



# Concrete Solutions

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# **APPLICATION OF PETROGRAPHY IN THE CONCRETE REPAIR INDUSTRY**

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**ABSTRACT:** Petrography is a branch of geology, which deals with textural, compositional, and mineralogical description and classification of natural rocks through mainly microscopy and supplemental physicochemical analysis. Petrography has significant applications in quality assurance and failure investigation of concrete and other construction materials. Petrography diagnoses the cause(s) and extent of various concrete deteriorations such as loss of mass and strength by cracking from various shrinkage or expansion mechanisms, surface scaling, spalling, delamination, blistering, dusting, abrasion, mortar lift-off, aggregate pop-out, discoloration, efflorescence, physical and chemical effects of acid/alkali/sulfate/salt/seawater attacks, frost/fire attacks, alkali-aggregate reactions, corrosion of steel in concrete, etc. Proper diagnosis of the cause(s) and mechanism(s) of deterioration and its effects on the existing condition are essential for choosing an appropriate repair material and a successful repair strategy to mitigate or eliminate the distress. Petrography also evaluates the performance of a repair material and method. Petrography can also determine suitable masonry units and mortar in rehabilitation of historic masonry structures. Engineers should consider petrography for evaluating conditions before and after the repair. The repair industry should give a new look to this old science.

## **RÉSUMÉ: APPLICATION DE LA PÉTROGRAPHIE DANS L'INDUSTRIE DE LA RÉPARATION DES BETONS**

La pétrographie est une branche de la géologie, qui traite de la texture, la composition, la description minéralogique et la classification des roches naturelles par des observations microscopiques et des analyses physico-chimiques supplémentaires. La pétrographie a des applications importantes dans la garantie de la qualité et la recherche de causes de rupture du béton et d'autres matériaux de construction. La pétrographie permet une diagnose des causes et de l'ampleur de diverses détériorations des bétons telles que la perte de masse et la fissuration induite par divers mécanismes rétrécissement ou expansion, écaillage, dilatation, décollement, formation de soufflures, abrasion, décollement de mortier, arrachement d'agrégats, décoloration, efflorescence, effets physique et chimique de produits chimiques, des attaques d'acide/alcalin/sulfate/sel/eau de mer, attaques du gel/du feu, corrosion des armatures du béton, etc. Le diagnostic approprié des causes et des mécanismes de la détérioration et ses effets actuels est essentiel pour choisir un matériau approprié et une stratégie de réparation réussie pour atténuer ou éliminer l'évolution néfaste. La pétrographie permet également d'analyser la méthode de réparation et le matériau utilisé. La pétrographie évalue correctement les parties maçonnées et le mortier de réhabilitation dans les structures maçonnées historiques. Les ingénieurs devraient utiliser la pétrographie pour évaluer les états avant et après la réparation. Cette vieille science mériterait plus d'égards.

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**Keywords:** Concrete, repair, petrography, petrographic, alkali silica, ASR, sulfate, seawater, fire, freeze-thaw

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## INTRODUCTION

The microstructure of concrete is its basic anatomy, which controls its properties and performance. Petrography is the 150-year old geological science of description and classification of natural rocks that can provide information about the composition and microstructure of concrete (the man-made rock) and other construction materials. Just as understanding the human anatomy is essential for proper diagnosis and prevention of a disease, an in-depth knowledge of concrete microstructure is essential for diagnosis and successful repair of concrete deterioration. Petrography, like medical science, has many outstanding applications in achieving that knowledge.

This article provides various mechanisms of concrete deterioration that call for repair or rehabilitation, their diagnosis by petrography, the importance of petrography in their repair, and various repair methods and materials. Petrography is useful to:

- Diagnose the type of deterioration and its causes;
- Provide information about the compositional and textural properties of concrete;
- Determine the original concrete materials used and the construction procedures employed;
- Determine the degree, extent, and location of the deterioration;
- Investigate whether the deterioration is related to improper design, construction procedures, materials, or environment;
- Evaluate the current condition of the concrete;
- Evaluate whether the deterioration will continue and the anticipated future damage.

Based on this information, an Engineer decides the appropriate repair material to select and the method to follow. The success of a repair technology depends not necessarily on

the choice of the best-advertised repair material on the market, but on the most suitable material for a particular problem, the repair design or strategy, and the workmanship – all these factors are important after the proper diagnosis of the problem. Petrography is an excellent forensic tool not only to diagnose a distress from various available evidences but also to evaluate the suitability of a repair strategy.

