Sherlock Holmes, Miss Marple, and other fictional detectives used their keen powers of observation to solve murders, bank robberies, and other puzzling crimes. If these literary detectives had been materials scientists, they might have turned their sleuthing skills toward concrete forensics.

Concrete is everywhere. The rock-hard construction material is the stuff from which the world builds bridges, buildings, roads, sewage systems, and more. We use more of it than any other material, save water: 30 billion metric tons of concrete around the globe each year. But even with all the experience we have with concrete, things can go wrong. Sometimes concrete unexpectedly cracks, chips, or flakes. It may also become discolored, corroded, and weak, failing to stand the test of time and provide the strength to support the structures for which it was designed. The damage can be unsightly, defacing a pricey building, or it can pose a safety threat, leading to facility shutdowns and costly repairs.

The source of the problem is often tough to pin down. That’s where the concrete detectives come into play. Scientists at engineering and consulting firms get called in when building owners, facility managers, or structural engineers find a problem with concrete and want to know how to fix it and, sometimes, who to blame.

With backgrounds in geology, engineering, chemistry, and materials science, these experts in cement and construction materials use microscopy, spectroscopy, and other tools to tackle concrete conundrums and decipher damage mechanisms. Their forensic-type analyses identify troublemaking components in the concrete mix, contractor errors, environmental contaminants, and other factors that adversely affect concrete’s appearance and structural integrity. Their findings may be used to mitigate the problem, to avoid it in the future, and sometimes to identify a legally and financially responsible party.

The Case of the Flaking Floor
In some cases, concrete damage comes mainly from physical factors. One example is the case of a medical supply warehouse in Tiffin, Ohio, in which the concrete floor, which was designed to support fork-truck traffic, underwent severe cracking just months after the floor was installed. What went wrong?
According to Richard L. Allen, president of Bowser-Morner, an engineering consulting and materials testing firm in Dayton, Ohio, this was a case of operator error. According to his team’s investigation, which included microscopy analysis of large samples—concrete cores—drilled from the damaged floor, the contractor simply added too much water to the concrete as workers installed the floor slab.

To understand how excess water can affect concrete’s performance, consider how the stuff is made. Concrete suppliers make the construction material by blending cement powder—the most common type is known as portland cement—with sand and gravel, also referred to as aggregate. They mix the dry materials with water, setting in motion a complex series of chemical reactions that converts the cement powder to a pasty glue that binds concrete and ultimately hardens to form a strong, rocklike solid.

Several reactions cause concrete to harden and endow it with strength. The main ones include hydration of tricalcium silicate in cement. That’s an exothermic process that releases calcium and hydroxide ions and forms calcium silicate hydrate. A similar reaction with dicalcium silicate also strengthens concrete.

At the job site in Tiffin, the contractor added what Allen calls “water of convenience,” water beyond what’s needed for cement hydration. The additional water was meant to keep the mixture fluid and easy to work with, so that concrete finishers—the workers who smooth the mixture and apply the final texture to the warehouse floor—could complete the job before the concrete became too hard.

But the contractor overdid it. As Allen explains, the concrete at this location was deliberately prepared with coarse aggregate, large pebbles of limestone (calcium carbonate) and dolomite (calcium magnesium carbonate). This is not an unusual choice. It’s well known that as concrete sets, it shrinks, Allen says. The shrinkage occurs in the cement paste, not the aggregate. So the Tiffin contractor sought to reduce the shrinkage by slightly reducing the amount of cement in the concrete mix and filling the volume with coarse rock.

That strategy often works, but not this time. The microscopy analysis of the concrete cores revealed the consequences of adding too much water to this particular mixture. The excess water made the concrete overly fluid and caused the coarse material to sink, leaving nearly pure cement paste at the top layer of the concrete slab.

As a result, the shrinkage caused a volume change that was confined mainly to the pure cement portion at the top of the slab. This shrinkage stressed that layer of the floor, so when the building opened for business, the floor cracked under the pressure from forklifts riding over it. To repair the floor, workers ground away the damaged layer and replaced it with a durable epoxy material—at significant cost.

Contractor error was also to blame when the floor in a new maintenance building on a farm in Fulton County, Ohio, started to delaminate. According to Allen, shortly after the building was erected, millimeter-thin sections of the concrete floor mysteriously began flaking away. As with the warehouse case, improperly added water played a key role in the fiasco, but as the team’s investigation showed, the circumstances and damage mechanism were different than those in the Tiffin case.

The building was constructed in late fall, as temperatures were dropping. Low temperatures slow concrete reaction kinetics, and the contractor wanted to speed the process to cut labor costs. To do so, he ordered a lightly air-entrained concrete mix.

Air-entrained concrete is designed for use outside in cold climates and typically includes a foaming agent. This compound forms a network of microscopic bubbles that functions like a buffer to protect against crack-inducing internal pressure. The pressure comes from residual water in the set concrete that expands and contracts as it undergoes freeze-thaw cycles. The Swiss-cheese-like structure can accommodate volume changes caused by large temperature swings. Air-entrained concrete typically contains 4–7% air voids by volume.

As hydration reactions in any concrete mixture proceed, the setting concrete expels heat, air, and water—referred to in the construction industry as bleed water. Allen explains that air-entrained concrete generates less bleed water than the type that is not air entrained.

To complete a job, concrete finishers need to wait for the material to set and harden enough to bear the workers’
weight yet remain adequately fluid to be workable. The contractor working on the farm building knew that the cold weather meant that his team would have to wait many hours for a floor made from non-air-entrained concrete to expel its bleed water—and for that water to evaporate enough for the material to be sufficiently hard to allow the finishers to go to work.

