Embedded reinforcing steel in concrete is normally protected from corrosion by the high alkalinity of the cement paste. In this environment, the steel forms a thin, "passivating" oxide layer that protects it from further

Photo 5 – Same column shown in Photo 3 during repairs.

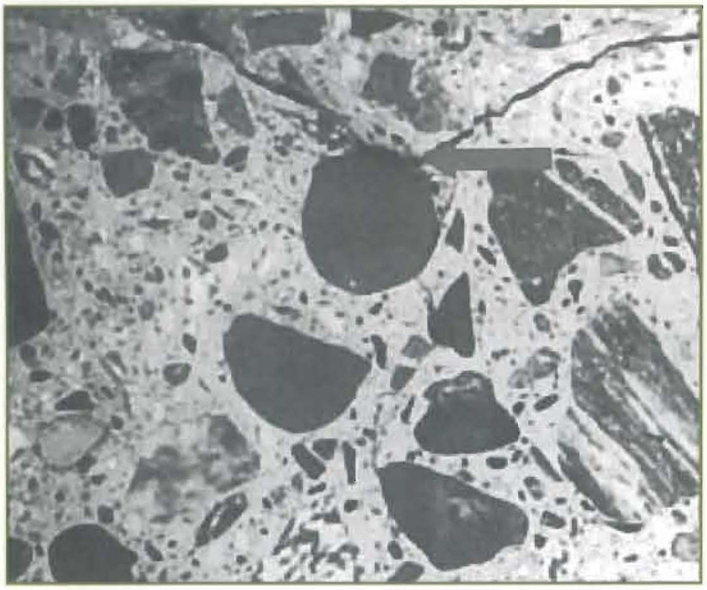

Photo 6 – Expansion of reinforcement due to corrosion will eventually lead to delamination of cover concrete. Note the build-up of corrosion products.

corrosion. However, if the environment within the concrete changes, or the passivating film is compromised, the steel may corrode. Corrosion of embedded reinforcing steel can be extremely detrimental to concrete structures. Corrosion products occupy four to five times more volume than the original steel. This volume expansion creates tensile stresses in the concrete. If the stresses exceed the tensile strength of the concrete, it will crack. Small cracks first develop within the body of the concrete at the site of the corrosion. More corrosion products form as corrosion progresses, further cracking the concrete and creating planar delaminations within the material (*Photo 6*). As the delaminations grow, they may run to the surface, forming surface cracks. Cracks provide an avenue for moisture and air to further infiltrate the concrete, resulting in continued corrosion. The delaminated concrete may then spall off the building, creating falling hazards and an unsightly facade. If the corrosion process continues, it will impact the structural integrity of the building as well.

The properties of the concrete and the design of the structure can directly affect the potential for corrosion. Porous concrete with a high water/cement ratio allows quicker infiltration and diffusion of moisture and air. Porous concrete experiences greater degrees of carbonation and has a higher electrical conductivity, supporting the corrosion mechanism. Concrete with added chlorides also has a higher potential for corrosion, as later discussed. Weak concrete with a lower tensile strength will crack earlier, under less tensile stress. Even good quality, properly placed concrete may experience corrosion if the design is inadequate. Moisture and air will infiltrate to reinforcing steel more rapidly if the concrete cover on the steel is insufficient. Structures with low concrete cover also experience increased spalling, as delaminations more easily reach the surface. Also, load-induced cracking will serve as a conduit for moisture and air, promoting corrosion.

Corrosion of embedded reinforcing steel is the result of an electrochemical process that occurs within the concrete. Under appropriate conditions, a low-level electric current develops, flowing through the concrete and steel (*Figure 1*). Four factors are required to support the current – an anode, a cathode, an electrolyte, and a conductive path. In reinforced concrete, the anode and cathode are specific sites on the surface of the steel, moist concrete serves as the electrolyte, and the steel bars, wires, chair supports, etc., provide the continuous electrical path. Furthermore, there must be sufficient moisture and oxygen present to support the corrosion reactions. In porous concrete exposed to the atmosphere, neither is commonly lacking.

To overcome the passivating nature of the concrete, a catalyst or change in the concrete environment is usually required to start corrosion. Carbonation of the cement paste can initiate corrosion. Carbonation lowers the pH of the paste, changing the passivating environment around the steel. However, carbonation occurs very slowly, advancing from the surface into the concrete. Thus, only very old structures or structures with shallow concrete cover are likely to experience carbonation-induced corrosion.

