Failure Mechanisms in Liquid-Applied Waterproofing Systems

Kami Farahmandpour, PE, RRC, CCA, CCCA

Keywords

Blistering, concrete, crack reflection, debonding, failure, LAM, liquid-applied, membrane, moisture vapor emission rate, pinholes, waterproofing.

Abstract

Waterproofing concrete substrates such as fountains, water-retaining tanks, plaza decks, parking decks, planters and other underground structures is substantially different from roofing. For this reason, it is imperative that the designers and contractors be aware of the differences and potential problems associated with waterproofing concrete substrates.

Improper waterproofing design and installation can lead to water leakage, deterioration of concrete substrate materials and waterproofing membrane delamination.

This article will provide a general overview of common failure mechanisms in LAMs, including crack reflection, high moisture vapor emission rates and curing problems, a summary of the current state of the industry and a detailed discussion of the following case history: evaluation of waterproofing system on Cincinnati Museum Center plaza fountain.

The fountain was constructed of cast-in-place concrete in the early 1900's. The original waterproofing system consisted of a lead sheet membrane placed directly over the structural concrete deck. The fountain was then constructed on this lead sheet and was surfaced with terrazzo. In a recent rehabilitation project, the exposed surfaces of the fountain were repaired and coated with a liquid-applied waterproofing membrane (LAM). Shortly after the rehabilitation project, leaks were detected below the plaza. The evaluation of the waterproofing system revealed inter-ply delamination of the LAM, delamination from the concrete substrate and cracking of the concrete components of the fountain. The field investigation included visual inspection, exploratory openings, water testing of the fountain features and sampling of concrete and membrane. Laboratory testing included microscopic examination of the membrane-concrete interface to evaluate the cause of membrane delamination.

Author Biography

Kami Farahmandpour is a principal of Building Technology Consultants, a forensic engineering firm specializing in the evaluation and repair of building envelope problems. Over his 17-year career in the construction industry, he has managed over 150 projects involving the evaluation and repair of building components. Mr. Farahmandpour is a Licensed Professional Engineer, Registered Roof Consultant, Certified Construction

Specifier and Certified Construction Contract Administrator. His expertise is concentrated in the area of building envelopes. He has performed numerous evaluations of concrete and masonry facades and roofing and waterproofing systems. He is an active member of several professional organizations including the Roof Consultants Institute, International Concrete Repair Institute and American Concrete Institute. He has authored a number of articles on building envelope evaluation and repair and has spoken at several seminars on the topic.

Introduction

Waterproofing concrete substrates, such as plaza decks, parking decks, fountains, water-retaining tanks, planters and other underground structures, is substantially different from roofing. In most cases, a waterproofing system is applied directly over a concrete slab (substrate). Therefore, it is imperative that the designers and contractors be aware of the differences and potential problems associated with waterproofing concrete substrates.

Improper waterproofing design and installation can lead to water leakage, deterioration of concrete substrate materials and waterproofing membrane delamination. Long-term water leakage into reinforced concrete structural slabs can lead to corrosion-induced cracking, delamination and spalling of concrete [1, 2].

In recent years, a number of failures associated with liquid-applied membrane (LAM) waterproofing systems have been blamed on installation deficiencies. However, in some cases, concrete substrate integrity and vapor emission rates have been shown to be the primary cause of the failures. In some cases, these factors are beyond the control or understanding of the installers.

This article will provide a general overview of common failure mechanisms in LAMs, including crack reflection, high moisture vapor emission rates and curing problems.

In addition, a detailed discussion of a case history involving failure of a liquid-applied waterproofing membrane will be presented.

Typical Failure Mechanisms in LAM

One of the important issues in understanding the failure mechanisms in LAMs is that their performances are highly dependent on the integrity of concrete substrates and the LAM's bond to the concrete.

Numerous factors can contribute to the failure of LAMs, the following being the most common:

- Crack reflection (tearing of the membrane because of movement of cracks in the concrete substrate)

- Blistering (localized or widespread debonding, typically because of high moisture emission rates from the substrate)
- Improper curing of concrete and/or LAM
- Improper installation

Other factors, such as material defects and chemical attack, can also lead to failure of LAMs. This article focuses on the failures associated with crack reflection and substrate moisture vapor emission rates.

