FORENSIC PROCESSES FOR WATER INTRUSION INVESTIGATIONS

Case Study

By Lonnie Haughton, CDT

The on-grade concrete slab addressed below was introduced to *Interface* readers in a November 2009 article, "Concrete Slab-on-Grade Moisture Tests: How Useful Are the Testing Data When the Vapor Barrier May Be Ineffective?"

While the word "forensic" has different meanings throughout North America, for this article, it is defined as "the puzzle-solving application of a broad spectrum of technical knowledge and expertise to answer questions of interest." The purpose of the following case study is to consider nonlinear puzzle-solving processes used during an extended water intrusion investigation—not to evaluate the merits of original decisions made by the building's contractors.

PRELIMINARY INVESTIGATION

Our firm was hired to investigate carpet/flooring failure at the offices of a nonprofit research facility (*Photo 1*) near San Francisco. The commercial building was constructed in 2005 with concrete tilt-up panels (*Photo 2*) atop spread concrete footings surrounding an on-grade concrete floor slab directly adjacent to a tidal estuary (*Photo 3*) at the mouth of a river flowing into a saltwater bay.

Photo 2 – 2005: Concrete tilt-up panels on "spread footings" surround on-grade concrete slab.

Photo 1 – Nonprofit research facility near San Francisco.

Photo 3 – The building was constructed atop a high water table adjacent to a tidal estuary.

As seen in *Photo 4*, our inspection confirmed deterioration of the latex adhesive used to secure the vinyl-backed carpet tiles, which were functioning as a barrier against the dissipation of water vapor rising through the floor slab. Such adhesive failure can result when “moisture traveling upward through the concrete brings alkalies to the surface where they can attack flooring materials.”[1] We expedited samples of the smelly, emulsified adhesive to a laboratory for assessment of potential health risks to the building occupants and then, as directed by indoor air quality (IAQ) specialists, removed the carpet tiles and deteriorated adhesive, exposing the underlying “wet” floor slab.

After safe removal of the failed carpet tiles, the pressing forensic questions included these:

a. How wet was the concrete slab at this point in time?
b. Were some areas substantially wetter than others?
c. Over time, would the now-exposed on-grade concrete slab begin drying?
d. Did the humidity data provide clues to the moisture source(s) wetting the slab?

Over the course of our investigation, we used two diagnostic tests to address such issues:[2]

1. An electrical impedance test using a proprietary meter[3] to determine near-surface moisture content (*Photo 5*) by transmitting a radio-frequency alternating-current field into the slab.[4]
2. An internal relative-humidity test carried out in conformance with ASTM F2170.[5] Holes are drilled to a depth of about 40% of the slab’s thickness to accommodate a tightly fit sensor that registers the approximate temperature and relative humidity (RH)[6] within the concrete.[7]

With the electrical impedance meter, we found that the near-surface moisture content of the slab ranged from about 5% to greater than 6%.[8] These high values clearly demonstrated some form of moisture-resistive performance failure in the design and/or construction of the on-grade concrete slab and its surroundings.

In *Figure 1*, which presents a floor plan of the building, our preliminary (Phase 1) and later (Phase 2) electrical impedance metering is summarized in three approximate zones of moisture content: “yellow” (5.0 to 5.7%), “green” (5.8 to 6.0%), and “blue” (>6.0%). The Phase 1 data suggested that primary origin(s) of the unintended moisture infiltration might be located at or near the western edge of the slab.[9]

Photo 5 – Electrical impedance confirms floor slab is saturated.

Photo 4 – Latex adhesives are emulsified and deteriorating, creating smelly IAQ problem.

By comparison, the matrix in *Table 1* summarizes mid-slab "internal RH" data collected from six sensors over a two-year period. The locations of the six sensors (S-1, S-2, S-3, S-4, S-5, and S-6) are identified in *Figure 1*. We see in *Table 1* that five of the six sensors have recorded surprisingly high humidity[10] levels within the concrete slab, while the other sensor (S-3) has recorded "dry" conditions.

Note: With these sensors, "Hi" indicates a value greater than 99% RH. While both values correspond to saturation of the concrete floor slab, significant additional moisture is required to register "Hi" instead of 99%.