Petrography encompasses the following procedures:

- Detailed visual examinations of a sample as received in the laboratory, or a structure in the field;
- Microscopical examinations of as received, saw-cut, fractured, lapped, polished, etched/stained, or thin (i.e., light-transparent) sections of concrete using a stereomicroscope, petrographic microscope, fluorescent-light microscope, metallurgical microscope, and scanning electron microscope;
- Identification and quantification of crystalline compounds by x-ray diffraction;
- Any supplementary physical, chemical, and thermal analysis needed for detailed description and purpose of the investigation.

The number of petrographic methods and instruments should be adequate for detailed evaluation of the original distressed concrete, the cause of the distress, the type of repair material (if present), the nature of the interface between the repair and the existing concretes, and the efficiency of the repair material and method in controlling the distress. Description of petrographic methods and techniques are beyond the scope of this article and can be found in many industry standards and references such as ASTM C 295 for aggregate petrography, ASTM C 457 for air void analysis in hardened concrete and mortar, ASTM C 856 for examinations of hardened concrete and other construction materials, and ASTM C 1324 for analysis of hardened masonry mortar. Usually, field reconnaissance, detailed written and photographic documentation of the overall condition of the structures and deterioration in the field, documents related to the materials, the mix design and construction procedures of the original concrete, the history of previous repairs, the locations and conditions of joints and bearings, the temperature and moisture condition of the concrete, the environmental exposure, the drainage condition, the weather conditions during construction, the age of the structure, the properties of the concrete during placement, past performance, and service records are some important background information that are helpful for a comprehensive petrographic investigation.

### **Cracking**

Cracking is the most common type of distress that calls for a repair. Cracking occurs when tensile stresses due to volume changes in concrete, loading, or uneven support exceed the tensile strength of concrete. Closed, polygonal-shaped map cracking on the concrete surface is a common consequence of concrete expansion or shrinkage that calls for crack repair. Petrography can diagnose:

- The causes of such cracking- whether it is due to drying shrinkage of the concrete, shrinkage related to the use of high-alkali and high-fineness cement, expansion

- due to alkali-aggregate reactions, cyclic freezing and thawing, or by other mechanisms;
- The width, depth, origin, extent, openness, and network or spatial distribution of such cracks;
  - Whether or not a crack is ‘dormant’ (i.e., will not widen with time) or ‘live’ (will widen with time);
  - Whether or not a crack was formed during the semi-plastic state in the concrete or after hardening due to various physical, chemical, thermal, or structural reasons;
  - The relative age of cracks<sup>1</sup>.

Various petrographic methods of identification of cracks include: (a) examinations of field photographs; (b) examinations of concrete cores at the cylindrical sides; (c) visual and stereo-microscopical examinations of lapped cross-sections containing the cracks; (d) impregnation of concrete with fluorescent dye-mixed very low viscosity epoxy or alcohol to highlight the cracks in UV light; (e) wetting and drying; (f) examinations of very fine microcracks in colored or fluorescent dye-mixed epoxy impregnated large-area thin-sections of concrete in petrographic microscopes; and (g) examinations of cracks in backscatter electron images by using a scanning electron microscope.

With sufficient background information and field reconnaissance, a petrographer can also diagnose the causes of various other types of cracks and surface defects as shown in Table 1.

| <b>Problem</b>                   | <b>Type of Defect</b>  |
|----------------------------------|--|
| <b>Cracking</b>                  | Random cracks on structural components;  |
|                                  | Longitudinal, transverse, or diagonal cracks on concrete slabs   |
|                                  | Plastic shrinkage or settlement cracks   |
|                                  | Cracks on portland cement plaster (stucco), shotcrete, concrete pipe   |
|                                  | Cracks due to uneven support   |
|                                  | Flexural, shear, torsion, punching shear cracks due to overloading   |
|                                  | Cracks due to various expansive chemical reactions in concrete, such as alkali-aggregate reactions, corrosion of steel in concrete, delayed hydration of free lime and/or magnesia, and internal and/or external sulfate attacks in concrete |
|                                  | Cracks induced by early thermal contraction, seasonal/daily temperature fluctuations, temperature gradient in mass concrete, or by fire damage   |
|                                  | Cracks due to abnormal properties or behaviors of cementitious materials   |
|                                  | D-cracking in pavement due to freezing of unsound aggregates   |
|                                  | Cracks due to poor construction practices such as excessive addition of water and cement, inadequate curing, inadequate formwork support, inadequate consolidation, improper installation of control and construction joints, etc.           |
| <b>Concrete Surface Distress</b> | Scaling due to cyclic freezing and thawing of a poorly air entrained, improperly finished, inadequately cured, or inadequately matured concrete <sup>2-4</sup>   |

