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Concrete Petrography: An Essential Component of Cost-effective Decision Making for Infrastructure Renewal

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Abstract

With provincial and municipal infrastructure budgets as stretched as ever, and greater accountability demanded with respect to sustainability in rehabilitation programs, the salvage value of existing infrastructure is of critical importance. From a sustainable development perspective, there is an imperative to utilize as much as possible of existing infrastructure, and to minimize waste generation when undertaking renewals. A key factor in this process, especially with respect to transportation structures, is to decide how much of the existing concrete can be salvaged. This is not just a question of establishing existing condition but predicting future life for a complex construction material that may already be 50, or more, years old. Unfortunately, the practical evaluation of old concrete is not as simple as reviewing the results of a series of standard laboratory tests such as compressive, tensile, or flexural strength, chloride profiling, and air voids content. Improving our ability to reliably determine the in-situ health of old concrete can support cost-saving engineering decisions to retain bridge piers and abutments while only replacing the deck; reline an existing tunnel rather than replace it; or to leave old concrete pavement in place beneath a multilane freeway. The techniques are varied and project-specific. They rely on an understanding of the components of structural concrete: steel, aggregates, and cement paste, and how they interact and deteriorate. The evaluation techniques comprise destructive and non-destructive testing but with the essential component of concrete petrography. This latter technique can detect the early stages of destructive chemical reactions and may be used to determine to what stage such reactions have progressed and might continue to progress; the signs of freeze-thaw damage; the impact on concrete integrity from the corrosion of reinforcing steel; and other aspects. With this detailed knowledge, the appropriate remedial solutions can be identified, taking advantage of the vast array of effective modern specialty concrete repair products and techniques that are available. This paper discusses the approaches to the condition evaluation of old concrete structures with a focus on concrete petrography and presents some case studies to illustrate the benefits of an effective concrete health check before deciding on full reconstruction.

INTRODUCTION

In this paper, we examine the ways in which the use of petrographic examination of concrete can support assessments of the service life of concrete. The contribution that concrete petrography can provide, within the context of a larger-based assessment of a concrete structure/s, can eliminate guesswork and confirm or refute unclear or assumed properties of the concrete, enabling a decisive selection when the choices are "replace" or rehabilitate".

In this way, cost-effective solutions can be achieved that assist in management of infrastructure that is (1) damaged / exhibits deterioration (2) reaching or already past its design service life and/or (3) under consideration for expansion, upgrading, or replacement.

BRIEF DESCRIPTION OF CONCRETE PETROGRAPHY

Concrete petrography is a microscopy-based method wherein samples of concrete are examined in the same way that geologic materials are examined. The word "petrography" in essence means "rock description", and in common usage, it is inferred that the method involves the use of microscopes and is carried out using the same techniques that are applied to the examination and description of rocks and minerals.

The most common approach for concrete petrography is given in ASTM C856, *"Petrographic Examination of Hardened Concrete"* (ASTM 2020). Supplemental, non-microscopy analytical techniques such as chemical testing, scanning electron microscopy and physical testing can be used to augment the visual procedures, as needed.

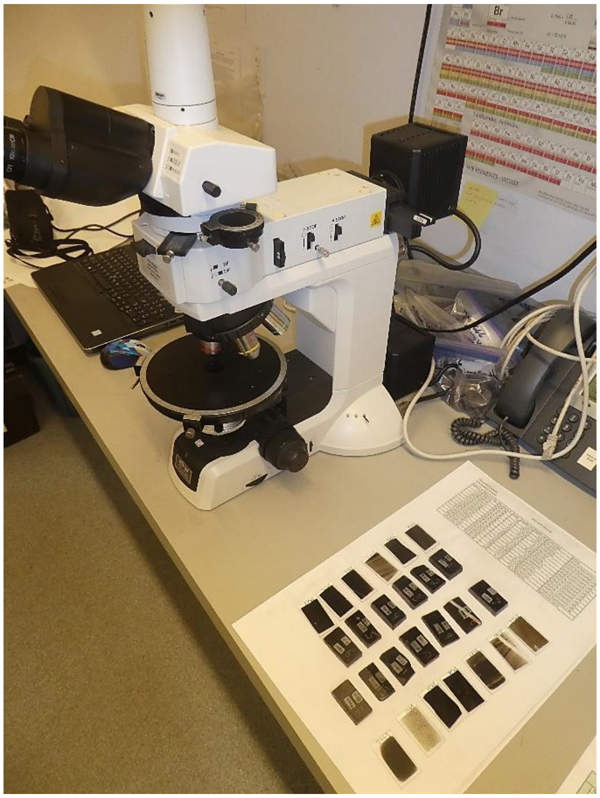


Figure 1: Polarizing microscope used in petrography.