Chlorides within the concrete are considered to be more of a factor leading to corrosion. Chloride-induced corrosion is also more prevalent, as chlorides can enter the concrete from a variety of sources. In many high-rise buildings, mainly those built before 1977, calcium chloride was added to the concrete mix as an accelerator. Chlorides may also be constituents of other concrete admixtures such as water-reducing agents. Aggregates may contain certain levels of chlorides, depending on their source. Although building facades are not usually exposed to de-icing salts, in coastal areas they can be exposed to sea spray and airborne salts. Finally, if potable water was not readily available during construction, the mix water may have contained chlorides. For most reinforced concrete buildings, a water-soluble

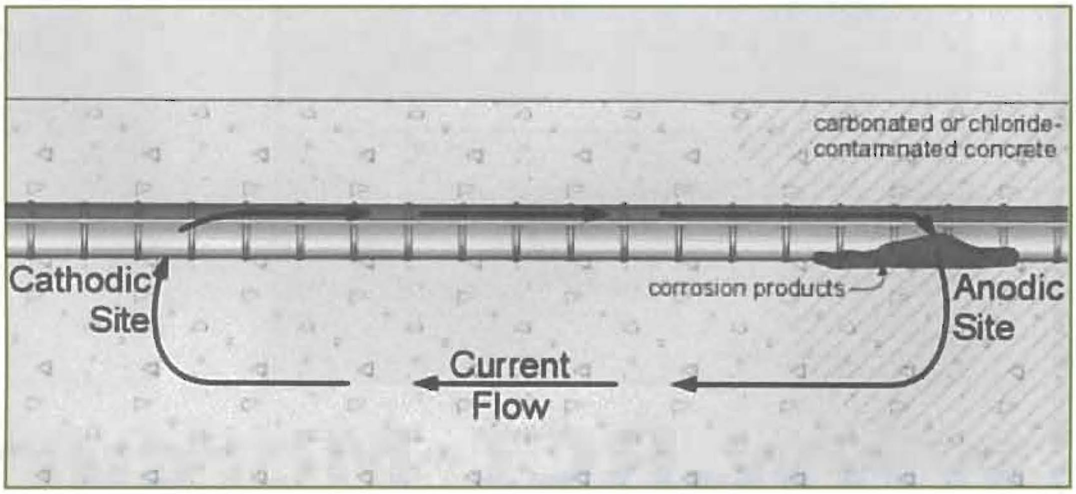

Figure 1 – Diagram showing current flow in corrosion process.

chloride ion content of 0.30% by weight of cement is the maximum allowable level, as stated by ACI 318[1].

Chloride-induced corrosion occurs when oxygen, chloride ions, and moisture meet at the surface of the reinforcing steel. Anodic sites form in areas where the passivating film is disrupted or in areas with energy differences at the steel/concrete interface. Differing energy levels can be caused by differing levels of chloride ion concentration, oxygen content, moisture content, or pH. An electrical current forms, leaves the steel at the anode, flows through the moist concrete, and re-enters the steel at the cathodic site. Corrosion then occurs through a series of chemical reactions at the anodic and cathodic sites. Ferrous material is consumed and corrosion products ("rust") are deposited only at the anodic sites. One characteristic of these reactions is that chloride ions are released back into the concrete pore water such that the ions are never really consumed in the corrosion process. The same chloride ions can be used again in later corrosion reactions. As a result, chloride-induced corrosion is auto-catalytic (self-perpetuating).

Macrocorrosion occurs between two reinforcing bars or even between two reinforcing mats if they are connected by tie wires, chairs, etc. In this case, one mat serves as the anode and accumulates corrosion products. The other mat acts as the cathode and does not show evidence of corrosion. Macrocorrosion more commonly occurs because of differing energy levels in different areas of the concrete.

If anodic and cathodic sites develop near each other on the same bar, as when the anode forms where the passivating layer has a slight defect, a microcorrosion cell forms. In this case, the anodic and cathodic sites are very close, and the electrons and hydroxyl ions do not have far to diffuse. Corrosion can occur at an accelerated rate, and significant loss of reinforcing bar cross section, in the form of pitting, can result.

2.3 Freeze-Thaw

Saturated concrete is susceptible to damage in freezing and thawing environments. As liquid water in concrete freezes, hydraulic pressure is caused by the nine percent expansion of water upon freezing. If the concrete is not resistant to the stresses caused by continuous cycles of freezing and thawing, microcracks will develop in the concrete. As the cycles continue, these microcracks will grow and become more prevalent on the concrete surface. Advanced freeze-thaw deterioration is visible in the form of cracking, scaling, and crumbling.

The resistance of hardened concrete to freezing and thawing in a saturated condition is significantly improved by the use of entrained air. Air-entrained concrete is produced by blending an admixture into the concrete mix. The air-entraining admixture produces small, spherical air voids that are distributed uniformly throughout the hardened concrete. These air voids allow room for freezing and migrating water to enter, thereby relieving pressures and preventing damage to the concrete.