Crack Reflection

LAMs depend on substrate integrity to perform properly. Although in some cases the membranes are reinforced with some type of fabric/scrim reinforcement, most LAMs are applied directly over a substrate without the use of reinforcing fabric/scrims. Reinforcing fabric/scrims can help distribute crack movements over a wider area. This will help reduce stresses on the membrane over the crack region. However, when reinforcing fabrics/scrims are not present, crack movements will typically cause high stress concentrations on the membrane over the crack, resulting in localized tearing of the membrane (Figure 1). This phenomenon is called crack reflection.

Blistering

One of the most prevalent modes of failure for LAMs is blistering and debonding of the membrane from the substrate. Because most LAMs are relatively thin (compared to sheet membranes) and do not have a reinforcing scrim incorporated into the assembly, local debonding can quickly cause membrane failures and water leakage.

Debonding of LAMs from concrete substrates is typically attributed to surface contamination and/or moisture emission from the concrete substrate. Of these two potential causes, moisture emission issues appear to be the more common mode of early failure of LAMs.

Concrete is a porous material. The porosity of concrete greatly depends on its overall quality and water-to-cement ratio (w/c). Because it is porous, concrete always contains some moisture in the same way most roof insulation boards contain moisture when at equilibrium with the environment. Depending on the relative humidity and temperature of the concrete and the relative humidity and temperature of the ambient air, concrete either emits or absorbs moisture in vapor form. This phenomenon is most often referred to as “breathing.” In addition, concrete can also absorb significant amounts of liquid water when exposed to it. Fresh concrete contains far more water than is required for the chemical reaction with cement. Therefore, newer concrete surfaces predominately emit moisture until they reach equilibrium with their surrounding environment.

In most cases, concrete surfaces that appear to be dry are either emitting or absorbing water vapor. If liquid water moves through the concrete, the concrete surface appears dry as long as the rate of evaporation from the surface is greater than the rate of moisture emission. If moisture moves through the concrete in vapor form, the concrete surface will not have a wet appearance regardless of the evaporation rate.

When a LAM is applied to the surface of concrete, it acts as a vapor retarder at the concrete surface, preventing evaporation or moisture emission. Water vapor moving to the surface of the membrane cannot escape, thus causing a buildup of water vapor pressure between the membrane and concrete surface. This phenomenon can occur within minutes of applying a LAM to a concrete surface. Because most LAMs are chemically cured and require several hours to cure and establish bond to substrates, buildup of water vapor pressure shortly after application can inhibit development of a proper bond between the membrane and concrete substrate. Zones of weakened bond can manifest quickly as blisters filled with water and can ultimately cause failure of the membrane (Figures 2 and 3).

In some cases, the moisture being emitted from the concrete surface works its way to the outer surface of the membrane before the membrane cures. This typically manifests as pinholes in the membrane that can lead to leakage under hydrostatic pressure. However, it is important to note that other causes of pinhole formation, such as entrained air because of application and formation of gases because of the membrane's chemical curing mechanism, do exist.

The Current State of the Industry

Despite the extent of problems associated with concrete substrate moisture emissions, there seems to be a lack of understanding in the industry regarding the required moisture conditions of concrete substrates prior to application of LAMs. There are also some myths regarding the causes of failure. For example, some believe that moisture vapor emission long after the membrane has cured can cause debonding and failure. With the exception of those few LAMs that are susceptible to alkali attack at the bond surface, such mechanism cannot cause debonding of the membrane after it has cured and established proper bond to the substrate. The bond strength of most membranes to concrete is in excess of 200 pounds per square inch (psi) [1,379 kiloPascals (kPa)], while, the water vapor pressure differences are less than 1 psi (6.9 kPa). As such, water vapor pressure alone cannot cause a physical failure at the bond line between a well-bonded membrane and the concrete substrate.

Another common myth in the industry is that if the concrete is cured for 28 days, it will be suitable for application of LAMs. Several membrane manufacturer application instructions indicate "fully cured" or "28-day cured concrete" as the only moisture criteria for application of their membranes. The most important factor to consider is service environment. If the concrete has cured for 27 days and then is exposed to rain, the moisture content in the concrete will be increased to a level close to the initial moisture content and will require a longer drying time than concrete that is kept continuously dry. Other factors, such as ambient temperature and humidity during curing, will also affect the rate of drying. The age of concrete does not correlate well with its moisture vapor emission rate (MVER).

Other manufacturers stipulate that the concrete “shall be dry” prior to application of their materials. If “dry” implies completely free of moisture, obtaining “dry” concrete in most construction projects is impractical, in the author’s opinion. The term “dry” needs to be defined clearly by manufacturers, and specific acceptance criteria should be provided.