“The contractor didn’t want to pay the crew to wait around all day, so he tried to cut a fine line” and ordered concrete with a fairly low air concentration, perhaps 3%, Allen says. Knowing that this custom air-entrained mix would set in a reasonable amount of time, the contractor then proceeded to add water to keep the concrete fluid and easy to shape and mold.

That was a tactical error. Adding this excess water stirred and agitated the foaming agent in the concrete, generating lots of tiny bubbles. Because of its low density, the air-entrained concrete rose to the surface. When the concrete finishers smoothed and troweled the concrete, they collapsed the bubbles, slightly compressing the layer and increasing its density. That layer hardened on top of a less dense, air-entrained layer just beneath the surface, which led to poor adhesion between the layers and caused the concrete to flake and delaminate.

The Curse of the Sewage Acids
Tiny bubbles can wreak havoc on concrete. So can tiny microbes. Those were the culprits in the case of a heavily corroded underground sewage holding tank at a wastewater treatment plant in Springfield, Indiana.

Nick Scaglione, president of Concrete Research & Testing in Columbus, Ohio, used microscopy and other methods to examine concrete core samples taken from the tank. He says the cement paste in those samples was discolored, severely corroded, and soft. And some of the concrete was cracked and eaten away, exposing underlying metal reinforcement bars.

According to Scaglione, the chemical culprit in this case was sulfuric acid, the source of which was a multistep biogenic process driven by bacteria that thrive in sewers. Bacteria convert sulfate compounds in sewage to hydrogen sulfide, which is then oxidized to sulfuric acid in the moist sewer environment. The acid attacks calcium hydroxide and calcium silicate hydrate in cement to form calcium sulfates, which discolor the cement and destroy its binding properties.

The damage, however, was confined to the near-surface area, the region directly exposed to sewage. Scaglione’s analyses showed that the concrete cores exhibited abrupt transitions between the corroded regions and unaffected regions just below the surface. And tests he conducted to assess the concrete’s compressive strength and weight-bearing capacity show that despite extensive and obvious corrosion, the underlying concrete remained structurally sound.

“In this case, the chemical attack was relatively shallow,” Scaglione says, and the concrete below the surface was still in good shape, enabling the municipality to repair the structure by replacing the damaged concrete with fresh material.

A similar corrosion process seemed to be eating away at concrete samples that came from the floor of a chemical plant in Salt Lake City. Like the Indiana samples, the ones from Utah were discolored, corroded, and cracked. Steel reinforcement bars buried inside the concrete were also corroded. But unlike the Indiana samples, the concrete from Utah contained unexpectedly high levels of calcium chloride that extended deep into the concrete. Once again, Scaglione’s analyses pointed to acid-induced corrosion. In this case, however, the culprit was hydrochloric acid,
which may have spilled and seeped into the floor, attacking the concrete’s calcium minerals.

**The Mystery of the Pesky Powders**

Sometimes concrete detectives are summoned to solve cases of mystery materials—often powders—that suddenly appear on concrete surfaces. Building owners want to know what the materials are, where they came from, and how to get rid of them. Scaglione has been called in on several such cases, like one in which the floor of an office building in Saint Charles, Virginia, seemed to sprout white fluffy powder during construction.

By analyzing the crystalline material with electron microscopy and X-ray methods, then combining the results with concrete common sense, Scaglione quickly identified the cause: efflorescence. This process involves water-soluble salts in concrete that form a solution with water and then seep to the surface. The water then evaporates, leaving behind a layer of salt.

Concrete for the Saint Charles building was poured in cold weather, so the contractor ordered a concrete blend containing an “accelerating admixture” to speed the hydration reaction and shorten the setting time. The commercial admixture, which consists mainly of calcium nitrate, reacted with potassium compounds in the concrete. As the concrete set, it emitted water rich in potassium nitrate, which crystallized on the surface of the new floor. Efflorescence doesn’t cause lasting trouble in these kinds of cases, Scaglione says. The salt is easily swept away, doesn’t corrode concrete, and stops appearing after the concrete dries.

The salt-forming process did cause trouble in the parking structure of an office building in Lima, Ohio. In that case, studied by Bowser-Morner scientists, efflorescence left white powder at the base of concrete support columns and caused spalling and cracking.

Deicing salts used on roads and sidewalks triggered the problem, Allen says. Composed mainly of sodium chloride and other chlorides, the salts dissolved in melted snow and ice and were splashed onto the columns by passing cars. The salty solution seeped into the pores of the concrete. As the water rose back to the surface, it evaporated and left behind salt crystals that grew each time the process was repeated. Eventually, the expanding crystals caused the concrete to crack.

The firm’s suggestion was to clean the columns and protect them with an epoxy or other impermeable coating to prevent further intrusion of salt solution. Allen notes that engineering firms often use these kinds of barriers to shield support structures for highway bridges from damage from deicing salt.

When it comes to concrete mysteries, “sometimes the bad actor is really obvious,” like an iron mineral in concrete that oxidizes and leaves an ugly stain, says Kevin M. Savage, assistant director of Bowser-Morner’s analytical sciences laboratories. “Other times you just sit there and scratch your head, wondering what went wrong.”

“Those are the fun jobs, the ones I live for,” Allen says. “They can be really challenging, but they give you the opportunity to stretch yourself and put your skills to good use.”

*Mitch Jacoby is a senior correspondent at Chemical & Engineering News, an independent news publication of the American Chemical Society. A version of this story first appeared in C&EN.*

[Efflorescence caused these potassium nitrate crystals to grow on the surface of a concrete floor in a Virginia office building. Credit: Nick Scaglione/Concrete Research & Testing.](https://doi.org/10.1021/acscentsci.1c00644)