Typically, petrographic examination begins with macroscopic examination of the concrete sample, which can be a drilled core, a cast cylinder test sample, a sawcut sample or even an irregular lump or broken chunk of concrete. The features and characteristics of the sample are notated, and images of the sample taken to illustrate. Usually, the sample is cut using a diamond-tipped blade to prepare smaller specimens that are suitable for examination under the microscope. The sawcut samples are polished to enable examination under a stereoscopic microscope.

Typically, thin-section mounts are prepared of the concrete as well, to enable an in-depth examination in the polarizing microscope (Figure 1). The size and number of thin-section mounts will depend upon the nature of the examination, the size of the sample, and the nominal maximum size and amount of coarse aggregate.

Petrographic Data

Information that is generated in the petrographic examination of concrete can include the following:

- Concrete consolidation/density
- Concrete aggregates:
    - Proportion of fine to coarse
    - Nominal size
    - Grading and distribution
    - Lithology – rock and mineral types
    - Quarried or gravel pit sourced
    - General quality
    - Shape
    - Reactive rock/mineral types
- Paste characteristics
    - Carbonated (yes/no; heavily/slightly; depth)
    - Hardness
    - Lustre
    - Air-entrained (yes/no)
    - Colour
- Deterioration
    - Type
    - Severity
    - Extent
    - Effects

Based on the examination a petrographic report is prepared that describes the findings and highlights the key issues with respect to the concrete condition that need to be considered by the structural engineer when evaluating options for repair, rehabilitation of replacements.

CASE STUDY EXAMPLES

Airport concrete – Two airports: one in the western United States, the second in central Canada

Evaluation of concrete airfield pavements was undertaken to determine the cause/s of deterioration that had been observed at two airports.

In both cases, alkali-silica reaction was considered a possible cause of the deterioration observed in the concrete. This was evidenced by map cracking, discolouration along crack traces, and occasional popouts in concrete flatwork, and map cracking, discolouration, and exudations in structural elements such as columns and curbs. However, both airports are located in areas that are subject to freezing conditions and snowfall, and are thus subject to application of de-icing salts as well as airplane de-icers; in both cases, the concrete was less than twenty years old.

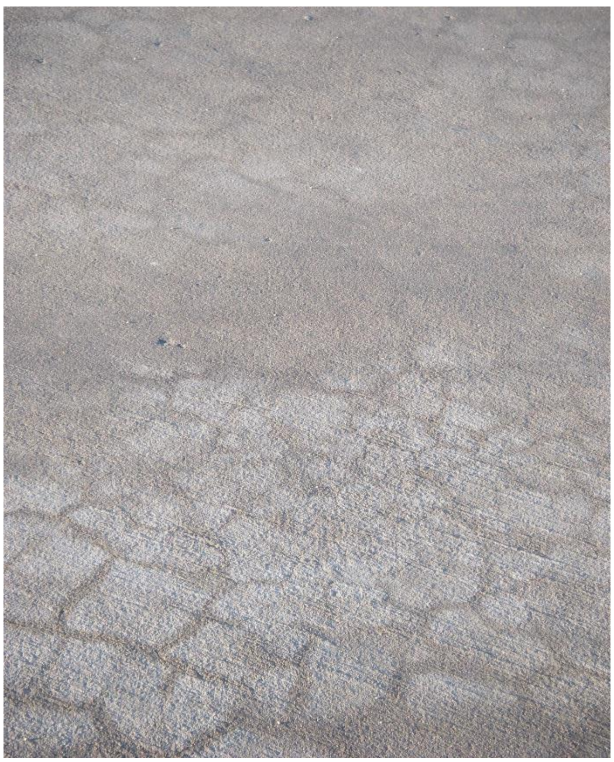
Samples of concrete were extracted at both sites from a series of locations that were representative of the range of condition of deterioration, from “slight/none” to “significant”.

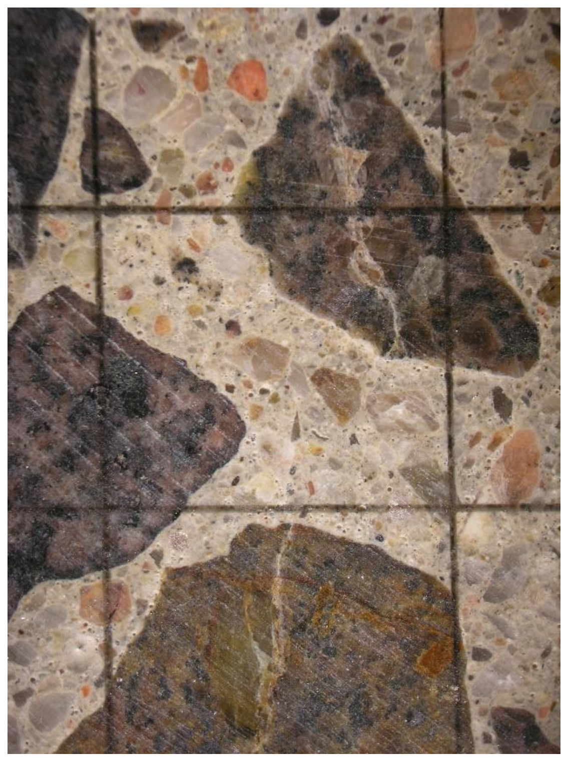
Petrographic examinations were conducted on the cores, followed by running the Damage Rating Index (DRI) method (Shrimer 2018), which provides a numeric measure of the amount of features observed in the sample that are considered to be related to ASR.