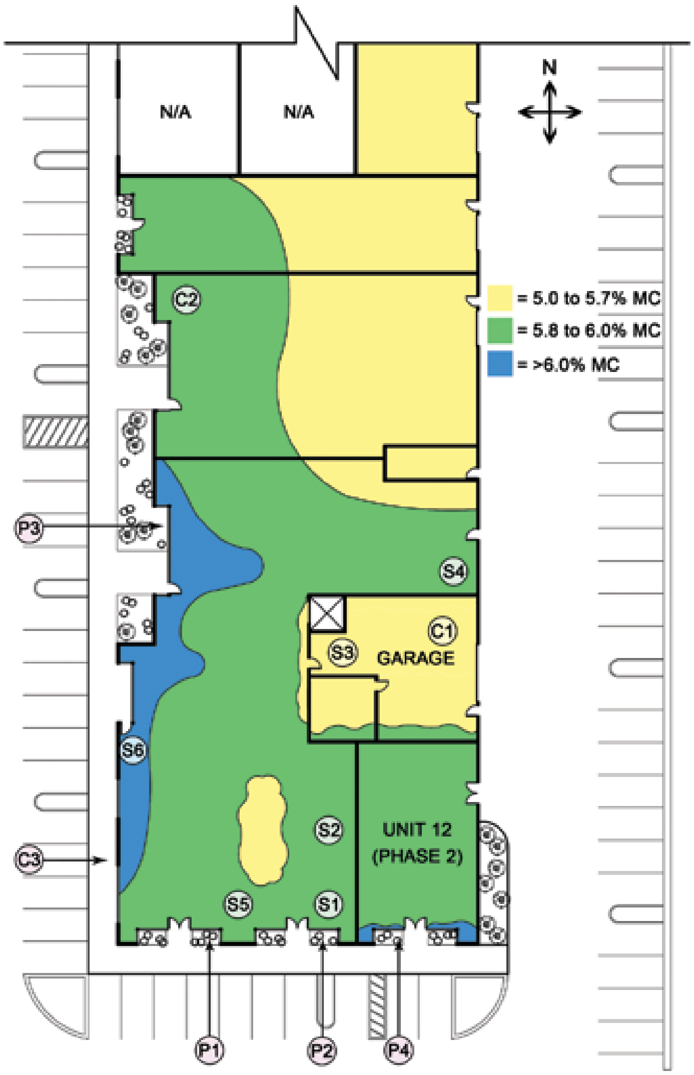

Figure 1 – Partial plan view identifies the "internal RH" sensors (S), the concrete test cuts (C), four inspected planters (P), and approximate moisture content (MC) measurements at the concrete slab.

The data from our moisture meters and RH sensors demonstrated that the on-grade concrete slab was unusually wet. The primary purpose for our ensuing puzzle-solving investigation was to explain why, how, and where this excess moisture infiltrated the slab. The foundation for this forensic process is the highly perceptive guidance published by architect William Rose: "Most moisture problems can be diagnosed by looking at the condition and asking how much water it took to create