On concrete facade components, freeze-thaw deterioration is uncommon due to the thermal protection provided by conditioned interior spaces. Most exposed concrete columns, slab edges, and spandrel beams are only partially exposed to the environment. In such instances, the steady-state heat conduction through the member significantly moderates the member temperature, preventing freeze-thaw cycles. However, freeze-thaw deterioration can occur in exposed members such as balcony slabs and slab overhangs. It can also occur in columns that are not partially protected by the building envelope.

2.4 Coating Failure

Various types of coatings are used on concrete facade surfaces. In most cases, these coatings are intended to improve aesthetics. However, most coatings can also reduce paste carbonation by reducing the surface permeability of the concrete. In some cases, coatings can also provide more resistance to water intrusion into porous concrete; and, in fewer cases, coatings can bridge non-moving hairline cracks.

Coating failures can occur for a number of reasons. They can be related to improper selection of the coating for the service condition, poor adhesion, contaminated substrate, incompatibility of the substrate and selected coating, and poor/inadequate surface preparation or application (*Photo* 7). The most common coating failures involve poor adhesion/bond to the concrete substrate. A poorly bonded coating will eventually fail, becoming detached from the concrete substrate. Inter-coat delamination, cracking, blistering, peeling, flaking, pinholes, holidays, and weathering are other types of failure mechanisms.

Formulation-related failures include chalking, erosion, checking, cracking, alligator cracking, wrinkling, and discoloration. Application failures include improper mixing ratios, incomplete mixing, and failure to follow manufacturers' recommendations for application, such as ambient temperature and humidity, recoat time, and curing environment.

Concrete is a non-uniform, porous surface containing moisture and air pockets, making it a difficult surface to coat. The coating must be resistant to moisture and an alkaline substrate. A cast concrete surface is one of the most difficult of all surfaces to provide with a consistent, uniform, air void-free coating. To avoid failures, the selected coating system must have a good service performance history in a similar application. The coating must also be compatible with the substrate and easy to apply.

Photo 7 – Failure of protective coating on a slab extension.

3.0 EVALUATION TECHNIQUES

3.1 Visual Inspections

One of the simplest and most useful tools for evaluating a concrete facade is visual examination. A wide variety of concrete problems express themselves on the surface. By visual inspection, an experienced person can identify freeze-thaw deterioration, corrosion of embedded reinforcing steel, overloading of the structure, moisture migration through concrete, poor placement of the original concrete, and previous repairs.

A good visual examination should begin with an overview of the building to become familiar with the structure. Based on this overall review, representative "drops" should be selected for close-up inspection and testing.

When performing a close-up visual inspection (usually from a swingstage scaffold), large cracks and areas of deterioration should be noted for further inspection. The general environment and exposure conditions should also be noted. If available, building plans and records of previous repairs should be reviewed. The detailed visual inspection should be performed in a methodical manner to ensure a consistent and thorough review of all areas inspected. Base drawings of the areas examined can serve as a guide and provide a place to write notes and sketch deterioration. Base drawings should be drawn to scale and should include elevation views of the facade and any other important architectural features.

When making observations, it is helpful to have an idea of the problems typically seen on concrete building facades. Scaling appears as a loss of surface paste, with fine or coarse aggregates exposed on what was a smooth, formed surface. Scaling is usually the result of freeze-thaw deterioration within the concrete. Freeze-thaw damage most often occurs on exposed slab ends and balcony slabs, as much of their surface area is exposed to the elements, and water can pond on the horizontal surfaces. Freeze-thaw cycling also causes very fine cracking parallel to the concrete surface. Cracks may run through the slab, parallel to the exposed vertical slab end, or they may run into the slab, parallel to the top horizontal surface. If scaling is observed, it is a good idea to look for this type of cracking to confirm that it is a result of freeze-thaw deterioration. If freeze-thaw damage is in an advanced stage, the concrete may even crumble when lightly picked. Areas suspected of exhibiting freeze-thaw deterioration should be sampled and microscopically examined to confirm the presence and extent of freeze-thaw deterioration.

The most obvious and significant items to note during a visual examination are cracks. Cracking can be the result of many different factors so it is important to document the location, width, orientation, and any deposits or other noteworthy features of a crack.

Spalling is the loss of whole concrete pieces from the surface; spalls can vary widely in size. When the spall exposes a reinforcing bar, it is most likely the result of corrosion of the steel and is an indication of advanced corrosion-induced deterioration of concrete. However, corrosion of the steel bar likely extends into the concrete well beyond the limits of the spall and can lead to further spalling if left untreated. Rust stains on the concrete surface also indicate corrosion of embedded reinforcing steel or other items, such as electrical conduit. Stains are usually deposited by water percolating through the concrete and often appear below cracks. While cracking results from corrosion and it is likely that stains will occur very near corroded steel, rust-contaminated water may migrate some distance through the concrete before reaching the surface. Thus, staining is not always an indication of nearby corrosion.