Airport 1, western United States

This airport pavement exhibited widespread occurrence of map cracking and typical ASR-discolouration along crack traces (Figure 2). Numerous cores were obtained and examined.

Airport 1





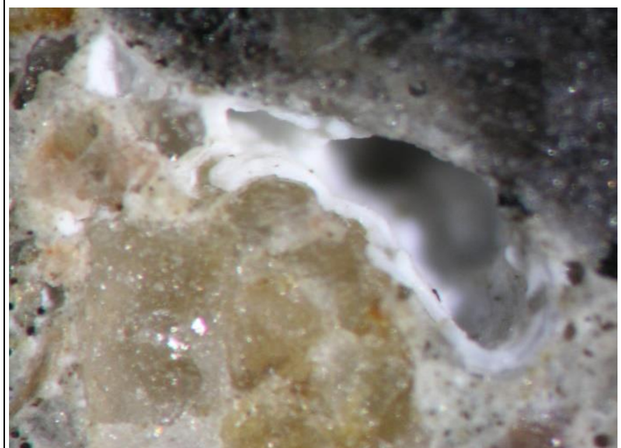
Taxiway pavement concrete exhibiting extensive map cracking. Area measures about 2. 5 m across.	Detail of lapped core face showing 10 mm-square grid used for Damage Rating Index (DRI) test. Image illustrates ASR-gel-filled cracks extending through aggregate particles and into adjacent paste.
	
DRI sample showing partly consumed aggregate at centre, and ASR-gel-lined crack extending through reaction rimmed aggregate particles into paste. View is about 15 mm across.	Detail showing an ASR-gel-lined cavity in concrete next to a reactive aggregate particle. View is about 4 mm across.

Figure 2: Airport pavement concrete damaged by alkali-aggregate reactivity.

DRI values for the US airport pavements ranged from a low value of “8” to a high value of “427”, which correspond to classifications of “negligible” or “minor” ASR severity and associated damage to “significant” as shown in Table 1.

Table 1: Damage Rating Index (DRI) scale of damage

DRI RANGE	ASR SEVERITY
0 - 40	Negligible
40 – 125	Minor
125 - 300	Moderate
300 – 500	Significant
500 – 650	Serious
>650	Very Serious

The DRI data were considered in the context of other physical, chemical, and engineering performance data for development of management, rehabilitation, and monitoring strategies for the taxiway pavement.

Airport 2, Canada

In the second airport, the observation of map cracking and efflorescence in various concrete elements caused engineering staff to undertake initial core sampling at the site as part of a program of physical characterization of the concrete elements. Some of the concrete samples were from concrete pavement and others were obtained from structural building elements such as columns and walls.

The core testing program included compressive strength, air voids and petrographic examination. An example of map cracking and ASR gel are shown in Figure 3.

<table>
<tr><td colspan="2">Airport 2</td></tr>
<tr><td></td><td></td></tr>
<tr><td>View of concrete wall showing map cracking and discolouration. View is about 2 m wide.</td><td>Detail of polished core surface showing ASR gel occupying crack along face of reacting aggregate particle. View is 9 mm.</td></tr>
</table>

Figure 3: ASR-damaged concrete from airport structures

The concrete ranged from about 15 years to about 20 years in age. Details about the construction -- such as mix designs, inspection and testing results, aggregate sources used, cement and supplementary cementitious materials contents -- were not available at the time of the investigation. The ASR damage was quite extensive (Figure 4). A program of concrete repair and partial replacement was warranted.