Some in the waterproofing industry have tried to establish a concrete substrate moisture criterion that is related to the concrete moisture content. The draft version of ASTM C 898 [3] recently circulated to ASTM Committee C-24 members stipulated a maximum concrete substrate moisture content of 8 percent as a requirement for application of LAMs. Direct measurement of concrete moisture content is impractical in most cases. Furthermore, good correlation between concrete moisture content and its MVER does not exist.

Before application of bonded flooring systems, the flooring industry typically specifies ASTM F 1869 [4] to measure the amount of moisture vapor emitted from concrete. This test takes approximately 72 hours to complete, and results are expressed in pounds [kilograms (kg)] of moisture vapor emitted through the surface in 24 hours for 1000 square feet (92.90 square meters) of concrete surface (Figure 4). The results obtained reflect only the condition of the concrete at the time of the test. In the author’s opinion, this test method is a good tool for evaluating the MVER of concrete surfaces despite its drawbacks. However, because of the time it takes to perform the test, it poses practical difficulties in scheduling work.

Currently, no industry standard exists for threshold MVER values obtained through ASTM F 1869 prior to application of LAMs. However, a value of 3 pounds in 24 hours/1000 square feet (1.4 kg in 24 hours/92.90 square meters) has been used by some as the threshold for application of impermeable membranes.

While concrete MVER can be remotely related to its moisture content, other factors such as ambient relative humidity and temperature and concrete temperature play a large role in determining MVERs from concrete surfaces.

More simplified methods have also been used to evaluate the substrate moisture conditions. One of these methods involves sealing a clear plastic mat over the concrete surface for a period of time and observing accumulation of condensed water below the sheet [5]. Such methods have been used successfully in waterproofing applications. However, they do not provide a quantitative measure of MVER.

Other methods, such as measuring the relative humidity gradients within the concrete slabs, have been used by Europeans with success. This method involves drilling holes in the concrete, placing relative humidity probes at different depths and monitoring drying of the concrete over time. Experienced operators are required to gather and interpret the data. These methods are currently somewhat sophisticated for everyday use at construction sites and have not gained widespread acceptance in the United States.

Case History: Cincinnati Museum Center Plaza Fountain

Constructed in 1933, the plaza fountain at the Cincinnati Museum Center is a tiered fountain built on a sloping structural deck over occupied space (Figure 5). The lower portion of the fountain and structural deck beneath the fountain's lower pool extend over a vehicular underpass. The structural deck consists of a reinforced concrete slab and is supported by a grid of steel beams and girders. The fountain's original primary waterproofing system was placed on top of the structural deck and consisted of a five-ply coal tar pitch waterproofing membrane covered with a lead sheet (lead pan). The fountain was cast with concrete to rough elevations on top of the lead pan. A trowel-applied mortar was then used to form the curved surfaces of the cascades before finishing the entire fountain with a green terrazzo surface. No topside waterproofing was specified originally.

The plaza fountain underwent a major rehabilitation in 1987. The fountain restoration included patching of concrete and terrazzo surfaces with cementitious and epoxy mortars and waterproofing of the exposed fountain surfaces with a polyurethane waterproofing membrane. The original lead pan was left in place.

After completion of repairs, water leakage onto the underpass and blistering of the waterproofing membrane were observed. In 1991, blisters were cut out and patched, and the fountain was re-coated with the waterproofing membrane. These repairs, and subsequent attempts, did not stop the water leakage. Therefore, an evaluation of the fountain waterproofing system was commissioned by the Museum Center.

Scope of Investigation

The scope of the investigation included a visual survey of the fountain, delamination survey of all fountain concrete surfaces, core sampling, peel tests of the membrane and laboratory examination of the samples taken in the field. The investigation also included a pressure test of the fountain water supply system to rule out the possibility of plumbing leaks.

Field Investigation

The plaza fountain was taken out of service approximately one week before the evaluation. Field investigation included a comprehensive visual review and delamination survey of vertical and horizontal surfaces of the plaza fountain. Concrete and membrane sample removal locations were selected to represent various conditions within the plaza fountain. Samples were removed from areas exhibiting membrane blisters and/or concrete delaminations and from areas where no apparent deterioration was observed.

Waterproofing Membrane Observations

The waterproofing membrane had debonded (separated from the substrate) and delaminated (separated from its underlying layers) in many areas of the fountain (Figures 6 and 7). Large sheets of membrane and color coat peeled away easily in some areas. In general, second and third applications of the membrane (previous repairs) were poorly bonded and could be separated readily. In a few cases, individual layers of the first application of membrane and color coat exhibited interlayer delamination. In most cases, the primer (identified by its red color) appeared to be well-adhered to the concrete.