Rust stains and cracking adjacent to embedded balcony railing posts should also be noted. Corrosion of embedded balcony railing posts typically results in radial cracking emanating from the railing post pocket (*Photo 8*). In some cases, deterioration of the filler in railing post pockets can also contribute to cracking of adjacent concrete. It is a good idea to expose the reinforcing steel arrangement around the railing posts to evaluate the presence of dissimilar metals and adequate reinforcement.

Efflorescence is a white, powdery residue on the surface of the concrete. It is caused by moisture migration through the concrete. Water dissolves soluble salts in the cement paste as it moves through the concrete. When the moisture reaches the surface (usually through a crack), it evaporates, depositing the dissolved compounds. Efflorescence itself is more of an aesthetic issue than a concrete problem, but it does indicate moisture movement through the concrete that can lead to corrosion or freeze-thaw deterioration.

If the facade evaluation is performed on a dry day, moisture or dampness noted on the concrete surface may indicate a moisture problem in the building. Porous concrete can absorb a large amount of precipitation, similar to a sponge. When the relative humidity of the air becomes lower than that within the concrete, moisture will migrate from the concrete to the surface. Moisture and dampness on the surface often indicate that the concrete is saturated with water, a condition that can lead to corrosion and freeze-thaw problems. Also, if the building absorbs water, there are likely to be leaks and moisture migration to the interior. Dampness on interior concrete surfaces can damage interior finishes and foster the growth of mold and mildew. Visual inspection of a facade after a rainstorm can also indicate patterns of wetting and drying and the potential for some facade surfaces to be exposed to moisture more than others.

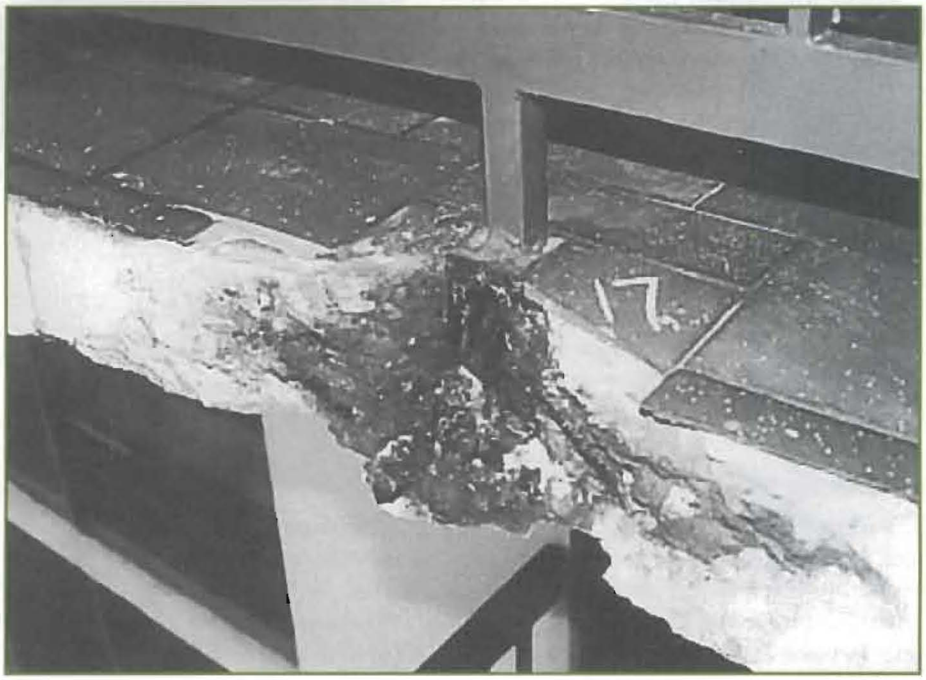

Photo 8 – Typical deterioration of balcony railing pockets.

Some concrete facade components are covered by a decorative coating. Newly applied decorative coatings can hide surface defects and provide improved aesthetics. Blistering or peeling of these coatings may be the result of moisture migration out of the concrete and should be noted as well.

Poor concrete placement may lead to other problems in the structure. Poor consolidation or honeycombing usually occurs within structural elements but is sometimes present at the surface. Honeycombing may result from the segregation of aggregates and cement paste, or inadequate vibration, especially around areas of tight reinforcing steel. If the voids are large, they cause a reduction in the effective cross-sectional area of the concrete member, reducing the structural capacity. Voids also allow water and air direct access to reinforcing steel that can lead to corrosion.

Any previous concrete repairs that are observed should be noted. While well-placed repairs covered by a coating can be nearly imperceptible, repair finishes are often slightly different than the surrounding concrete and may be more easily seen if the light source is at an angle to the surface (e.g., early or late in the day). Previous repairs indicate that the concrete has experienced deterioration. If corrosion is the underlying problem, it is likely that deterioration will continue beyond the limits of the repair because of the anodic ring effect. In this case, the area around the repair should be examined more closely and "hammer sounded" for delaminations.