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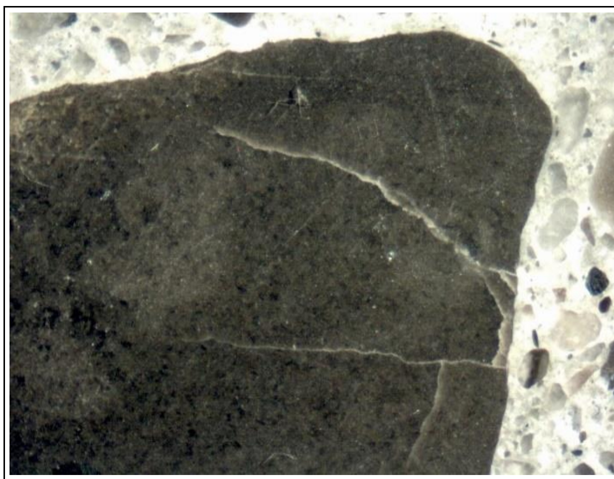
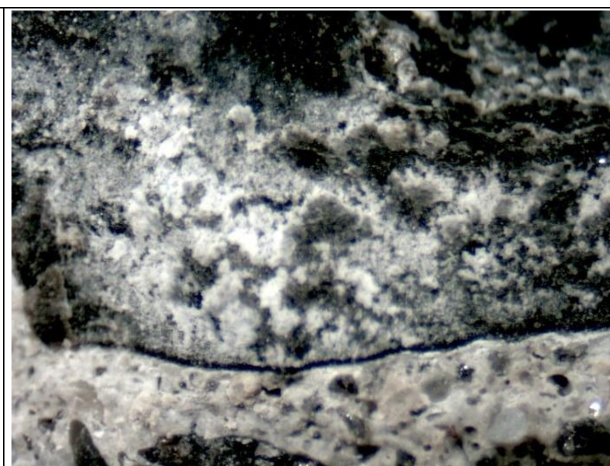
<tr><td></td><td></td></tr>
<tr><td>Microscope view at 10x magnification showing ASR-gel-filled cracks extending through a siliceous aggregate into the surrounding paste. Field of view is 8.7 mm.</td><td>ASR gel is observed on a reacting aggregate particle with a darkened reaction rim. Field of view is about 8.5 mm.</td></tr>
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Figure 4: ASR-damaged aggregate giving rise to concrete map cracking

Canal Bridge, Ontario

A bridge that was constructed in the 1920s was scheduled to be replaced. Serving a small community as the only link across a canal, the bridge was critically important. However, facing budgetary constraints, the municipality required an assessment of the condition of the concrete of the foundation piers, which had sustained nearly one hundred years of service in an environment that experienced freeze-thaw cycles, water saturation, traffic loading and the use of de-icing salts.

Although the decision had been taken to replace the bridge deck, evaluation of the possible rehabilitation and re-use of the piers was undertaken in order to consider alternate budgetary scenarios that might represent lower costs than outright replacement. Petrographic examination of cores (Figure 5), along with DRI assessments, supported the service-life and economic analyses. Data obtained from petrographic examination indicated that there was variable intensity not only of freeze-thaw damage but also of ASR-related damage in the concrete and thus the piers needed to be replaced.

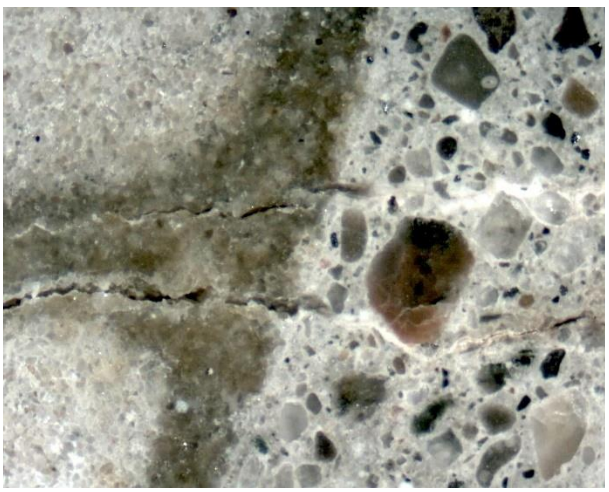
	
Microscope view at 10x magnification showing ASR-gel-filled cracks extending from a sandstone aggregate at left into the surrounding paste. Field of view is 8.7 mm.	Cracking in core includes ASR-induced as well as freeze-thaw induced cracks extending through paste and aggregates. Field of view is about 100 mm.

Figure 5: ASR and freeze-thaw damage in bridge piers requiring replacement

Urban overpass, Vancouver region

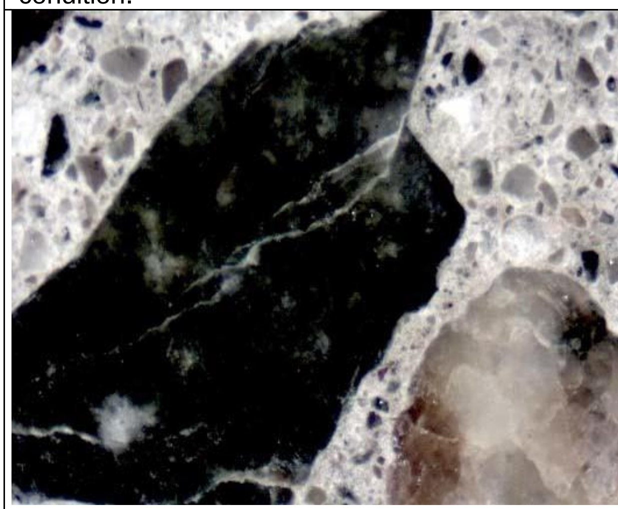
A nearly sixty-five-year-old four lane overpass was evaluated with respect to overall concrete condition, since it was to be incorporated into the design for a new major bridge project.