| Problem | Type of Defect   |
|---------|--|
|         | Scaling due to exposure of a poor quality or improperly constructed concrete to deicing salt, or an inadequately matured concrete to deicing salt at an early stage <sup>4</sup>   |
|         | Scaling by physical salt (sulfate or carbonate salts) attacks (salt hydration distress)  |
|         | Pop-outs due to expansion and fracturing of near-surface, unsound aggregates due to moisture absorption, freezing, oxidation of ferruginous phases in aggregates, or by alkali-silica/carbonate reactions  |
|         | Mortar lift-off due to improper finishing and/or inadequate curing practices   |
|         | Spalling due to corrosion of steel in the concrete, or impact, or surface-parallel, freezing-related cracking  |
|         | Delamination due to cyclic freezing, corrosion of steel, premature finishing prior to the cessation of bleeding, surface crusting (top-down stiffening), prolonged finishing, or machine-trowel finishing an air-entrained slab  |
|         | Dusting due to excessive carbonation of the surface concrete, inadequate curing, finishing in the presence of excess water at the surface, or excessive laitance   |
|         | Discoloration due to long-term weathering, differential water-cementitious materials ratio of paste at the surface, improper finishing/curing of the concrete, excessive laitance, or the presence of calcium chloride set-accelerating admixture in the concrete (that delays hydration of the ferrite phase) |
|         | Staining due to oxidation of ferruginous components in the aggregates  |
|         | Efflorescence due to moisture migration through the concrete followed by dissolution of salts and cement hydration products from the interior and their re-precipitation at the surface  |
|         | Blistering due to entrapment of air and/or water beneath the finished surface due to improper workmanship  |
|         | Surface abrasion due to improper finishing, curing, or abrasive aggregates at the surface  |
|         | Joint/crack edge chipping/spalling by vehicular traffic, thermal expansion of slab, or poor joint sealant;   |

**Table 1** *Types of Defect that can be Examined by Petrographic Methods.*

Any assumption about the cause of cracking without a detailed petrographic examination can lead to an unsuccessful repair. A petrographer can assist an engineer in evaluating if repair is possible and the appropriate repair scheme. Various methods of crack repair are available to the Engineer. These include<sup>1</sup>:

- Epoxy injection under pressure;
- Routing and sealing of fine pattern or larger isolated cracks with a joint sealant;
- Stitching cracks with metal staples;

- Additional reinforcement;
- Drilling and plugging/grouting straight vertical cracks;
- Gravity filling cracks of 0.001-0.08 in. surface widths by low viscosity monomers and resins;
- Portland cement or chemical grouting;
- Drypacking low water content mortar;
- Low-viscosity monomer impregnation that will solidify by polymerization in cracks;
- Placement of bonded overlay, liquid or preformed sheet membranes, and other surface treatments;
- Autogenous healing of cracks by cement hydration and carbonation of calcium hydroxide.

Epoxy resin, polyester resin, synthetic latex, or cement grout are the common fillers for dormant cracks. Elastomers (polyurethane resin, polysulphides, silicones, acrylic gels), mastics (non-drying oils, butyl rubber), thermoplastics (bitumen, asphalt, pitches, tar), and flexible epoxy resin are the flexible sealants for live cracks<sup>1</sup>. Prior to large-scale applications, a small test area should be considered and evaluated petrographically by taking core samples or saw-cut sections for the effectiveness of the repair. Petrography determines the depth of penetration of epoxy or other crack filling compounds into the cracks, the degree of filling of cracks by other methods such as by autogenous healing; and the tightness of bond between the overlay or surface treatment and the original concrete. Core samples having minimum diameters twice the size of the nominal maximum size of coarse aggregate are taken from the repaired cracks by dry or wet drilling (drilled preferably to full depth of the repaired crack) and examined petrographically on the side and in cross-section for determining the depth of epoxy penetration<sup>1</sup> - usually 1 to 2 cores for every 100 ft. (30m) of injection are taken at random locations<sup>1</sup>; penetration is considered adequate if more than 90 percent of the crack is filled with epoxy<sup>1</sup>. Efficiencies of the above-mentioned crack-filling methods and compounds can be evaluated by petrography.