Numerous water-filled blisters, ranging in size from ¼ inch to 4 inches (6 mm to 100 mm) in diameter, were observed. Several of these blisters were cut open to determine the location of the water layer within the coating system. The location of blistering varied, occurring between coats of the first-application membrane, at the primer/membrane interface, at the color coat/membrane interface or between layers of the color coat.

In some areas, the membrane contained embedded sand (aggregate) within the first application of membrane. In these areas, the coating exhibited a rough surface texture with the tips of the aggregate commonly exposed. A second application of coating did not completely cover the exposed aggregate. When this coating was peeled away, it contained numerous pinholes.

In several areas, cracking of the substrate concrete had reflected through the membrane directly over the crack (Figure 8).

Concrete Delamination Survey

A delamination survey was performed at all surfaces of the fountain. A delamination is an internal crack in a concrete member that is oriented parallel to the exposed surface of that member, resulting in a planar discontinuity. The survey was conducted using the hammer-sounding method in general accordance with ASTM D 4580 [6]. Using this method, changes in emitted acoustical frequency between delaminated and sound concrete can be detected readily, provided the delamination is within a few inches of the top surface of the concrete. Delaminations deep within the concrete cannot be detected using the hammer-sounding method.

Approximately 10 percent of the fountain surfaces exhibited sub-surface delaminations when sounded with a hammer (Figure 9). The delaminations were primarily in areas where previous repairs were performed using an epoxy repair mortar. Core sampling at these locations showed that the epoxy repair material had debonded from the substrate concrete.

Examination of cores during sampling indicated widespread delaminations deep within the fountain concrete. Most of these areas containing deep delaminations were not detectable by hammer sounding (Figure 10).

Exploratory Opening Observations

Two exploratory openings were made to evaluate the condition of the lead pan. Observations indicated that the lead pan was in good condition with no signs of lead corrosion products. Thickness measurements averaged 0.078 inch (1.98 mm).

At the lower exploratory opening (Figure 11), water was observed running into the opening at the level of the lead pan, indicating water had migrated to and was ponding on the lead pan. Water continued to enter the exploratory opening for the duration of the field investigation. The drain within the exploratory opening did not appear to be original. The existing 3-inch (75-mm) drain line was placed in an 8-inch (400 mm) diameter hole in the structural slab, presumably from the previous drain line. Backer rod was placed in the annular space between the 3-inch (75 mm) drain line and the concrete, and approximately 1 inch (25 mm) of grout was poured on top of the backer rod. The lead pan overlapped the original drain flange (still in place) but was not attached to the new drain. Therefore, the waterproofing system was not continuous and did not protect the structural slab around the drain.

A portion of the lead pan and bituminous waterproofing membrane was removed. The surface of the underlying structural deck was damp. A partial-depth concrete core (taken from Exploratory Opening No. 1 to evaluate the condition of the structural slab) indicated severe cracking and delamination.

Stone Coping Cap Observations

Selected stone coping caps on the perimeter of the fountain were removed to evaluate the waterproofing system terminations. Several holes were observed in the sealant joints between the stone coping caps around the perimeter of the plaza fountain. No holes were observed between the coping caps within the pool. Upon removal of the coping caps, the underlying waterproofing membrane and Neoprene flashing appeared to be intact.

Fountain Plumbing

A pressure test of the fountain plumbing was performed to evaluate the possibility of plumbing leaks. The test revealed no loss of pressure within the fountain supply piping. Therefore, it was unlikely that the fountain water supply system contributed to the leaks.

Laboratory Testing

Microscopic Examinations – Concrete Cores

Core samples removed from delaminated areas of the fountain concrete confirmed the presence of subsurface delaminations. Furthermore, during drilling of concrete samples, the drill water traveled through the horizontal delamination plane and emerged through a vertical crack approximately 6 inches (150 mm) from the core location. This indicated that paths were available for water to penetrate into the concrete and travel through the horizontal delaminations.

In addition to the surface delaminations, many cores exhibited extensive cracking and delaminations deep within the fountain concrete. Core samples removed from areas where hammer sounding did not detect surface delaminations indicated that deep delaminations and cracking were widespread throughout the fountain.