To determine whether it would be possible to avoid demolition and replacement of the existing overpass, evaluation of the current condition was undertaken; this work included a detailed field condition survey, extraction of cores, testing of the cores for various physical parameters, petrographic examination of the concrete and Damage Rating Index testing, after the petrographic work indicated that the concrete was affected by ASR.

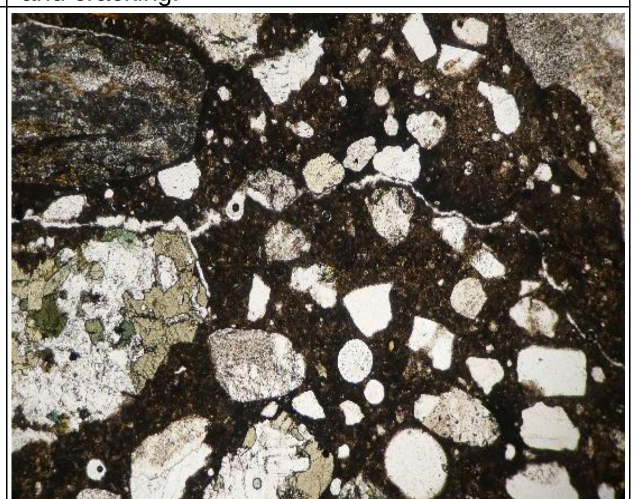
In the field survey, the overall condition of the concrete elements was found to be good, with only minor concrete deterioration noted in limited amounts (Figure 6).

Walls and underside of slab, showing general condition.

Detail of east wall showing minor efflorescence and cracking.



Photomicrograph, 10x magnification, showing ASR-gel-filled cracks extending from a siliceous aggregate at left into the surrounding paste. Field of view is 8.7 mm.



Thin section, viewed in plane polarized light, shows cracks that extend through paste and along aggregates, some with ASR gel. View is at a magnification of 50x, 3 mm across.

Figure 6: 65-year-old overpass concrete with minor ASR damage allowing continued serviceability.

Evidence for ASR damage in the concrete was, similarly, found to be limited in extent and location.

The Petrographic examination noted that there was some evidence that ASR had affected the concrete (Figure 6), but the severity of the reaction and the amount of damage associated with the reaction had not been quantified, other than a conclusion that it was not severe.

Since the engineering team required further information concerning the state of ASR in the concrete, a Damage Rating Index (DRI) test was commissioned. The result was a DRI of “87”, which is consistent with a severity classification of “minor”, thereby confirming the previous petrographic results.

It was concluded that the structural concrete elements were of adequate quality to provide extended service life that would enable retention of the existing structure without the need to demolish and reconstruct.

Fire-damaged concrete - Hamilton, Edmonton, and Toronto

Three concrete transportation structures were the sites of fires that occurred for various reasons, including truck collisions. The infrastructure owners required assessment of the severity and extent of damage in the affected concrete elements, to determine whether rehabilitation approaches would be required, to what depth and for what components, or whether removal and reconstruction would be required. While structural concrete is reasonably resistant to damage from fire, when exposed to extended temperatures above about 300°C permanent reduction in compressive strength can result. Reinforcing steel can also be affected.

In addition to taking cores for unconfined compression tests, cores were drilled to enable petrographic examination of the concrete to determine the characteristics of the cement paste, the aggregates, and the overall physical condition of the concrete. The petrographic examination of a cut section of concrete allows the impact of high temperatures at the surface of concrete to be identified. The transition from affected to unaffected concrete can be established allowing the required depth of concrete removal and replacement necessary to address the problem (Figures 7 and 8).