Compressive and splitting tensile strengths of cores containing the epoxy injected repaired cracks (oriented parallel to the loading direction) and cores of sound concrete and nondestructive field testing (ultrasonic pulse velocity, impact echo, and spectral analysis of surface waves) are other common methods of evaluating the quality of epoxy injection<sup>1</sup>.

### **Concrete Surface Distress**

Petrography is the most powerful method of diagnosing the causes and extent of various types of concrete surface distress (scaling, aggregate popout, mortar lift-off, spalling, dusting, discoloration, staining, efflorescence, blistering, delamination, joint or crack edge chipping, surface abrasion) in pavements, sidewalks, driveways, gutters, bridge and parking garage decks, and industrial floors that call for repair. Table 1 lists examples of common concrete surface deteriorations, which can be diagnosed by petrography. In all cases, petrography determines: (a) whether or not a distress is due to improper materials, construction procedures, installation practices, or environmental impacts; (b) the extent and severity of the distress; and (c) the amount of concrete needed to be replaced (i.e.,

full or partial-depth repair). The common repair strategies are surface preparation, partial or full-depth removal of the distressed concrete, and placement of a repair material or a new concrete. Various methods of surface preparation and concrete removal are listed in Table 2<sup>1</sup>:

|   |  |
|---|--|
| <b>Surface Preparation Methods</b>              | Chemical cleaning (detergent scrubbing, low-pressure water cleaning, acid etching);  |
|   | Mechanical removal of thin surface layers of concrete by impacting tools (breakers, scabblers), grinders, and scarifier                  |
|   | Removal of thin surface layers by abrasive equipment such as sandblasters, shotblasters,   |
|   | High-pressure water blasters (dry or wet blast cleaning).  |
| <b>Methods for Concrete Removal<sup>1</sup></b> | Blasting (explosive blasting)  |
|   | Cutting (high/ultra-high pressure water jetting, sawing, diamond wire cutting, mechanical shearing, stitch drilling, or thermal cutting) |
|   | Impacting by hand-held breakers, boom-mounted breakers, or scabblers   |
|   | Milling and scarifying;  |
|   | Hydrodemolition  |
|   | Presplitting by hydraulic splitter, water pulse splitter, or expansive agents  |
|   | Abrading (sandblasting, shotblasting, flame blasting, scarifying, needle scaling, or high-pressure water blasting)                       |

**Table 2** *Methods of Surface Preparation and Concrete Removal*

Improper surface preparation, inadequate concrete removal, or inadequate cleaning of the prepared surface of dirt, dust, oil and grease will all impair the bond to the repair material. Petrography can diagnose the intimacy of the bond between the original and repaired concrete materials. The repair material may be a protective system of sealer, coating, or waterproofing membrane, or an overlay of a cementitious and/or a polymer-based product such as portland cement mortar or concrete, silica fume based portland cement mortar or concrete, polymer concrete, polymer-impregnated concrete, or polymer modified portland cement mortar or concrete. All require intimate bonding to the substrate and should have adequate durability and properties to fulfill the deficiencies of the original concrete. Various cementitious repair materials are dry pack, ferrocement, fiber-reinforced concrete and mortar, cement and chemical grouts, low slump dense concrete, magnesium phosphate cement concrete and mortar, preplaced-aggregate concrete, rapid-setting cements, shotcretes, shrinkage-compensating concrete, and

cement, epoxy or latex based bonding agents<sup>1</sup>. Repair materials are generically classified as<sup>1</sup>: inorganic (portland cement with or without polymer-modification, silicates/silicofluorides), organo-metallic (siliconates, stearates), organo-silicon (silanes, siloxanes, silicones), and solvented, water-borne, or solvent-free organics (thermosetting – epoxy and polyurethanes; acrylic or vinyl thermoplastics, and synthetic rubbers).

The choice of an appropriate repair material depends on various properties such as the bond to distressed concrete, compressive strength, coefficient of thermal expansion, shrinkage, permeability, modulus of elasticity, color, chemical and volume stability, and compatibility of these properties to the existing concrete. The decision of partial or full depth replacement should be based upon a petrographically based diagnosis of the extent and the causes of surface deterioration. Besides repair, other reasons for surface treatments are enhancement of a new surface in appearance (color, texture, opacity, reflectance), chemical resistance (from acid, sulfate, sewage, dairy or brewery products), control of ingress of chloride, CO<sub>2</sub>, oxygen, moisture, and resistance to abrasion, salt crystallization, impact, and skid.