In general, the epoxy repair mortar had delaminated from the cementitious substrate. The majority of the deterioration and cracking was found in the original concrete layer. The original concrete was not air-entrained. Therefore, it is susceptible to freeze-thaw damage when saturated with water. Extensive sub-parallel cracking, typical of freeze-thaw damage, was present in the original concrete

Microscopic Examination – Waterproofing Membrane

The specified waterproofing membrane consisted of an epoxy primer, followed by three layers of one-component polyurethane membrane averaging 12 dry mils (0.305 mm) each and topped with two layers of a green color coat averaging 3.5 mils (0.089 mm) each. The design total coating system thickness was 43 mils (1.092 mm).

Microscopic examination of samples obtained in the field indicated the first application of the waterproofing membrane consisted of a red primer applied directly to the concrete/repair mortar substrate, followed by multiple coats of a light gray membrane and topped with multiple coats of a green color coat. In some areas, the membrane contained embedded aggregate up to 52 mils (1.321 mm) in diameter while the membrane did not contain any aggregate in other areas. The first application of the waterproofing membrane thickness was highly variable. Primer thickness ranged from 1 mil to 5 mils (0.025 mm to 0.127 mm). Membrane thickness ranged from 1 mil to 57 mils (0.025 mm to 1.448 mm), and color coat thickness ranged from 1 mil to 20 mils (0.025 mm to 0.508 mm). The coating system on sidewalls and sloped surfaces typically was thinner. Figures 12 through 14 depict various membrane configurations that were observed.

In some areas, it appeared that second and third applications of the waterproofing membrane were applied. The second application of membrane ranged from 5 mils to 45 mils (0.127 mm to 1.143 mm) in thickness, with its color coat thickness ranging from

1 mil to 10 mils (0.025 mm to 0.254 mm. The third application of membrane ranged from 17 mils to 20 mils (0.432 mm to 0.508 mm) thick with its color coat thickness ranging from 2 mils to 5 mils (0.051 mm to 0.127 mm).

Examination of the waterproofing membrane revealed numerous small pinholes in the primer and water-filled blisters at the primer/membrane interface (Figure 15). Interlayer debonding of the membrane was common. In general, second and third applications of the membrane were poorly bonded and could be separated readily. In a few cases, individual layers of the first application of membrane and color coat exhibited interlayer delamination. In most cases, the primer appeared to be well-adhered to the concrete. Tears and breaches of the membrane were typically reflections of cracks in the substrate.

Conclusions

Failures in the waterproofing membrane consisted primarily of cracks in the membrane reflecting over cracks in the substrate (crack reflection) and to a lesser extent membrane blistering, pinholes and delaminations. Once the water had bypassed the topside waterproofing system, it dispersed through a large network of delaminations and cracks within the fountain substrate until it reached the original waterproofing system, the lead pan and the underlying membrane.

Cracks observed within the membrane lined up with cracks in the substrate. These cracks were attributed to deterioration of repair patches, as well as cracking and deterioration of the original concrete within the fountain. Because the original fountain concrete was not air-entrained and did not have a topside waterproofing membrane for many years, it was susceptible to freeze-thaw deterioration. Also, a drainage layer was not provided at the level of the lead pan. Therefore, water penetrated and saturated the concrete above the lead pan. During winter months, the trapped water froze and cracked the saturated concrete. This deterioration likely began shortly after construction and has continued through the life of the fountain.

During the fountain rehabilitation, hammer sounding was used to locate deteriorated concrete to be removed and replaced. However, the hammer sounding method could not detect the extensively cracked and delaminated concrete deep within the fountain above the lead pan. Therefore, this deteriorated concrete was not removed. Patch repairs placed over the deteriorated concrete cracked and delaminated because of the instability and further cracking of the concrete substrate.

Numerous small pinholes and blisters in the first application of the primer and membrane were observed. There was no record of water vapor emission tests having been performed before application of the LAM. Therefore, it was concluded that the concrete substrate was saturated and exhibited high water vapor emission rates during and immediately after application of the membrane system. This high water vapor pressure resulted in the formation of pinholes in the primer. These pinholes facilitated the formation of blisters.

Subsequent coats of membrane within the first membrane application also contained pinholes and air voids. The pinholes and air voids typically lined up with those in the primer and first coat of membrane that, under hydrostatic pressure, could result in water leakage through the membrane during normal fountain operation.

