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 1 – Nonprofit research facility near San Francisco.

Photo 2 – 2005: Concrete tilt-up panels on “spread footings” surround on-grade concrete slab.
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 alkalis to the surface where they can attack flooring materials.” 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:

1. An electrical impedance test using a proprietary meter to determine near-surface moisture content (Photo 5) by transmitting a radio-frequency alternating-current field into the slab.

2. An internal relative-humidity test carried out in conformance with ASTM F2170. 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) within the concrete.

With the electrical impedance meter, we found that the near-surface moisture content of the slab ranged from about 5% to greater than 6%. 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.

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 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%.

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

<table>
<thead>
<tr>
<th>ASTM F2170 Sensors</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
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<tr>
<td>RH (% RH)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>9-Dec-2008 99% (67°)</td>
<td>97% (67°)</td>
<td>73% (62')</td>
<td>96% (66')</td>
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<td>n/a</td>
<td>71% (60')</td>
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<td>99% (67')</td>
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<tr>
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<td>99% (64')</td>
<td>69% (62')</td>
<td>n/a</td>
<td>99% (66')</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>17-Feb-2009 “Hi” (67')</td>
<td>“Hi” (66')</td>
<td>72% (62')</td>
<td>98% (66')</td>
<td>97% (68')</td>
<td>“Hi” (59')</td>
<td></td>
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<tr>
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<td>73% (66')</td>
<td>n/a</td>
<td>“Hi” (67')</td>
<td>“Hi” (63')</td>
<td></td>
</tr>
<tr>
<td>31-Mar-2009 99% (70')</td>
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<td>70% (70')</td>
<td>96% (74')</td>
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<td>99% (71')</td>
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<tr>
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<td>“Hi” (60')</td>
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<td>67% (71')</td>
<td>81% (70')</td>
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<td>“Hi” (64')</td>
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<tr>
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<td>77% (60')</td>
<td>91% (64')</td>
<td>“Hi” (64')</td>
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</tr>
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</table>

Table 1 – Internal relative humidity readings per ASTM F2170.
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 retarder12 (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
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 soil13 from the high water table14 (Photo 3) traveling vertically through the punctured vapor retarder15 (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 America18 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...
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 re-assess 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. 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 landscaped 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.”

While our preliminary Phase 1 survey led us to hypothesize vertical percolation
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 atop the LTS pad.

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, 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. 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.” The hallmark of good building envelope forensics is a willingness to remain open to new information, no matter what it reveals.

REFERENCES

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.).”
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.”
For this project, we used the Rapid RH® sensors marketed by Wagner Meters (www.wagnermeters.com).

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.

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.

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.

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Lonnie Haughton, CDT, is a principal codes/construction consultant with Richard Avelar & Associates in Oakland, CA. He is a member of RCI, the Forensic Expert Witness Association, the Construction Specifications Institute, Western Construction Consultants Association (Westcon), Construction Writers Association, and is an EDI-certified EIFS Third Party Inspector. Lonnie is one of about 800 individuals nationwide who has been certified by the International Code Council as a Master Code Professional. He is the primary author of the paper “Qualitative Sampling of the Building Envelope for Water Leakage,” published in the Journal of ASTM International, and has a passion for solving complex moisture intrusion puzzles.