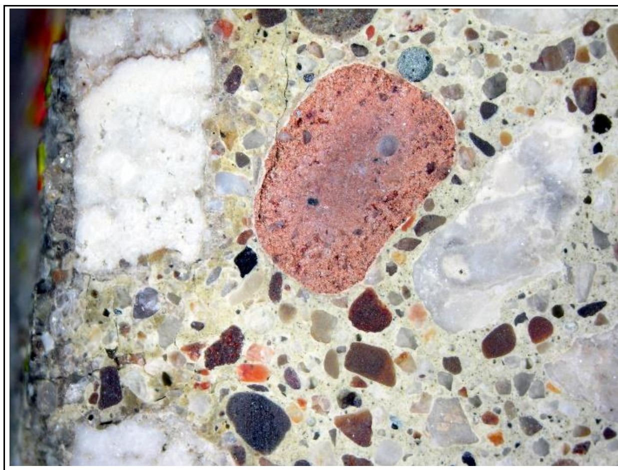
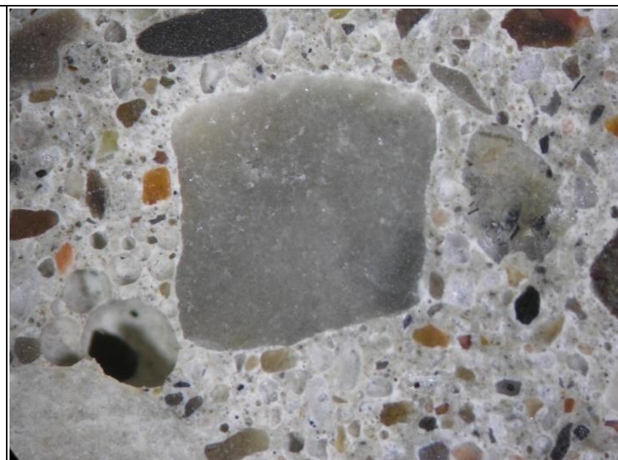
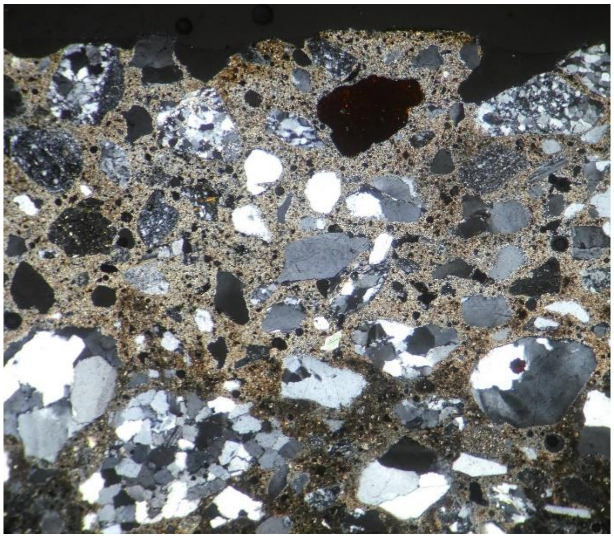
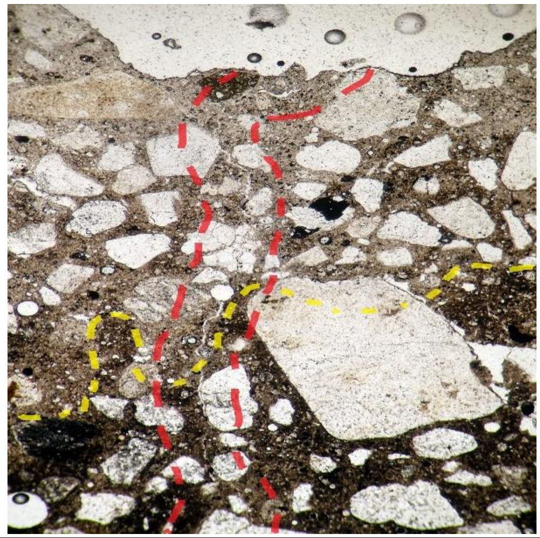
	

Photo showing discoloured paste extending from outer surface at left to a depth of about 20 mm. Cracks extend through paste along aggregate. Field of view is 25 mm.	Concrete from about 50 mm below the outer surface exhibits typical light grey paste, no cracks, and unaffected aggregates. Field of view is about 25 mm across.

Figure 7: Microscopic images of concrete affected by fire and high temperatures.





Thin-section viewed in cross-polarized light, with outer surface at top. The paste colour is light, indicating porous and heat-affected cement paste. At a depth of about 2 mm the paste transitions to normal density as indicated by the darker colour observed in this thin-section view, which is seen at a magnification of 50x.	Another thin-section view, seen in plane polarized light. Light-coloured paste here denotes fire-damaged, weaker, and more porous material. One crack extends vertically into concrete. Yellow dashed line indicates extent of fire-damaged paste. Mag.50x; field of view is about 3 mm across.

Figure 8: Petrography used to establish depth of fire-damaged concrete

The petrographic data was confirmed by other observations and tests made and concluded that the concrete elements were permanently affected but only to moderate depths, enabling rehabilitation work to proceed without the need for wholesale reconstruction of the elements.

Two Examples of Assessing Concrete Quality in Composite Pavements

QEW Widening, Ontario

The Queen Elizabeth Way through St. Catharines (Figure 9), Ontario was originally constructed in 1937 as a concrete highway with two lanes in each direction and a grass median. Over the years it was improved and overlayed with hot mix asphalt and became a composite pavement. In 2004 an investigation was undertaken to allow a 7-kilometer section of the highway to be upgraded to six through lanes. The design traffic volumes were over 100,000 vehicles per day with 17% commercial traffic.

Figure 9: Section of QEW to be widened.

A critical question at the time was whether the old concrete pavement could be left in place or needed to be completely reconstructed. Given the major upgrading works planned, this was considered to be the best opportunity to remove the old concrete if it could not be counted on to perform well over the next 50 to 100 years. The conventional drilling and coring investigation were supplemented with Falling Weight Deflectometer (FWD) and Ground Penetrating Radar (GPR) surveys to map the continuity of the underlying concrete. The average concrete thickness was 230 mm, but it was supporting on average 230 mm of hot mix asphalt overlay that had been placed over the highway’s 60 year plus service life.