ASTM F2170	S1		S2		S3		S4		S5		S6	
Sensors:	RH	(°F)	RH	(°F)	RH	(°F)	RH	(°F)	RH	(°F)	RH	(°F)
9-Dec-2008	99%	(67°)	97%	(67°)	73%	(62°)	96%	(66°)	95%	(68°)	99%	(65°)
22-Dec-2008	*n/a*		*n/a*		71%	(60°)	99%	(62°)	99%	(67°)	99%	(60°)
6-Jan-2009	99%	(63°)	99%	(64°)	69%	(62°)	*n/a*		99%	(66°)	*n/a*	
17-Feb-2009	"Hi"	(67°)	"Hi"	(66°)	72%	(62°)	98%	(66°)	97%	(68°)	"Hi"	(59°)
2-Mar-2009	"Hi"	(67°)	"Hi"	(67°)	73%	(66°)	*n/a*		"Hi"	(67°)	"Hi"	(63°)
31-Mar-2009	99%	(70°)	97%	(71°)	70%	(70°)	96%	(74°)	99%	(71°)	99%	(67°)
14-Sep-2009	99%	(71°)	99%	(71°)	*n/a*		*n/a*		99%	(71°)	99%	(70°)
28-Dec-2009	"Hi"	(65°)	"Hi"	(64°)	69%	(66°)	98%	(64°)	"Hi"	(66°)	"Hi"	(60°)
8-Jan-2010	"Hi"	(63°)	"Hi"	(64°)	73%	(64°)	95%	(64°)	"Hi"	(65°)	"Hi"	(60°)
4-Mar-2010	"Hi"	(70°)	99%	(70°)	73%	(67°)	95%	(66°)	*n/a*		"Hi"	(63°)
27-Apr-2010	"Hi"	(67°)	98%	(70°)	73%	(70°)	95%	(70°)	"Hi"	(70°)	"Hi"	(66°)
1-Nov-2010	"Hi"	(69°)	97%	(68°)	67%	(71°)	81%	(70°)	"Hi"	(67°)	"Hi"	(64°)
23-Dec-2010	"Hi"	(63°)	99%	(64°)	77%	(60°)	91%	(64°)	"Hi"	(64°)	"Hi"	(65°)

Table 1 – Internal relative humidity readings per ASTM F2170.

Photo 7 – Test cut C-1 exposes the overlap joint of the 10-mil polyethylene vapor retarder.

Photo 6 – Widespread cracking of concrete tilt-up panels was an exacerbating source of water infiltration.

that problem. Solving the problem amounts to asking where that amount of water could have come from and where it should go."[11]

Even though we already had identified a variety of exacerbating sources of water leakage into the building and onto the slab-on-grade concrete, including improperly installed aluminum-framed storefront windows and widespread cracking of the concrete tilt-up panels (*Photo 6*), these defects could not have produced sufficient amounts of water to make the floor slab so wet.

Conditions under the concrete floor slab were investigated destructively at three locations (C-1, C-2, and C-3) identified in Figure 1. In test cut C-1 (*Photo 7*) near the S-3 sensor, we found multiple punctures in the 10-mil polyethylene vapor retarder[12] (*Photo 8*) installed between the compacted granular base and granular subbase. No evidence of free water was found in this hole.

At test core C-2, near the western edge of the concrete floor slab, pooling water (*Photo 9*) was found directly under the floor slab. Similarly, at test cut C-3, after excavation below the sidewalk, water began seeping outward (*Photo 10*) from under the concrete tilt-up panel, indicating the existence of a pool of water under the slab at its western perimeter.

Upon digging into planters P-1 and P-2 (see *Figure 1*) between the front of the building and the sidewalk, we found corroded rebar and the exposed edge of a blackish 10-mil polyethylene vapor retarder (also punctured). In other words, as seen in *Photo 11*, the contractor had not closed off (or "turned down") the edge of the concrete slab to provide a water migration barrier between the planter soil and the granular base and subbase under the concrete slab. However, within these two planters, we found no evidence of ponding or trapped water, and we observed that the granular fill supporting the sidewalk promoted good

Photo 9 – Test core C-2: Pooling water was found directly under the floor slab.

Photo 8 – The polyethylene vapor retarder was found to have numerous punctures.

Photo 10 – Test cut C-3 at sidewalk: Water began seeping outward from under the concrete tilt-up panel.

Photo 11 – Soil in planter directly abuts the granular subgrade under the concrete slab. The punctured polyethylene vapor retarder is visible under the corroded rebar.

drainage away from the building.

At this point in the forensic analysis, it seemed reasonable to hypothesize that a primary moisture source for the wet floor slab was some form of upward "percolation" of unintended moisture (water and/or vapor) through the underlying clay soil[13] from the high water table[14] (*Photo 3*) traveling vertically through the punctured vapor retarder[15] (*Photo 8*) into the on-grade concrete slab.