In some areas of the fountain, sand particles had been broadcast into the membrane during installation. The tips of the sand particles typically were exposed, creating pinholes within the membrane. These pinholes could allow water penetration under hydrostatic head, filling voids and creating interlayer blisters. The inclusion of sand particles was not specified by the membrane manufacturer and is not common to waterproofing systems designed for this service condition. The sizes of sand particles placed in the first membrane application were large enough that their tips were typically exposed through subsequent membrane applications.

Reapplication of the membrane had failed in numerous areas, primarily because of lack of proper bond between the first membrane application and subsequent applications. Bond failure was typically caused by inadequate surface preparation techniques. The lack of interlayer bond provided voids that collected water and created blisters. The water collecting in these voids penetrated through pinholes and other deficiencies in the membrane.

Given the service conditions for the plaza water fountain, the overall durability of the rehabilitated fountain was considered poor. The original concrete components above the lead pan were extensively cracked and delaminated because of freeze-thaw deterioration. Patch repairs had cracked and delaminated in only seven years, because of the unsound substrate. The cracks in these patches had reflected through the waterproofing membrane, allowing a direct path for water to enter and saturate the concrete and thus continue the freeze-thaw cycles. Deterioration of the fountain was expected to continue and become progressively worse with time.

Based on the findings of this investigation, it was concluded that the only viable, long-term solution for rehabilitation of the fountain was a complete reconstruction of the fountain above the lead pan. It was recommended that the lead pan be left in place and repaired as a redundant waterproofing membrane.

Closing Remarks

Further research is needed to better understand the mechanisms involved in moisture-related failure of LAMs. Manufacturers of liquid-applied waterproofing products need to clearly specify acceptance criteria relating to the moisture condition of the concrete substrate. This would involve specifying the type of testing and interpretation of the data. The author recommends that manufacturers of LAMs evaluate their installation instructions and incorporate meaningful and measurable criteria for acceptability of substrate conditions.

Although methods to evaluate MVER from concrete surfaces are available, manufacturers of each membrane should establish acceptable thresholds for MVER. ASTM F 1869 is a tool that can indicate potential moisture-related problems. Because the curing time of LAMs varies greatly, the impact of MVER on bond development will be different for various products and should be evaluated for each product separately. The author acknowledges the logistical and scheduling difficulties associated with all moisture emission tests currently available.

LAM manufacturers and specifiers should be aware of the impact of MVER on membrane bond development under various ambient conditions. For example, application of a LAM on a concrete surface in late afternoon typically results in a higher MVER. This is because of the higher temperature of concrete as a result of solar gain. The higher temperature of concrete increases the vapor pressure within the concrete and results in a higher MVER. Conversely, application of a membrane on a concrete deck in morning hours may result in a lower MVER because the concrete may be cooler than the ambient temperature in morning hours.

In the author's opinion, better guidelines for application of LAMs over substrate cracks should also be developed. At a minimum, routing and sealing of cracks that are greater than 0.05 inches (1.27 mm) wide should be required. Narrower cracks may also have to be repaired in a similar manner. Regardless of the width of a crack, all moving cracks should be treated carefully to provide for distribution of stresses over the crack.

References

1. Farahmandpour, K., Jennings, V., Willems, T., Davis, A. "Evaluation Techniques for Concrete Building Envelope Components," RCI Interface, March 2002.

2. American Concrete Institute, ACI 222R "Corrosion of Metals in Concrete."

3. American Society for Testing and Materials, ASTM C 898 "Standard Guide for Use of High Solid Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane with Separate Wearing Course."

4. American Society for Testing and Materials, ASTM F 1869, "Standard Test Method for Measuring Moisture Vapor Emission Rate of Concrete Subfloor Using Anhydrous Calcium Chloride."

5. American Society for Testing and Materials, ASTM D 4263 "Standard Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method."

