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Petrography: A powerful tool for solving common concrete problems

The science of rock microscopy can play a significant role in concrete quality control and failure investigation

By Dipayan Jana

Petrography, the once-esoteric 150-year-old science of rock description, is rapidly becoming an accepted testing tool in construction technology. Investigation of deteriorated concrete or mortar — from visual observations to evaluations at significantly high resolution and magnification by advanced petrographic instruments like optical microscopes — allows a petrographer to study many fine details of materials-related structural problems.

Three common optical microscopes (and their associated magnifications) widely used in petrographic investigations are stereomicroscopes (3.75X to 450X), reflected- and transmitted-light (metallographic) microscopes (25X to 1,000X), and polarized-light microscopes (5X to 1,000X).

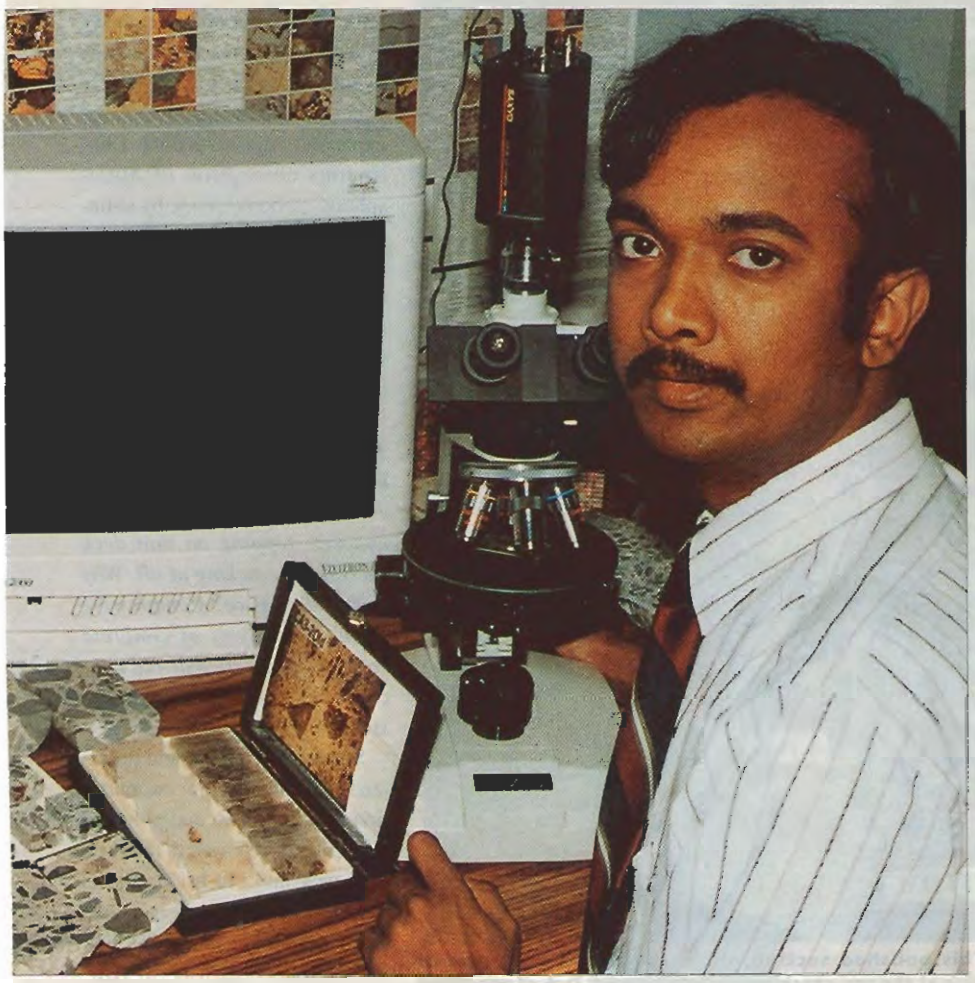
Optical microscopic investigation remains at the nucleus of modern petrographic research that can provide fast and easily-obtainable solutions to structural failure problems. In addition, X-ray diffractometry provides identification of many constituents in the paste and ultra-fine particles in the aggregates. Scanning and transmission electron microscopy and electron probe microanalysis, which play a significant role in classical petrographic investigations, are relatively new to the concrete industry and have a promising potential future in extending concrete examination one step further. These instruments help to examine the ultra-fine particles, cement hydration products, surface features, and submicroscopic defects at much higher magnifications (>10,000X). They are also useful in examining the elemental compositions of the concrete and mortar particles quite rapidly and accurately. Infrared microscopy, another fertile field in concrete technology, may be helpful in detecting the chemical composition of various organic admixtures used in the concrete mix.