In retrospect, we had reached this seemingly reasonable—but erroneous —hypothesis by overly focusing on the heavily punctured vapor retarder due to our past experiences with failed or missing underslab vapor retarders at other projects.[16]

PHASE 2 INVESTIGATION

Upon subsequent review, our theory was found to suffer from a fatal flaw: the concrete floor slab and its subslab granular layers had been installed onto a 30-in.-thick lime-treated soil (LTS)[17] pad constructed atop the locally common adobe clay soil, which can be highly expansive (i.e., has a high shrink/swell potential when its moisture content decreases or increases). Our destructive testing (with a jackhammer) supplemented research indicating such dense LTS pads are resistant to water and vapor infiltration.

Many areas in North America[18] have expansive clay soils with high shrink/swell properties that can be stabilized with hydrated lime treatment, which causes the clay surface mineralogy to be altered, producing reduced plasticity, reduced moisture-holding capacity, reduced swell potential, improved stability, and the ability to construct a solid working pad.[19]

While it is far more common to encounter these relatively expensive LTS stabilization programs during roadway construction and at large commercial projects than at small office/warehouse buildings, with 20/20 hindsight (considering the adobe clay soils and the river mouth location), it makes

Photo 13 – Close view of P-3 planter.

Photo 12 – Overview of P-3 planter.

Photo 14 – Phase 2 investigation occurred at Unit 12.

great sense that the construction site first had been prepared with a thick, dense, and relatively water-impenetrable LTS pad.

During our initial forensic surveys, perhaps blinded by our focus upon the punctured vapor barrier and the high water table, our incomplete surveys at the P-1 and P-2 planters and the C-1, C-2, and C-3 test cuts caused a failure to consider the underlying LTS pad (not shown on the provided construction drawings). In hindsight, it is obvious that we also should have inspected the other planters sooner.

The thick LTS pad extends beyond the building's footprint, under the adjacent sidewalk. Beyond the sidewalk, the at-grade hardscape slopes away from the concrete slab and sidewalks. These conditions certainly seemed to discredit any theory that the wet floor slab was indicative of vertical "percolation" of moisture from the underground water table.

The puzzle-solving process for complex water intrusion investigations can be a highly nonlinear maze. When arriving at a roadblock or dead end, the next step is to reassess previously collected observations and data for evidence of alternate pathway(s). Again, the advice of architect William Rose is fundamental: Solving complex moisture problems always entails asking where that amount of water could have come from.[20] For this particular puzzle, if the problematic water apparently was not migrating vertically, then we needed to reconsider potential routes for horizontal intrusion atop the newly recognized LTS pad.

Our initially collected moisture data had indicated the wettest ("saturated") areas of the wet concrete floor slab were at its western edge. Upon excavation into the infill planter (P-3) seen in *Photos 12* and *13*, we found wet soil, the exposed edge of the polyethylene vapor retarder, and water trails leading under the concrete slab and granular base and subbase atop the LTS pad. And, even though some, but not all, of these planting areas were serviced by landscaping drains, the inlets for these through-the-sidewalk drain pipes were located about two inches above the LTS pad, thus serving no functional purpose.

Finally, even though our excavation at the P-1 and P-2 planters at the front of the building had revealed a drainable granular base under the adjacent sidewalk, here at the P-3 sidewalk, we found native clay soil that was highly sticky and water-saturated, providing minimal drainage, if any, from the planter. In short, at the four sides of the P-3 planter, only the granular base and subbase under the slab provided drainage routes.

Meanwhile, we had received permission to take moisture content readings of the concrete floor slab inside south-facing Unit 12 (see *Photo 14*), which had become vacant. As shown in *Figure 1*, the entire floor in Unit 12 was found to be very wet, with the wettest readings at the southern edge adjacent to the planters.

We excavated into the P-4 planter (*Photo 15*), again finding wet soil, the exposed edge of the polyethylene vapor retarder, and visual evidence that water migration under the concrete slab was occurring atop the LTS pad, which was found to have an undulated surface that could pond water. Then, under the P-4 sidewalk, we again found native clay soil that was highly sticky and water-saturated, providing minimal drainage, if any, from the planter. (Also note the plastic piping for the landscaping irrigation in *Photo 15*.)