While every component of a facade should be examined during a visual inspection, certain concrete elements experience higher rates of deterioration and should be reviewed more carefully. Exposed columns and walls have considerable areas of concrete surface. Corrosion of embedded reinforcing steel in these components is more likely to occur over a sizeable area, and spalls can be quite large, creating fall hazards. If columns have reveals or other architectural features, these often experience more deterioration and should be carefully examined. To reduce construction costs on high-rise buildings, the columns of upper floors (with their lower dead loads) may have been built with lower compressive-strength concrete. Lower compressive-strength concrete is likely to be more porous, allowing greater moisture and air infiltration. As a result, corrosion may be more of a problem on upper floors than on lower floors with stronger, less permeable concrete.

Photo 9 – Removal of slab extensions adjacent to columns during repairs can lead to a significant reduction in shear transfer capacity at the column-slab connection.

Photo 10 – Early indications of reinforcing steel corrosion inside a building adjacent to an exterior window.

Exposed floor slab edges can be especially susceptible to freeze-thaw damage because of the amount of surface area exposed and the potential for ponding on their top surfaces. Also, hooked slab reinforcing bars often have inadequate concrete cover and are susceptible to corrosion. If corrosion of slab edge reinforcement is severe, it might extend to the building interior, requiring intrusive and expensive repairs. Slab edge deterioration directly adjacent to columns should be specifically noted because of floor load transfer and shear considerations at the slab/column interface (*Photo 9*). It is also a good idea to view the underside of exposed slab edges in addition to the front face. While the front face may appear to be intact, the underside can reveal cracking, small spalls, and staining.

Balcony slabs seem to be more susceptible to deterioration, especially due to corrosion of reinforcing steel. Corrosion can be the result of standing water on the horizontal surface and water retention by outdoor carpeting. Depending on the degree of corrosion, deterioration may extend to the interior (*Photos 10, 11,* and *12*). Embedded metal railings often experience corrosion problems as well. The edges of balcony slabs are susceptible to freeze-thaw damage, similar to exposed floor slab edges. Balconies sometimes include exterior electrical outlets, with conduit embedded in columns or walls. If moisture infiltrates the concrete or enters embedded conduit, corrosion of the conduit is a serious problem from both a concrete and electrical perspective. Repairs to corroded conduit can extend well into the interior of a building and are often costly. Thus it is important to note any deterioration observed around electrical outlets.

Additional areas to consider in a visual examination include any other horizontal concrete surfaces, architectural projections, and locations with embedded metal railings or conduit. If base drawings are used to note observations, reviewing the drawings after examining certain areas may reveal patterns in the deterioration and indicate areas or features to examine more carefully.

The visual inspection should also include a thorough review of other building envelope components such as window perimeter caulking, masonry infill walls, and HVAC unit penetrations.

3.2 Exploratory Openings

Observations made during visual inspection and results of non-destructive tests should be verified through exploratory openings. Exploratory openings can be made by removing concrete cover over embedded metals at selected locations. On large concrete members, exploratory openings can also be made by removing core samples from selected locations; the core holes can then be inspected with fiber optic cameras or borescopes.

If exploratory openings are made by removing concrete cover from reinforcing steel, they should be large enough to facilitate observing the size, spacing, depth, and condition of the embedded materials. These observations will serve to verify covermeter readings. They will also provide information regarding extent of corrosion of the embedded metals.

Exploratory openings are also often needed to evaluate the extent of concrete delamination in slab edges and overhangs. In such situations, corrosion of the reinforcing steel may be limited to the exposed portion of the slab. However, in many cases, the corrosion may extend to the inside of the building past the window line. A definitive determination of the extent of corrosion-related delamination in slab edges can only be made through exploratory openings at areas exhibiting corrosion damage. If corrosion damage is found inside the building, interior slab surfaces should also be sounded to evaluate the extent of delamination past the window line. Similar situations are often encountered in balconies where the exposed balcony slab extends inside the building. Since repair of deteriorated concrete inside the building is significantly more expensive than exterior repairs, evaluating how far the delamination extends inside the window line is essential for estimating repair quantities and costs. Small variations in estimating interior slab repair quantities can lead to significant variation in actual construction cost.

Photo 11 – Corrosion of reinforcing steel that has extended inside a building.

Photo 12 – Corrosion-related delamination that has extended inside the building.

The exploratory openings should be patched properly by a qualified contractor after observations have been completed.

3.3 Water Penetration Testing

Typical concrete framed construction with exposed concrete elements results in a barrier-type building envelope system. As such, deficiencies in the concrete facade elements such as delaminations and cracking, as well as debonding of coatings, can result in water penetration into the building envelope.