The recovered concrete cores were examined visually (Figure 10) and select cores were examined petrographically. The majority of the concrete examined was of very good quality with well distributed fine and coarse aggregate, no evidence of deleterious reactions from alkali-silica reaction, no evidence of freeze-thaw damage or salt scaling. The measured compressive strengths were an average of 68 MPa. Ultimately, over 80% of the old concrete was considered suitable to remain. The areas to be reconstructed were mainly the result of poor joints and other performance issues not related to the concrete quality.

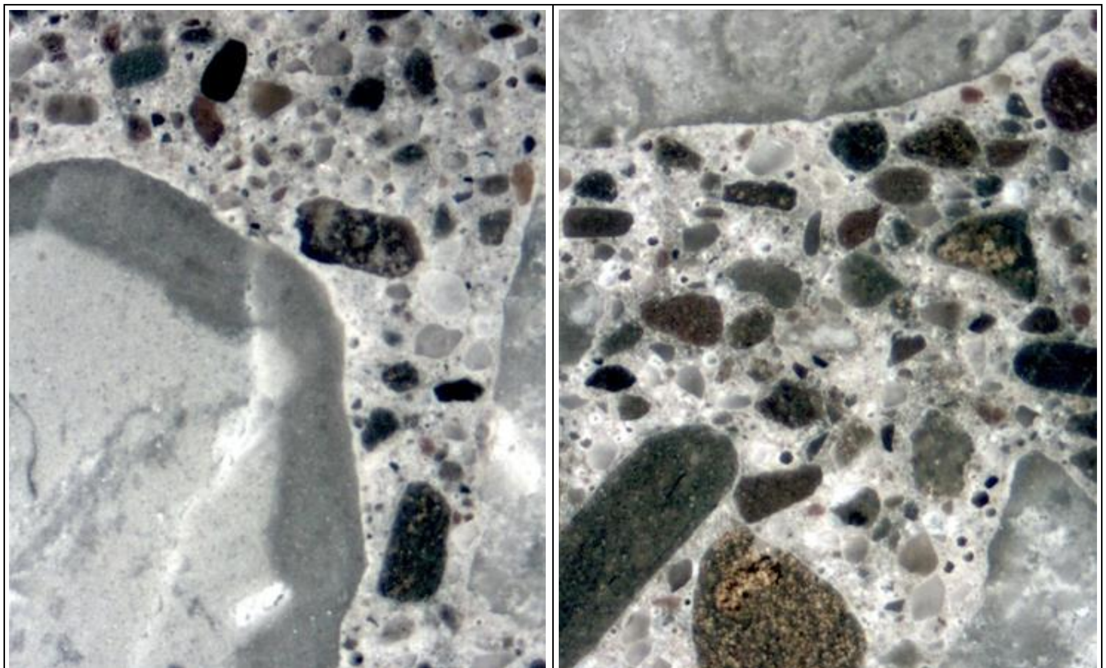
Figure 10: Cores through composite pavement showing very good quality 65-year-old concrete.

Rehabilitation of Section of Highway 405, Ontario

The four-lane highway section was constructed as a 230 mm thick jointed plain concrete pavement in 1963 and subsequently overlayed with hot mix asphalt. Petrographic examination of the concrete in recovered cores supplemented FWD and GPR surveys to evaluate the condition of the concrete slabs and joints. The average concrete strengths were 55 MPa. The aggregates in the cores were all well-graded and the concrete was generally dense and well-consolidated. The steel mesh was fresh and uncorroded (Figure 11).

Figure 11: Prepared concrete core with clean uncorroded mesh

The coarse aggregate consisted of grey-white-cream quarried dolomite and minor grey limestone. The fine aggregate was natural sand comprised of different types of geologic deposits. Minor carbonation was observed in the cores and minor alkali-silica gel was observed in one of the cores. The investigations confirmed that the almost 60-year-old concrete was in good condition and was providing good support for the pavement. The minor signs of ASR noted in one of the cores was not expected to have a significant impact on the durability of the pavement given its current age. Based on the load transfer efficiency across certain joints, as determined by the FWD, some localized full depth concrete repairs and joint / crack sealing / resealing were recommended.



Reaction rim on a chert aggregate particle, with an internal ASR-gel-filled crack. Magnification 10x, field of view 8.5 mm	General view of the concrete showing dense paste that encloses fine and coarse aggregates. Magn. 10x, FOV is 8.5 mm.

Figure 12: Good quality almost 60-year-old concrete pavement.

Tunnel Drainage Sumps, Ontario

A condition survey was undertaken on a 50-year-old tunnel drainage system to establish the scope of necessary remedial works. All distresses in the exposed concrete walls, floors and soffits were mapped. A series of concrete cores were taken for testing and petrographic examination. At some locations, the concrete floors were disintegrated/spalled to depths of 40 mm to 80 mm and further concrete could be removed by hand. The ring beams surrounding the sump pits were severely deteriorated with 75 mm to 140 mm of concrete missing to expose corroded reinforcing steel (Figure 13). Compressive strengths of the intact concrete were good with recorded strengths in the range of 30 MPa to 60 MPa.