SUMMARY DISCUSSION

In many litigation cases, forensic analyses of building envelope performance move forward sporadically due to legal, logistical, access, and/or budgetary constraints. This article does not attempt to describe or explain the timeline of the extended investigation carried out at this building.

A critical goal of the forensic process is tying together cause(s) and effect(s). "Within the limits of the investigator's commission: a) the consequences of leakage are established; b) the severity, consistency, and distribution of these consequences are determined; and c) leakage pathways from construction defects and other types of building envelope failures are identified. This investigative process commonly is both inductive and deductive and should be carried out with methodological competence, intellectual rigor, and professional integrity."[22]

While our preliminary Phase 1 survey led us to hypothesize vertical percolation

Photo 15 – The pour strip (or pour-back strip) [21] within Unit 12 was saturated. The planter drains under the slab via the LTS pad.

from the natural water table as a primary explanation for the wet slab and resultant flooring failure, subsequent evidence, including the Phase 2 survey, led us to conclude that a primary source was horizontal migration—via the granular base and subbase under the slab—from the poorly drained planters, creating a perched water table[23] atop the LTS pad.[24]

In retrospect, the early information gained from the moisture content values summarized in *Figure 1* and the subgrade conditions (see *Photo 11*) exposed at the interface between the P-1 planter and the slab easily could have been sufficient to solve this moisture-migration puzzle. However, even if our conclusions perhaps came slowly, our forensic process remained consistent with the investigative methodology prescribed in ASTM E2128,[25] which includes the following guidance: "The information systematically accumulated in a leakage evaluation is analyzed as it is acquired. The new information may motivate a change in approach or focus for subsequent steps in the evaluation process."

Even though E2128 specifically addresses leakage evaluations of building walls, its forensic principles are valid for all building envelope evaluations.[26] As the investigation progresses, new conditions and sampling questions may emerge that confirm, enrich, modify, or challenge the investigator's understanding of the observed phenomena: "The evaluation of water leakage...is a cognitive process in which technically valid conclusions are reached by the application of knowledge, experience, and a rational methodology."[27] The hallmark of good building envelope forensics is a willingness to remain open to new information, no matter what it reveals.

REFERENCES

1. Reference Howard Kanare's excellent manual, *Concrete Floors and Moisture*, published by the Portland Cement Association (www.cement.org).
2. The uses and potential limitations of such testing meters and equipment were explored in this writer's article in the November 2009 issue of *Interface*. We also recommend ACI 302.2R-06, "Guide for Concrete Slabs That Receive Moisture-Sensitive Flooring Materials," published by the American Concrete Institute (www.concrete.org).
3. Tramex Concrete Encounter CME4 meter (www.tramexltd.com).
4. Kanare. "Such instruments can provide useful information on relative differences in moisture conditions to a depth of 50 mm (2 in.)."
5. ASTM F2170-1, *Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in-situ Probes*, ASTM International (www.astm.org).
6. Kanare. "Moisture moves through concrete in a partially adsorbed or condensed state by diffusion, not simply as unbound, free water vapor or liquid. The rate of moisture transmission depends on the degree of saturation, which is a function of the relative humidity on each side of the concrete. Therefore, the driving force for water vapor movement through a slab is the relative humidity differential through the slab's depth, not simply the vapor pressure differential...RH probes are a method of directly measuring this property."