The most common mechanism for water penetration into the building through concrete elements is as follows:

1. Wind-driven rain penetrates through-thickness cracks in exposed slab edges. Since these slabs are continuous to the inside of the building, the cracks typically extend approximately 6 inches to several feet inside the units. It is not unusual to see water damage in ceiling plaster several feet inward from exterior windows.
2. Delaminated concrete typically opens a path for water penetration, especially if delamination planes extend to the building interior.
3. Water penetration can occur at interfaces of the concrete elements with other building envelope components such as windows, masonry panels, and HVAC units.

In some cases, a thorough visual inspection by an experienced engineer can identify potential sources of moisture. However, water testing may be required from time to time to pinpoint water penetration sources. There are several protocols for performing water penetration tests on exterior building components. These include modified ASTM E-514[2], ASTM E-547[3], ASTM E-1105[4], AAMA 501.2[5]. In general, water penetration tests can be divided into three categories: those that utilize a pressure differential across the tested surface, those that utilize hydrostatic pressure of water, and those that rely on kinetic energy of water to penetrate openings. Although the test methods that utilize a pressure differential are more representative of wind-driven rain, they are typically more difficult to set up from swingstage scaffolding. Therefore, in most cases, one of the other two categories of tests is performed as a screening test to evaluate sources of water penetration. Since these tests are not used for evaluating conformance of building envelope components with standards, simple tests such as AAMA 501.2, or simply spraying the surface with water delivered to a nozzle at high pressure will help evaluate water leakage sources.

When performing water penetration tests, the interiors of the unit should be monitored carefully to detect the first indications of water leakage. If testing is being performed by spraying water on the exterior surfaces, various elements should be isolated by sequencing the spraying patterns or masking certain areas prior to performing the tests.

In some cases such as top surfaces of concrete overhangs, testing may be performed by constructing a temporary dam around the perimeter of the test area and flooding the surface with approximately two to four inches of water.

When water testing concrete surfaces containing cracks that are suspected of causing leakage, one should anticipate long test durations. Depending on the width and length of the cracks, water may take several hours to travel to the inside of the building. Several factors, including absorption by concrete, width of the cracks, pressure differentials caused by the building HVAC system, pressure differentials caused by stack effects, etc., will greatly affect the ability of water testing to identify potential leak sources. In some cases, the stack effect or pressure differentials caused by mechanical equipment can completely offset the kinetic effects of the water spray and prevent the manifestation of water leaks during the test. However, leaks may occur at the tested source once the pressure differentials between the interior and exterior of the building change or are exceeded by the wind pressure. Therefore, it is important to evaluate pressure differentials between the interior and exterior of the building prior to performing water testing. These pressure differentials can be readily measured using a digital micromanometer.

3.4 Delamination Surveys

Hammer sounding is a quick, easy, and accurate method for locating delaminated areas of concrete, even if there is no associated surface cracking. When a concrete surface is struck with a hammer, vibrations and sound waves propagate through the material. If the concrete is solid, it will absorb the vibrations and produce a high-pitched "ping" sound. If there is a delamination plane parallel to the surface, the concrete/air interface at the delamination will reflect the vibrations and sound waves. The hammer strike will produce a dull, hollow thud, and the concrete between the surface and delamination will vibrate. For this reason, it is often helpful to keep one hand on the concrete surface to feel for vibrations while striking the surface. When delaminations are deep within the concrete (usually deeper than two inches), it may be hard to distinguish hollow sounds. In such cases, nondestructive testing methods are required to locate delaminations.

To ensure a thorough delamination sounding, it is a good idea to work in a grid pattern while striking the concrete surfaces. The size of the grid will depend on the size of the concrete component and the time available for sounding. When hollow sounds are heard, the grid can be tightened to better define the limits of the delamination. The ideal hammer for a delamination sounding has some weight, but is comfortable enough to use for several hours of striking hard concrete. Masons' hammers work well, but any type of hammer can be used.

Chain dragging is similar in principle to hammer sounding and is somewhat faster on horizontal surfaces such as balconies or large floor slab projections. Metal chains will produce a distinctly different sound when dragged over shallow delaminations compared to solid concrete. While chain dragging is faster and more convenient than hammer sounding for large horizontal areas, it does not readily identify small delaminations. It is also more difficult to accurately determine the limits of delaminations by chain dragging.

Base drawings similar to those for the visual survey should be used to document the locations of delaminations. The base drawings can then be compiled to give an overall view of the extent of delaminations on the facade. While it does take a short time to become accustomed to the different sounds produced by striking concrete, hammer sounding is a valuable tool for determining delaminated concrete on building facades.

3.5 Nondestructive Evaluation

Nondestructive evaluation (NDE) of building envelopes is a relatively new way to determine the full extent of damage or defective construction, with minimal cost outlay. Recent advances in testing techniques, equipment, and on-site computer software have brought reliability to this approach. Construction defects ranging from cracking in cast stone lintels to cladding support on tall buildings can be tackled with very little disturbance, either to building occupants or to the structure itself. A judicious blend of visual inspection, NDE, and a small amount of intrusive material sampling can reduce cost and cover a larger area when compared to traditional investigations.