6. American Society for Testing and Materials, ASTM D 4580, "Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding."

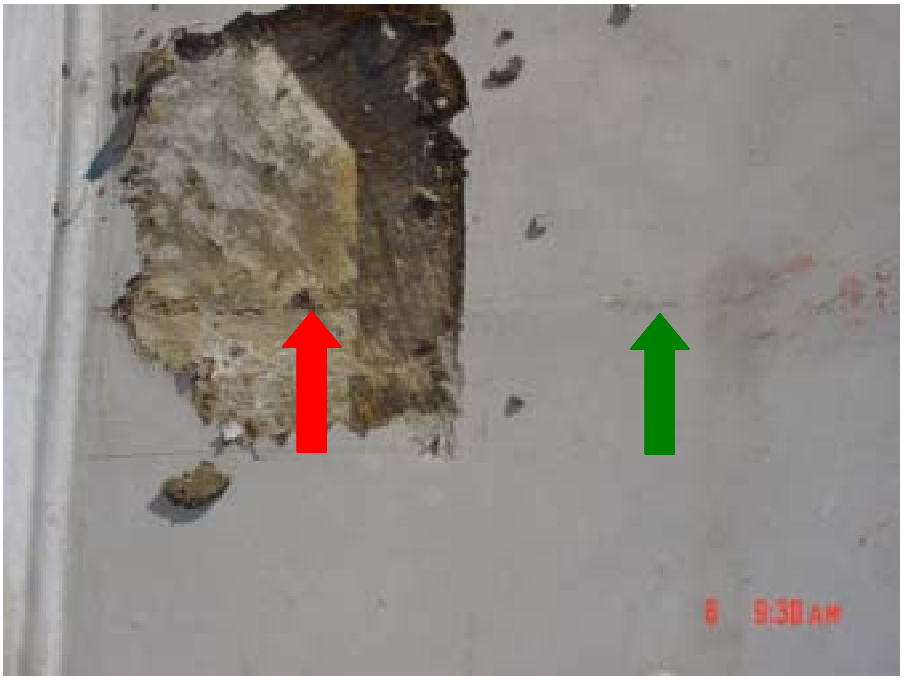

Figure 1 – Crack (tear) in a reinforced liquid-applied membrane (left arrow) coincides with substrate crack (right arrow).

Figure 2 – Water-filled blister in a liquid-applied membrane.

Figure 3 – Water entrapped in the blister shown in Figure 2.

Figure 4 – ASTM F 1869 test being performed for evaluation of carpeting installation on a concrete floor.

Figure 5 – Front view of the Cincinnati Museum Center with the fountain.

Figure 6 – Large interlayer delaminations of the membrane.

Figure 7 – Interlayer membrane delaminations at various interfaces. Note the substrate crack reflecting through the first light green application of the membrane.

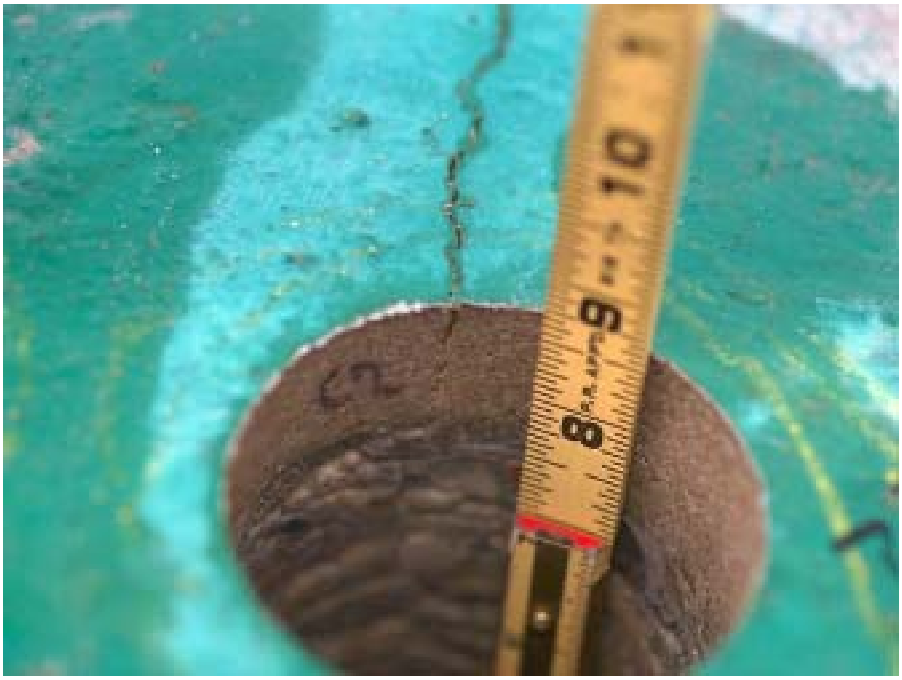

Figure 8 – Substrate crack reflecting through the membrane.