The most important applications of petrography are in evaluating the effectiveness of the bond of the repair material to the existing concrete, effectiveness of various surface preparations and treatments, and evaluations of repair materials and surface treatments in providing the intended performance, durability, resistance to external agents, and improved resistance to mechanical and physical processes.

### **Corrosion of Steel in Concrete**

Corrosion of steel is the most common problem in a reinforced concrete structure that causes cracking, rust staining, spalling, delamination, loss of cross-sectional area of steel, and the loss of concrete cover. Depending on the severity, corrosion of steel can impose a structural threat. Petrography diagnoses: (a) whether the corrosion is chloride-induced and/or carbonation-induced, (b) the pathways of corrosion, (c) the composition and extent (infiltration into paste) of corrosion products, (d) the thickness, quality, and durability of the concrete cover over the corroded steel and its role in causing, delaying, or combating steel corrosion, and (e) the condition of the corroded steel. Petrography also evaluates the quality of the new repair cover, its suitability for corrosion resistance (i.e., whether it is compatible or incompatible with the original substrate to prevent any macrocell formation), and the nature of the bond between the repair cover and the substrate. The degree of bonding of the repair cover to the substrate can be evaluated by petrographic examinations of cores or saw-cut sections through the repair and substrate concretes.

In repair of corrosion-induced delamination, the judgment of full cover repair versus surface patch repair should be based upon petrography. If the depth of spalling or delamination extends to the level of the corroded reinforcing bars, then the entire concrete cover should be replaced and the corroded surface of the steel should be thoroughly cleaned. Isolated patching of the delaminated surface without determining the actual depth of corrosion may not necessarily guarantee the corrosion resistance if the supply of moisture, oxygen, and chloride is still available through the pre-existing cracks underneath the repaired patch or through newly formed cracks on the repair patch. The effectiveness of various methods of corrosion protection such as improved quality and depth of concrete cover, cathodic protection, use of epoxy-coated or galvanized (zinc-

coated) reinforcing steel, corrosion inhibiting admixtures, and re-alkalisation can be evaluated by petrographic examinations of the treated and untreated concretes.

### **Alkali-Aggregate Reactions**

If the alkali-content of Portland cement is higher than the optimum limit (i.e., 0.60 Na<sub>2</sub>O equivalent), under favorable moisture conditions (i.e., greater than 80 relative humidity at 23°C), certain aggregates in concrete may undergo reactions with cement alkalis and form an alkali-silica reaction product. The hydroxyl ions in concrete pore solutions break down the silicon-oxygen bonds in the reactive siliceous aggregate surfaces and form alkali-silica reaction gel. Absorption of moisture causes swelling of the gel, and possible expansion of concrete, which, if exceeds the tensile strength of concrete leads to cracking. Reactive aggregate, high alkali, and moisture are the three essential ingredients of ASR, all of which are needed together for the reaction to occur. Examples of potentially alkali-silica reactive aggregates are opaline, microcrystalline, or chalcedonic silica in different rocks like chert, flint, siliceous shale, vesicular basalt, or as microscopic veinlets in innocuous carbonate rocks; strained quartz and other silica polymorphs (tridymite and cristobalite); volcanic glasses like obsidian and pumice; and glassy to cryptocrystalline matrix of fine-grained siliceous volcanic rocks such as rhyolite, dacite, andesite, etc.

In a concrete structure with suspected ASR, the petrographic diagnosis starts with the detection of the following evidences:

- Alkali-silica reactive coarse or fine aggregate particles (mere detection of potentially reactive particles, however, does not necessarily indicate such a reaction unless favorable alkali and moisture conditions are also present and the reaction products are detected);
- Internal radial or peripheral cracking in coarse aggregate particles with cracks emanating from the reactive particles and extending into the mortar or paste fraction;
- Dark reaction rims at the periphery of the reactive particles (reaction rims, unlike weathering rims on aggregate surfaces are abruptly truncated against the intersecting air voids);
- Opaque, translucent, glassy clear to white, massive (dense) optically amorphous (isotropic), spongy (textured, grainy), or finely crystalline (lamellar or rosette-like, needle or rod-like, or, blade-like crystals), rubbery, waxy, viscous or watery (when fresh), or, hard and brittle (when dried) alkali-silica gel and microcrystalline reaction products occurring as fracture fillings in aggregates, inside the cracks in paste, as linings or fillings in air voids, as reaction rims around the aggregates, or as exudations and efflorescence on the surface;
- Strong signal of high alkalis in the reaction rims or in alkali-silica gel deposits in cracks or voids in SEM-EDS examination; SEM-EDS analysis further provides the spatial variation of gel compositions from one place to another;
- Weak paste-aggregate bond due to overall expansion of aggregates;