7. For this project, we used the Rapid RH® sensors marketed by Wagner Meters (www.wagnermeters.com).
8. While the porosity (and thus the maximum possible moisture content) of concrete can vary, when evaluating on-grade concrete slabs in the San Francisco Bay area, we often find it reasonable to roughly categorize such moisture content measurements as follows: “typical” (3.0 to 3.7%); “potentially problematic” (3.8 to 4.3%); “wet” (4.4 to 5.0%); “very wet” (5.1 to 6.0%); and “saturated” (> 6.0%). These categories, which differ from those defined for this article, also are qualitative and comparative and intended solely to aid the forensic evaluation process.
9. However, as discussed in this writer’s article, “Anatomy of a Leakage Investigation at a Concrete Floor Slab,” published in the July 2008 issue of *Interface*, it should be noted that widespread lateral migration of moisture within a concrete slab can occur from undetermined point source(s) of water infiltration—potentially complicating the puzzle-solving process.
10. Actual “moisture content” values within a concrete slab are a function of both RH and temperature. For our puzzle-solving purposes, it was sufficient to observe that the RH data indicate the slab is much “wetter” at Sensors 1, 2, 4, 5, and 6 than at Sensors 3. It is this writer’s experience that some investigators tend to get bogged down with data quantification in lieu of rapidly proceeding forward with simple qualitative comparisons of differing data sets. Similarly, while the precise accuracy of some moisture content readings can be important, for many forensic surveys the investigator only needs to consider the broad differences between “wet” and “less-wet” data from identical sensors.
11. W.A. Rose, *Water in Buildings – An Architect’s Guide to Moisture and Mold*, John Wiley & Sons, Inc., 2005.
12. Reference: ASTM E1745, *Standard Specification for Plastic Water Vapor Retarders Used in Contact With Soil Or Granular Fill Under Concrete Slabs;* and E1643-11, *Standard Practice for Selection, Design, Installation, and Inspection of Water Vapor Retarders Used in Contact With Earth or Granular Fill Under Concrete Slabs.*
13. ASTM E1643 notes, “Soils with comparably higher clay contents are particularly troublesome because the relatively high capillary action within the clay allows moisture to rise under the slab.”
14. Kanare: “Although moisture vapor causes most floor problems, sometimes a high water table provides a direct source of liquid water in contact with the underside of a concrete slab.”
15. *Ibid*: “A properly designed vapor retarder must be installed without gaps, punctures, or tears in order for it to function as intended.”
16. *Ibid*: “It is important to note that a capillary break will not stop the free movement of water vapor. The actual depth of the water table below a slab is not important insofar as moisture vapor movement is concerned. Whether the water table is one meter (3.3 feet) or many meters below the slab, the subgrade and subbase will have close to 100% relative humidity; it is the presence of an infinite supply of water vapor that often causes flooring systems to fail. The slab must be protected by an adequate vapor retarder under the concrete.”
17. www.lime.org/uses_of_lime/construction/soil.asp.
18. See map at http://geology.com/articles/soil/.
19. *Lime-Treated Soil Construction Manual*, National Lime Association (www.lime.org): “Lime can modify almost all fine-grained soils, but the most dramatic improvement occurs in clay soils of moderate-to-high plasticity. Modification occurs because calcium cations supplied by hydrated lime replace the cations normally present on the surface of the clay mineral, promoted by the high pH environment of the lime-water system.”
20. W.A. Rose.
21. Kanare: “Concrete tilt-up wall construction is often used for large area buildings, such as warehouses and manufacturing facilities, where the finished floor surface is used as a casting bed for the walls....A 900- to 1500-mm (3- to 5-ft.-) wide strip around the perimeter of the floor is usually left out of the initial floor pour; this is called a pour-back strip, leave-out strip, perimeter strip, or fill-in strip.”
22. L. Haughton & C. Murphy, “Qualitative Sampling of the Building Envelope for Water Leakage,” *Journal of ASTM International* (www.astm.org), Vol. 4, No. 9 (10/2007) – republished by ASTM in 2009 in STP 1493 (*Repair, Retrofit, and Inspection of Building Exterior Wall Systems*).
23. Kanare: “A ‘perched’ water table forms when surface water, such as precipitation, cannot percolate downward through a relatively impermeable layer to the natural water table.”
24. It still remained possible that vertical infiltration of groundwater onto the LTS pad was occurring where the pad was penetrated by a trench serving the main sewer line; however, this alternative was ruled out after additional destructive testing.
25. ASTM E2128-12, *Standard Guide for Evaluating Water Leakage of Building Walls*, ASTM International (www.astm.org).
26. L. Haughton & C. Murphy.
27. ASTM E2128-12.

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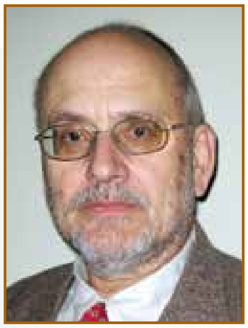

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