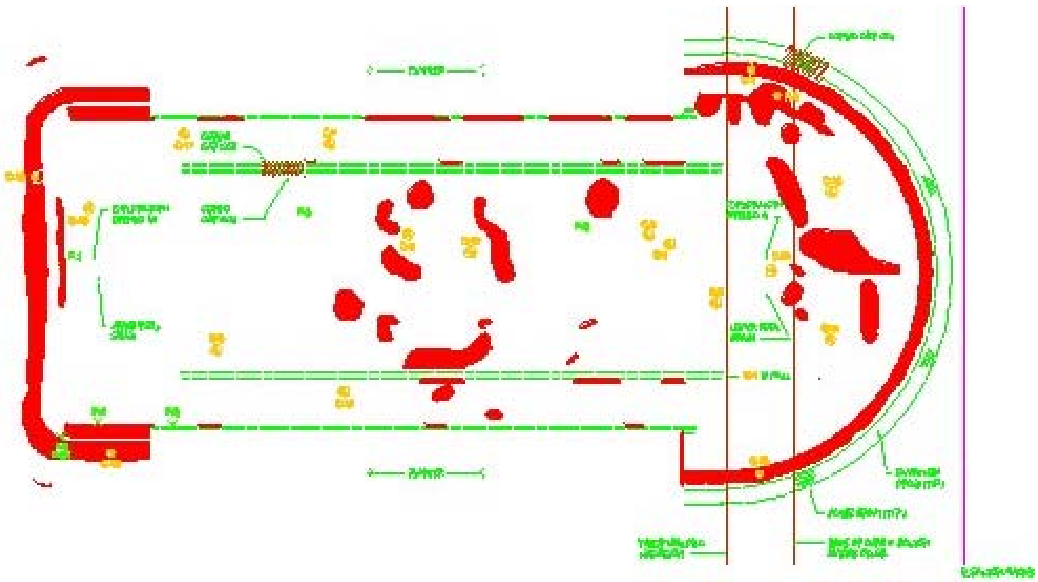

Figure 9 – Delamination survey results. Red areas indicate delaminations detected by sounding.

Figure 10 – Core retrieved from a wall section revealed extensive delaminations in the center portion of the wall. The outer layers do not exhibit delamination.

Figure 11 – Overall view of Opening 1 showing the original lead pan and a retrofit drain.

Figure 12 – Photomicrograph of the membrane in an area with three membrane applications. Note interlayer delaminations at various layers.

Figure 13 – Photomicrograph of the membrane in an area with three membrane applications. Note bridging of the bottom layer by a sand particle.

Figure 14 – Photomicrograph of a membrane area with sand particles broadcast into the bottom layer.

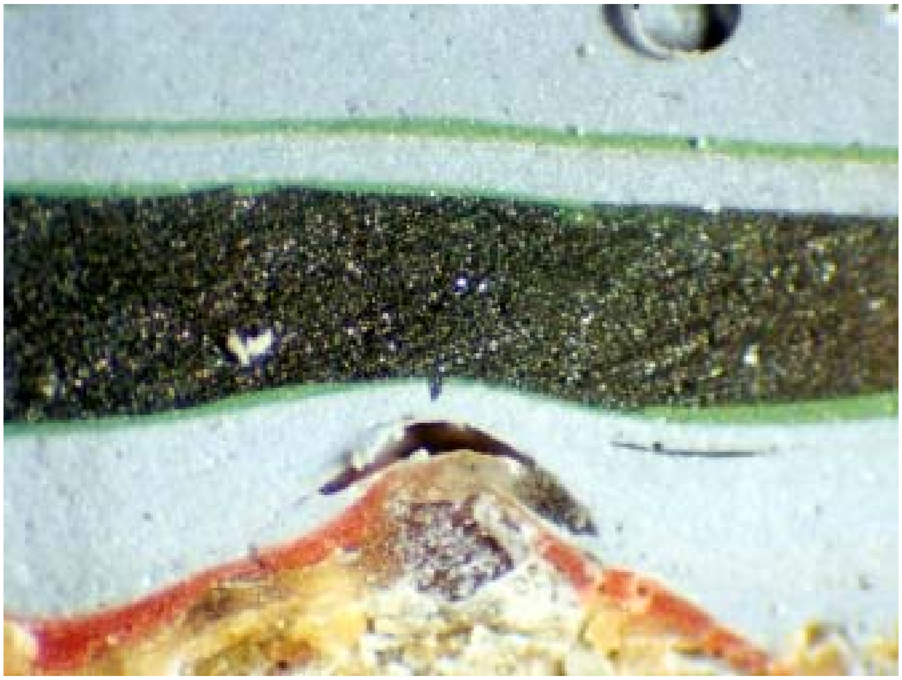

Figure 15 – Photomicrograph of a membrane blister directly over a substrate peak. The peak appears to have caused a breach in the primer (red material).