For commonly encountered structural problems, however, the optical microscopic investigation alone can often provide the fastest, easiest, and most cost-effective answers for engineers. Information obtainable from optical microscopes helps reflect the detailed anatomy of deteriorated concrete or mortar.

INFORMATION OBTAINABLE FROM PETROGRAPHIC STUDIES

Detailed information about the quality of concrete or mortar can be obtained quickly and accurately from petrographic studies. Such details include:

- Type, shape, gradation, and distribution of coarse and fine aggregates;
- The presence of harmful or chemically-reactive aggregates that could cause potentially expansive cracking and disintegration of concrete;
- The presence of volumetrically-unstable water-absorptive minerals, such as clays, in the aggregate, or the soft, porous nature of the aggregate itself in a concrete exposed to severe freeze-thaw fluctuations;
- The presence of chemically-reactive or expansive minerals (e.g., pyrite, gypsum, clays, zeolites) in aggregates that could cause interior chemical deterioration, staining, and cracking in the concrete;
- The segregation of coarse aggregates toward the bottom and fine particles (with bleeding channels) toward the top;
- Honeycombing (excessive amounts of large gaps between coarse aggregates);
- Tightness of paste-aggregate bonds;
- Physical properties of paste, including color, hardness, lustre, porosity, crystallinity,



density, and texture;

• Compositional homogeneity or variation in paste properties from top to bottom;

• Identification and proportion of various unhydrated cement particles in the paste;

• Identification of cement hydration products (i.e., the extent of cement hydration);

• The presence and amount of mineral admixtures (such as fly ash, silica fume, or blast furnace slag) in the concrete;

• Identification, location, and quantity of secondary deposits in the paste;

• Depth and extent of paste carbonation;

• The presence of undesirable, chemically-reactive contaminants in the paste;

• Corrosion products;

• The presence of soft, discolored, or cracked paste with dehydrated products due to fire damage;

• The proportion (volume percentage) of coarse and fine aggregates, paste, and air voids in the hardened concrete;

• The amount, distribution (clustering, if any) and spacing of air voids in the paste;

• The nature, extent, and severity of cracking in the concrete;

• The extent and severity of ice crystal impressions; and

• Unit weights of the concrete and mortar.

GETTING ANSWERS TO STRUCTURAL FAILURE QUESTIONS

The above list clearly shows the wealth of information that can be gathered from a simple petrographic investigation of a deteriorated concrete. Consequently, several possible causes of concrete deterioration can be obtained from these observations. Some petrographic data may be subject to different interpretations. Accumulated petrographic evidence correlated with other test data, on the other hand, allows an experienced petrographer to go beyond the limits of personal judgment and provide definitive causes of failure to the concerned engineer. Several commonly asked questions can be answered by petrographic investigations. For example:

• Was the initial concrete mix well-proportioned, well-mixed, well-compacted, and well-cured?

• Did the aggregates in the concrete mix have the proper size, shape, and gradation to optimize cement and water requirements?

• Did the aggregates in the concrete mix have the desired physical and mineralogical properties to build a structurally lightweight, normal weight, or massive heavyweight fire-enduring concrete?

• Was the concrete made with excessively high water/cement ratios?

• Was the placed concrete in the entire structure from the same mix design?

• Was the concrete over-vibrated during placement?

• Was the concrete mix re-tempered (the addition of excess water to make a mix workable)?

• Did the concrete undergo significant bleeding (upward migration of water) before setting?

• Did the concrete undergo freeze-thaw-related cracking due to either inadequate air entrainment in the paste or the presence of a high amount of fine-grained, porous, water-absorptive aggregates?

• Was the concrete affected by freeze-thaw-related cracking due to large spacing of air voids even though the concrete itself is air-entrained?

• Did the concrete become soft and friable due to significant carbonation of the paste?

• Did the concrete lose its workable strength due to a high water/cement ratio or excessively high air entrainment?

• Did the concrete scale and spall due to expansion of frozen water in the paste?