- Map or pattern cracking of concrete surfaces due to volume increase by direct in-place enlargement of the affected aggregate by gel formations and moisture absorption of gel;
- Reactive silica inclusions in otherwise non-reactive carbonate rocks;
- The characteristic greenish yellow fluorescence of ASR gel on moist, freshly fractured surface treated with uranyl acetate solution and viewed in dark with short wavelength UV light;
- Slow exudation of soft, white ASR gel efflorescence on the exposed surface of an ASR-affected concrete sample after wetting and drying;
- Oil immersion mount examination (in a petrographic microscope) of ASR gel deposits extracted from a shiny gel-lined void, where gel shows the characteristic morphology and optical properties.

Identification of ASR gel is an unequivocal evidence of such a reaction in concrete, but identification of reaction does not necessarily indicate ASR as the sole cause of deterioration unless no other expansive mechanism beside the ASR is found in the affected concrete. Before any repair scheme is suggested, petrography should be used not only to rapidly diagnose ASR but also to investigate whether cracking and deterioration are mainly due to ASR or, instead, due to some other mechanisms (e.g., cyclic freezing and thawing, corrosion of embedded steel, drying shrinkage, chemical attack), which have preceded and therefore set forth the stage for ASR to occur. Epoxy-injection of cracks formed by ASR, lithium salt treatment, installation of a waterproofing membrane or sealer on the surface to prevent moisture penetration are some common repair strategies followed in the rehabilitation of an ASR-affected structure.

Certain dolomitic limestone or calcic dolomite coarse aggregates (containing substantial amounts of both dolomite and calcite crystals, and a clay-rich acid insoluble residue), in the presence of high-alkali cement can create expansion and cracking in concrete by alkali-carbonate reaction (ACR). The typical ACR mechanism involves initial 'dedolomitization' reaction between the dolomite crystals in carbonate coarse aggregate with alkali hydroxide in pore solution forming brucite, calcite and alkali-carbonate. Subsequent expansion, either due to growth and rearrangement of solid high volume reaction products (especially brucite), or, due to absorption of water and alkali ions into the reaction products and/or into the exposed acid insoluble clay residues in the aggregate matrix can induce cracking in concrete. The alkali-carbonate reactive aggregates show a characteristic composition of almost equal proportions of calcite and dolomite and a characteristic texture of relatively large, rhombic crystals of dolomite set in a finer-grained matrix of calcite, clay and fine-grained quartz. Typical ACR texture shows: (a) development of fibrous brucite reaction rims around the dolomite rhombs; (b) a variation in Ca/Mg (or calcite/dolomite) ratio in the reacted aggregate particle from the core to the rim (which can be determined from SEM-EDS or XRD analysis); and (c) sometimes reaction rims in the reacted particles in concrete. Cracking by ACR is similar to that formed by ASR – petrography is used to diagnose the cause of cracking, based on which an appropriate repair strategy is followed.

### **Frost Attack and Freeze-Thaw Damage**

Exposure of unprotected, freshly placed concrete to subfreezing temperatures can cause early stiffening, strength loss due to freezing of mix water, and other problems due to restricted cement hydration in cold weather. Petrography determines the depth of frost attack in plastic or semi-plastic concrete from ice crystal imprints and softened, inadequately hydrated paste, and the depth/amount of frozen concrete needed to be replaced.

Cyclic freezing and thawing of a non-air-entrained or poorly air entrained hardened concrete at critically water-saturated conditions causes deterioration of sidewalks, pavements, driveways, bridge decks and other outdoor slabs including scaling, spalling, and surface-parallel cracking. Petrography determines the depth of freeze-thaw damage and the extent of removal of the deteriorated concrete for repair. Petrography diagnoses whether cracking, spalling or scaling of concrete by cyclic freezing and thawing is due to a poor air-void system, unsound aggregates, low strength, soft and porous nature of paste, improper finishing practices, inadequate curing, premature exposure to deicing salts at an early age, or physicochemical actions of deicing salts on the concrete.

Petrography also detects the unsound aggregate particles that are responsible for aggregate popouts or D-cracking in concrete pavements. After the repair, freeze-thaw durability and performance of repair material, thickness and intimacy of the bond of various repair materials (e.g., mortar topping, concrete overlay, cement and/or polymer based composite, high performance concrete or cementitious products) to the original concrete substrate (that has been ground down to the sound concrete) can be evaluated by petrographic examination of cores or saw-cut sections.