An analogy can be made with the medical profession, which has always relied on indirect sounding methods for patient examination whenever possible. The obvious advantage of this approach to the patient has led to the development of very sophisticated sounding techniques, and a number of these have spun-off into NDE of civil structures. The defense industry has also contributed to this technology. Typical examples are ultrasound and CAT-scan from medicine; radar and infrared thermography from defense research; and stress wave monitoring from the aerospace industry.

Table 1 presents the range of NDE methods available today for the inspection of building envelope components. All these test methods are fully described in the American Concrete Institute Report ACI 228.2R[6]. Nearly all require access to the face of the building; however, miniaturization and computerization of equipment has accelerated testing rates, and large surface areas can be covered in a relatively short time. It should be emphasized that all NDE programs require at least some intrusive sampling and laboratory testing to correlate the results obtained.

TABLE 1 – NDE METHODS FOR DURABILITY AND INTEGRITY

METHODS & PRINCIPLES	FINDINGS & APPLICATIONS
Ultrasonic Pulse Velocity (UPV) – Travel time of an ultrasonic pulse over a known path length.	Gives relative quality of the concrete: the faster the pulse, the better.
Impact-Echo – Stress waves echoed from opposite side of member or from defect are monitored. Frequently, analysis gives distance to reflector.	Locates defects such as delaminations, voiding, honeycombing, and cracking. Maximum element thickness is slightly over 6 feet; minimum 3".
Impulse Response (Mobility) – Uses stress waves to measure the "Mobility" of the structural element. Lower frequency range than Impact-Echo allows wider area to be tested.	Measures stiffness and mobility of structural elements such as walls and cladding. Identifies presence of low density concrete and honeycombing.
Infrared Thermography – Heat conduction properties of the concrete are measured by differences in surface temperatures during testing in correct ambient conditions.	Locates delaminations in walls and cladding, as well as the presence of moist insulation in buildings. Can also determine presence or absence of grout fill in CMU walls.
Radar – Electromagnetic waves are used. Interfaces between materials with different dielectric properties are detected.	Locates metal embedment (reinforcing) and voids. Indicates thickness of elements.
Cover Meter – Measures location and depth of steel inclusions using magnetic induction.	Locates reinforcing steel, as well as its depth and size. Maximum practical depth: 4 inches.
Half-Cell Potential – Measures the negative potential between steel reinforcement and the concrete surface. Larger negative potential means greater corrosion.	Allows the mapping of steel reinforcement corrosion in reinforced concrete elements.

Table 1 – NDE Methods for Durability and Integrity

3.6 Laboratory Testing

The objectives of the evaluation will dictate the laboratory procedures to be used. Usually, a comprehensive evaluation will characterize the general properties of the concrete and determine a cause of deterioration. This information is needed in order to determine if the concrete is capable of performing as intended and will provide long-term durability if the necessary repairs are performed.

The success of the laboratory evaluation rests solely on the selection of representative samples. It is recommended that an experienced material technologist familiar with evaluation techniques be involved with the selection of the samples. Sampling requires judgment to determine the location and number of samples in order to be truly representative of the conditions to be studied. The samples should be of sufficient size and number to allow for all the recommended laboratory tests to be performed.

Laboratory tests are usually grouped into tests that establish physical properties, microscopic evaluation of constituents, failure analysis, and chemical analysis to determine the composition of the concrete.

3.6.1 Physical Testing

Physical testing characterizes the properties of hardened concrete. Tests include compressive strength, unit weight, tensile strength, air content, permeability, and resistance to freezing and thawing. Physical property testing provides a way to evaluate general quality and uniformity within different parts of the structure.

3.6.2 Microscopic/Petrographic Examination

Visual and petrographic/microscopic examinations are performed on concrete samples to evaluate overall condition and characteristics. Examinations are performed in accordance with reference standard ASTM C-8567. The evaluation starts with a visual examination (with the unaided eye) of all samples removed during the field investigation to document sample size, condition, and general characteristics. Microscopic examination involves use of a stereoscopic microscope at magnifications of 10 to 40 times and a polarizing light microscope at magnifications of 100 to 400 times.

Petrographic examination is a valuable tool and provides important information to aid in evaluation of concrete. An experienced petrographer can determine the overall condition, quality, causes of deterioration, and probable future performance of the concrete. Other observations include characterizing the air void system and identification of contaminants. If the concrete was non air-entrained or has a poor air void system, it is susceptible to freeze-thaw damage when saturated with water. Extensive sub-parallel cracking associated with freeze-thaw is easily identified by petrographic examination.