• Did the concrete deteriorate by continuous exposure to moist, chemically-corrosive (e.g., sulfate-rich) soil or water?

• Did the concrete expand and crack due to cement-aggregate reactions?

• Was the concrete severely damaged by exposure to fire? If so, to what extent?

• Was the mortar over-sanded or does it have a high water/cement ratio?

CASE STUDIES

A typical petrographic investigation follows a series of steps beginning with a detailed field investigation of the deteriorated concrete and mortar, the selection of location, and coring of samples from areas that, on visual examination, appear undamaged to those that are severely deteriorated (showing scaling, spalling, staining, cracking, surface delaminations, etc.). The concrete samples are then sectioned and polished before inspection. Inspection proceeds from visual and stereomicroscopic investigations, reflected-light and polarized-light microscopic investigations, and so forth.

Aggregates, paste, hydration products, unhydrated particles, admixtures, air voids — all concrete and mortar components can

be studied thoroughly according to the ASTM test procedures (C-295: "Petrographic Examination of Aggregates for Concrete," C-457: "Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete," and C-856: "Petrographic Examination of Hardened Concrete"). In addition, a computer-controlled video-microscopic image analysis of the hydrated paste and air voids can help to determine the proportion of cement particles, air void amount, distribution, and spacing quite clearly and rapidly.

Table 1 shows the advantages of petrographic examination in investigating various properties of hardened concrete compared to other evaluations. A few typical case studies are included below.

1. Concrete stairs, pavements, and floors around a residential complex in metropolitan New York area showed significant scaling, spalling, and delamination within one year of construction. What went wrong?

Fresh fracture surfaces, as well as polished-slab and thin-section (20-micron thickness) examination of a concrete core drilled from the deteriorated areas showed soft and friable, light-colored paste with abundant calcium hydroxide flakes and very few unhydrated cement particles toward the top. Consequently, the estimated water/cement ratio showed an increase toward the top with a laitance. Honeycombing was observed at the top, whereas numerous subparallel cracks around the coarse aggregates were observed at the bottom (Photo 1). The concrete was not air entrained. A treatment with phenolphthalein solution and hydrochloric acid showed significant paste carbonation at the top. From these petrographic observations it can be inferred that the initial concrete mix was not thoroughly compacted and had experienced excessive bleeding. Cyclic freeze-thaw events caused cracking where water in the paste had frozen and expanded after hardening. Continuous absorption of atmospheric carbon dioxide by abundant hydrated products of cement had caused carbonation, making the concrete soft and friable. All of these combined factors caused scaling, spalling, and delamination of the concrete.

Photo 1. This polished section, shown at actual size, reveals honeycombing at the top, cracking at the bottom, a lack of entrained air, and a differential water/cement ratio — all undesirable properties of concrete.

2. An 80-year-old concrete bridge deck in Ohio showed severe cracking. But a 20-year-old concrete topping on that deck showed no cracking at all. Why such a difference? Compressive strength analysis of concrete cores from the 20-year-old concrete showed progressively lower strength toward the top. Why?

Stereomicroscopic and polarized-light microscopic examination of a sectioned and polished concrete core drilled through both new and old bridge decks showed a sharp change in air entrainment of the concrete from a 5.5% entrained air in the 20-year-old concrete to literally no entrained air in the 80-year-old concrete (Photo 2). Cracking in the 80-year-old concrete appeared to be due to

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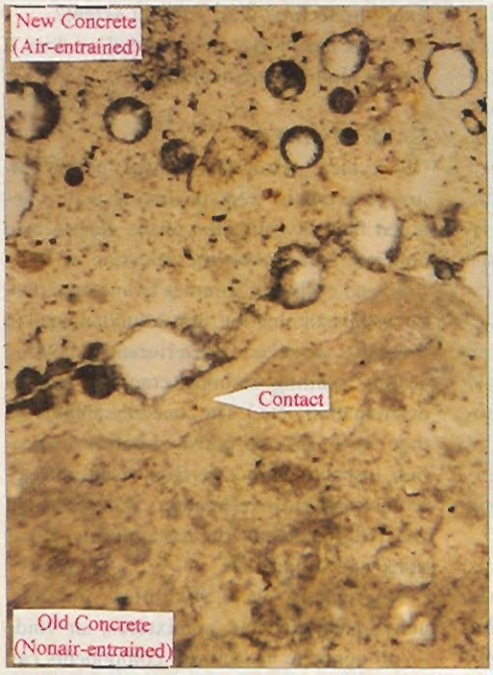

Photo 2, left. Contrasting air voids are seen between two concretes with a 60-year age difference. Photo 3, right. Expansive alkali-aggregate reaction was determined to be the cause of cracking and deterioration.