### **Fire Damage Assessment**

In a fire-damaged concrete structure, petrography determines the severity and extension of fire from the degree of thermal alteration of the concrete, the depth of the extension of fire-induced alterations, deteriorations from dehydration, decomposition, and discoloration of cement paste matrix in concrete, the depth of thermal cracking and spalling, and phase transitions (mineralogical changes) in concrete due to exposure to high temperatures. Determination of the maximum temperature attained and the extent of damage are the first steps in a repair, which can be determined from petrographic examinations of lapped and thin-sections of core samples taken from the fire-damaged components. Petrography can diagnose the maximum temperature attained from the characteristic discoloration, microcracking, and changes in mineralogical and optical properties of cement paste at high temperatures. At temperatures above 250-300°C, concrete commonly shows a change in color from normal gray to pink or red due to dehydration and oxidation of iron hydroxide compounds in siliceous aggregates; at 500-600°C a further color change from pink/red to purple/whitish gray occurs due to the reaction between ferric oxide and lime forming light-colored calcium ferrites. With further increase in temperature, the color changes to buff at 900°C-1200°C; and to yellow at above 1200°C. The pink discoloration at 300°C coincides with the beginning of heat-induced loss of compressive strength of the concrete. Fire-induced dehydration of cement hydration products and subsequent cracking cause a reduction in compressive strength of concrete, which continues linearly with temperature – almost 80 percent loss of strength occurs by 650°C, and almost complete loss of strength occurs by 1000°C.

Initial surface crazing, cracking, initial explosive spalling, strength loss, and later slow, gradual spalling of concrete are the common consequences of fire attack. Cracking on various scales and spalling of concrete can occur by:

- Differential thermal expansions of successive layers of concrete;
- Differential thermal expansions of aggregate particles, and shrinkage of paste (especially above 250°C);
- Anisotropic thermal behavior of different crystalline constituents in aggregates;
- Internal vapor pressure of inward advancing moisture front that turns to a superheated steam by the superimposed thermal front;
- Expansive phase transitions of minerals such as the transformation of quartz from alpha to beta form at 573°C in concrete containing quartz, chert, or flint aggregate;
- Re-hydration of calcium oxide (in the presence of moisture after fire) that was formed either by thermal dehydration of calcium hydroxide component of cement hydration above 400-450°C or by calcining limestone aggregate or carbonated concrete by prolonged heating above 900°C.

All these mechanisms of cracking and spalling can be diagnosed by petrography. Lightweight and slag aggregates provide better fire resistance to concrete than normal weight aggregates. Carbonate aggregates provide better fire-resistance than siliceous aggregates. Repair of a fire-damaged structure should be done after detailed petrographic examinations of the intensity and the depth of fire-damage in the structure.

### **Chemical Attack**

Sulfates, chlorides, and acidic solutions cause chemical alteration and decomposition of concrete, and loss of mass and strength. Interaction with these chemicals leaves several compositional imprints (e.g., high sulfate/chloride/low pH levels in concrete) and microstructural signatures in concrete such as leaching and decomposition of paste, cracking due to expansive reactions between the chemical agents and the cement hydration products, and the presence of the products of such reactions in cracks, voids, and confined or open spaces in paste. Petrography, along with supplementary chemical analysis can determine the chemical and microstructural imprints to properly diagnose the cause of distress. Following are some examples of common chemical deteriorations in concrete, which can be diagnosed by petrography:

- Attack of external sodium, calcium, magnesium, or ammonium sulfate solutions causes cracking, exfoliation, softening, loss of mass, and loss of strength of concrete by decomposition of cement hydration products, expansive formation of ettringite and/or gypsum in paste, and precipitation of these reaction products in voids and surface-parallel cracks.
- Reactions of sulfate and carbonate solutions to the aluminates phases in concrete in cold and humid conditions can cause thaumasite attack.
- Internal sulfate attack in concrete causes expansion of paste and cracking by sulfates released at a late stage from the paste at moist conditions (delayed ettringite formation), or, from sulfates or sulfides in aggregates.