Microscopic examination of a coating system provides information relating to the integrity of the coating as well as the condition of the coating/concrete interface. For coatings, the thickness, number of layers, presence of voids, and interlayer delamination can be observed and documented. Specific emphasis would be on the near surface concrete to look for contaminants or other conditions that would inhibit coating bond. During the examination, features such as a weak concrete surface, lack of profile, poor surface preparation, failure planes, contaminants, and relative bond are documented.

3.6.3 Chemical Analysis

Other chemical tests are available to evaluate the composition of the concrete or presence of contaminants. Depending on the exposure conditions, chemical testing of the concrete prior to coating may be warranted.

Because of the increased potential for corrosion-related distress, the chloride level of the concrete is routinely determined. Chloride levels of concrete can be determined at varying depths to evaluate chloride infiltration, as well as background level of naturally occurring chloride in the concrete. Some naturally occurring chloride exists in the cement, aggregate, mix water, and admixtures that constitute concrete. Therefore, all concretes will have some chloride.

3.7 Instrumentation and Monitoring

Monitoring of the performance of a building envelope implies that a baseline survey of the parameters to be monitored has been made at some stage in the life of the envelope. Ideally, this is done shortly after construction. However, this is usually not the case because owners and engineers typically turn their attention to problems in the envelope when they first appear. A typical example is cracking caused by structural movement that can occur early in the life of the building but becomes more apparent at a later date. A baseline survey would include mapping the location, length, and width of all the cracks. Installing crack gauges at strategic points on the envelope would monitor development of critical cracks. Modern gauges are unobtrusive and can be remotely monitored, causing minimum disruption to the structure.

The nondestructive tests described in Paragraph 3.5 above can also be used for ongoing monitoring of building envelope performance. The initial NDE program can be used as a baseline survey, and changes in properties such as corrosion of steel reinforcement and cladding support can be monitored by additional surveys at periodic intervals. This is an approach successfully applied in highway and bridge maintenance, with periodic inspections typically every five to seven years.

At the present time, research is progressing in the application of contactless monitoring using the acoustics of the envelope and envelope surface vibrations detected by laser in order to measure the progression of localized distress in envelopes. These techniques are not yet readily available but should be relatively commonplace within the next decade.

4.0 METHODS OF ESTIMATING REPAIR QUANTITIES

One of the key objectives of any building envelope evaluation should be the development of repair schemes that can address the causes of the deterioration rather than the symptoms. For example, caulking of the cracks associated with early stages of corrosion-induced delamination will not address the corrosion issue and may actually accelerate the corrosion process by entrapping moisture.

Since most contractors cannot determine the required quantity of repairs prior to submitting a bid for the rehabilitation of a concrete facade, most facade repair projects are performed on unit price basis. Therefore, repair cost budgets are based on an estimate of repair quantities. Due to cost constraints, most concrete facade evaluations do not include a close-up inspection of all facade surfaces from swingstage scaffolding. Therefore, the required repair quantities are typically based on an extrapolation of the anticipated repair quantities on those building tiers where close-up inspection and hammer soundings have been performed.

When extrapolating repair quantities based on deterioration found at a limited number of building tiers, the following precautions should be taken:

1. Estimates of the repair quantities largely depend on the scope of work performed during the evaluation. Detailed and comprehensive evaluations cost more. However, extent of deterioration and repair quantities can be better defined. Such comprehensive evaluations typically save money in the long run by providing a better estimate of repair quantities and providing a higher degree of certainty in repair costs.
2. Corrosion and other types of concrete deterioration progress at a continuously accelerating rate. Therefore, the extent of deterioration – and repair quantities – will likely increase from the time the evaluation is performed to the time the repairs are initiated. The estimates of repair quantities should take into consideration this continued deterioration.
3. Extent of deterioration may change from one elevation to another. This is typically due to variations in construction type or in environmental exposure that can cause temperature differentials and differences in water evaporation rates. It is possible to have significantly different repair quantities between the north and south elevations of the same building.
4. Repair types will differ depending on the configuration of the concrete elements at various sections of the building. Varying repair types and geometries can drastically impact their unit costs. Therefore, extrapolations of repair quantities should be made from representative tiers.
5. Repair quantities can change from the top of the building to the bottom of the building. This is likely due to variations in required concrete quality and possible variations in chloride levels. (Some floors may have been constructed in cold winter months when the use of calcium chloride accelerators was deemed necessary.)

Regardless of the extent of care taken to develop estimates of repair quantities, the owners should be cautioned that actual repair quantities (and their cost) will vary from the engineer's estimate. Repair quantity estimates should be used only for budgeting and bidding purposes. ■

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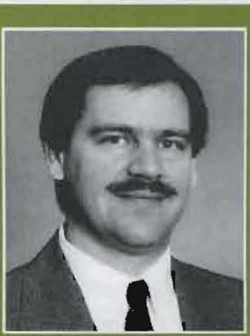

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