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cyclic freeze-thaw-related expansion of non-air-entrained paste where the internal stresses during freezing were released by crack development. By contrast, air voids in the 20-year-old concrete helped to release the freezing-related hydraulic stresses without creating any cracking. A continuous profile of air void amount from bottom to top of the 20-year-old concrete showed an almost three-fold increase (~15%) in air content. Every 1% increase in entrained air void usually decreases the compressive strength by 3% to 5%. The strength reduction toward the top was probably due to the increase in the amount of air voids.

3. Concrete surface wall of a store in a Nevada mall showed a network of severe cracking through aggregates and paste, with significant deterioration. What could be the plausible causes?

Polished slab-section and thin-section microscopy of the deteriorated concrete specimen showed the presence of chemically-reactive, cracked, siliceous coarse aggregates containing silica minerals (Photo 3), dark reaction rims surrounding the aggregates, and cracks emanating from within the aggregates. Cracks were wider at the center of aggregates and became narrower toward the rims. Paste-aggregate bonds were very weak. Expansive alkali-aggregate reaction was the cause of cracking and deterioration.

PROPERTIES OF HARDENED CONCRETE	Field evaluations	Non-destructive testing	Physical testing	Chemical testing	Petrographic examination
Admixtures				●	●
Aggregate quality					●
Air content					●
Alkali-aggregate reaction		●			●
Carbonation				●	●
Cement content				●	●
Chloride content				●	
Coating-concrete-substrate adhesion/bonding character	●	●		●	●
Compaction	●				●
Compressive strength		●	●		
Corrosive contaminant				●	●
Cracking	●	●	●		●
Degree of cement hydration					●
Efflorescence, coating failure, discoloration	●			●	●
Fire resistance					●
Freeze-thaw durability			●		●
Honeycomb, pop-outs, segregation, stratification	●				●
Mixing evaluation					●
Mortar quality evaluation				●	●
Paste quality and bonding					●
Permeability			●		●
Proportioning					●
Pull-out strength		●			
Rebar corrosion	●	●		●	●
Scaling, spalling, bleeding, dusting, delamination	●	●			●
Sulfate-resistance					●
Surface hardness		●			
Uniformity	●	●			●
Water/cement ratio				●	●

Table 1: Methods of investigation. *Source: ACI 364.1R, "Guide for Evaluation of Concrete Structures Prior to Rehabilitation," 1993.*

4. Concrete columns in an old bridge in California showed significant spalling at the bottom with progressively less deterioration toward the top. Is the soil corrosive to concrete or is it an internal problem of the concrete itself?

Thin-section examination of the concrete specimen showed the presence of abundant needle-like radiating secondary deposits (ettringites) covering the entire paste, air voids, and fractures, like a termite-attack in an old wooden house. Ettringite is a high-sulfate form of calcium sulfoaluminate hydrate whose creation may cause significant expansion of paste. It forms when a concrete is exposed to moist, sulfate-rich soils or water where the water-soluble sulfates react with hydrated cement paste and form ettringite with significant volume expansion, cracking, and spalling. High permeability and absorptivity of concrete enhance sulfate attack. So the observed spalling seemed mainly due to exposure to sulfate-rich water. Subsequent independent water analysis by a chemical laboratory confirmed a high sulfate concentration in the water consistent with petrographic interpretations.

SUMMARY

Obtaining a desirable compressive strength, maximizing workability and finishability, minimizing shrinkage and cracking, controlling the water/cement ratio, controlling aggregate type, size, and gradation, and controlling the amount of admixtures are common goals of any construction team as it attempts to build durable concrete with excellent performance. An experienced petrographer can play multiple roles in achieving these goals by giving expert opinions on the quality of fresh concrete mix, the reasons behind failures of hardened concrete, or recommendations for better future performances. ■

Dipayan Jana is a consultant petrographer at Materials Technologies, Ossining, N.Y. He has 13 years of experience in petrographic research of various geological and construction materials and is currently conducting research in the application of various petrographic techniques in investigation of common structural problems.