- Acid attack shows characteristic compositional zonation of paste, lack of the calcium hydroxide component of cement hydration in the altered zone due to leaching, a drop of concrete pH, and preferential dissolution of paste relative to the siliceous aggregates, causing proud exposure of siliceous aggregates above the dissolved surface of the paste. The rate of attack of concrete by acid is rapid for hydrochloric, nitric, sulfuric, and concentrated organic (acetic, formic, lactic) acids; moderate for phosphoric, tannic, and humic acid; slow for carbonic acid; and negligible for oxalic acid. The acidic nature of many dairy/brewery products can cause slow disintegration of concrete.
- Acid rain by dissolved SO<sub>2</sub>, CO<sub>2</sub>, or NO<sub>2</sub> in air can cause cosmetic distress by etching of the concrete surface.
- Sulfuric acid attack on the moist, inner, aerated portion of the concrete liner of sewage pipes by aerobic, sulfur-oxidizing bacteria causes dissolution of paste, precipitation of gypsum at the crown, and loss of thickness of the lining.
- Exposure of PCCP and RCP pipes to acidic soil can cause severe loss of pipe thickness.
- Chloride attack can form calcium chloroaluminate and Friedel's salt in the paste and staining, rusting, cracking, spalling of concrete by galvanic corrosion of embedded ferrous and nonferrous (aluminum, zinc, copper, and lead) metals.
- Seawater causes magnesium sulfate/chloride attack (petrographically diagnosed by formation of brucite, magnesium silicate hydrate, and gypsum/ettringite by reactions with cement hydration products), dissolved CO<sub>2</sub> attack (petrographically diagnosed by formation of aragonite, calcium carboaluminate hydrate, gypsum, thaumasite, silica gel), loss of mass by lime leaching, chloride attack and corrosion of steel, and salt weathering due to cyclic wetting and drying in the splash zone (the last one is a physical attack).

In each of the above-mentioned types of attack, petrography can determine the cause of the attack, the agent of distress, the depth and degree of chemical alteration, the role of the quality, composition, and permeability of the concrete in mitigating or advancing the attack, the importance of the various types of surface treatments (film-forming coating, film-forming or penetrating sealers, surface hardeners) in mitigating the chemical ingress, the appropriate type of repair material and the method to use to prevent future ingress, and most importantly, the depth of the distressed concrete that is needed to be replaced.

## **CONCLUSIONS**

Petrography has the following applications in the concrete repair industry<sup>2</sup>

- Proper diagnosis of the problem to decide the appropriate repair scheme;
- Determination of the depth, extent, and severity of the distress and depth of removal of the distressed concrete;
- Determination of whether the problem is ongoing and how much damage is expected in the future;
- Determination of the detailed composition and microstructure of the existing materials;

- Evaluation of relative influences of materials, construction procedures, design, and environmental exposure conditions in causing a deterioration;
- Assistance in an effective choice of a repair material based on the determination of the type of the original material to be repaired;
- Determination of the type and composition of an architectural concrete or historic masonry mortar so that a matching concrete or mortar material can be found for the repair;
- Determining whether any damage was done on the concrete substrate during the removal of the deteriorated concrete;
- Evaluation of the resistance of a concrete cover to ingress of chloride, oxygen, and moisture during repair of damage due to steel corrosion;
- Evaluation of improved durability of a damaged structure after repair;
- Anticipated performance and durability of a repair material based on evaluation of its various properties such as composition, drying shrinkage, thermal expansion, density, permeability, resistance to freezing and thawing and scaling, resistance to ingress of external deleterious agents, alkali-aggregate and other internal expansive reactions, abrasion resistance, degree of cement hydration in cementitious repair materials and curing, effects of hot or cold weather on repair material, etc.;
- Nature or intimacy of bond between the original concrete and repair materials;
- Evaluating compatibility/incompatibility between the repair material and the existing concrete;
- Evaluation of various causes of repair failures due to improper repair material, improper design, poor workmanship, or continuation of ongoing concrete deterioration to the repair material;
- Evaluation of whether the manufacturer's recommendation was followed with the repair material and its installation procedure; .....the list goes on.

Obviously, the importance of petrography is significant. It is a cost-effective, investigative science, which every repair engineer should consider. In many cases, more importance has been paid on diagnosing the causes of repair failure or rehabilitation of a structure without thorough investigation of what went wrong in the first place. It is the lack of that proper pre-repair/reconstruction diagnosis of the problem that causes improper implementation and subsequent failure of a repair or reconstruction scheme. Even the best, most suitable material or method may not necessarily work due to the wrong interpretation of the distress. Many times an obvious but unfortunate wrong assumption is made about the cause of distress without any proper investigation, which leads to improper application of repair material or method.

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