	
Concrete ring beam spalled to a depth of 80 mm exposing corroded reinforcing steel.	Cut face of concrete core. Discoloured paste and damage on exposed (left) face of core.

Figure 13: Heavily damaged 50-year-old concrete from exposure to high sulphate concentrations.

However, petrographic examination revealed that the concrete exhibited defects to depths of 65 mm below the exposed surface. Networks of micro-cracking were visible extending through the aggregate and paste and frequently along the paste/aggrege interface. These cracks were lined with ettringite, confirming sulphate attack from external sources (Figure 14). This degradation mechanism occurs when sulphate ions from flowing water infiltrates the concrete and reacts with the calcium aluminate in the cement paste to precipitate a secondary sulphate, typically ettringite or gypsum. The crystal growth causes internal stresses and leads to the propagation of cracking and ultimately spalling.

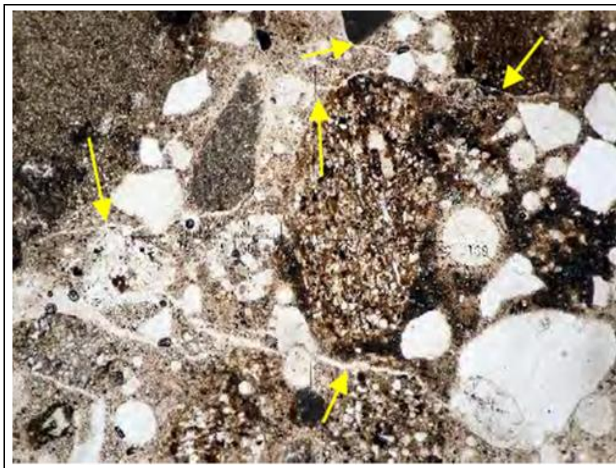
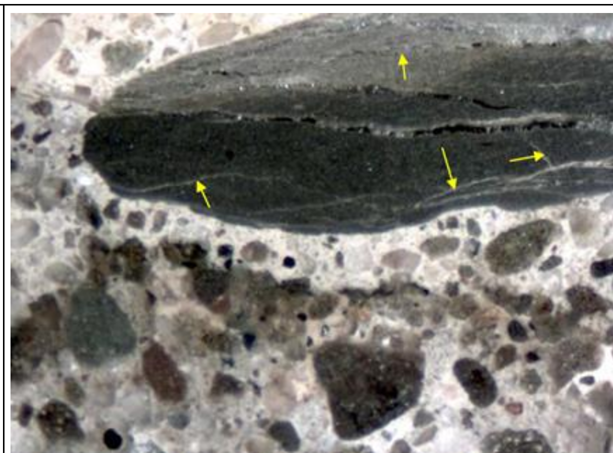
	
Thin section view of micro-cracking and voids lined with ettringite to a depth of 35 mm. Field of view: 3.3 mm.	Severely damaged aggregate particle with ettringite-lined cracks throughout. Field of view: 8.7 mm

Figure 14: Aggregate and paste damage as a result of expansive external sulphate attack.

This problem necessitates the removal and replacement of all affected concrete and replacement with concrete specifically designed to be resistant to sulphate attack.

DISCUSSION

The foregoing cases provide an array of examples where petrographic examinations were of importance in understanding the nature of concrete deterioration, its extent, severity, and the possibility of continued or further deterioration, particularly where progressive deterioration such as ASR is involved.

While we generally recommend that infrastructure evaluations be done by means of a comprehensive and broadly-based program that involves a thorough desktop review, field survey, documentation of concrete condition, and a comprehensive laboratory-based core sample testing program, in our experience it has been found that petrographic examination provides added insights that cannot generally be determined by physical testing or visual field observation alone. This is due to the harnessing of observation and documentation of the relationships between aggregate and paste, the characteristics imparted by various causal mechanisms on the aggregate and the paste, and the explanatory descriptions that can be the result of the examinations.

In this sense, data that are generated from physical tests provide only objective measurements, while the petrographic examination can provide qualitative explanation of what is observed. Although this is not a guaranteed outcome for every sample that is submitted, it generally is possible to provide supplementary qualitative information. This information can identify the direction for further investigation and inform the infrastructure management program by providing the “why”, the “how” and the “when” and so allow cost-effective rehabilitation strategy to be decided.

The petrographic examination, and related analyses such as the Damage Rating Index, can also provide further insight into possible or probable behaviour of the concrete over time.

Figure 15 shows a theoretical ‘typical’ progression of ASR in concrete, based on experience in assessing numerous cases of this reaction in a wide range of concrete structures. Internal sulphate attack from reactive sulphides (e.g., pyrite, pyrrhotite, marcasite) in aggregate would likely follow a similar trend of progressive damage.

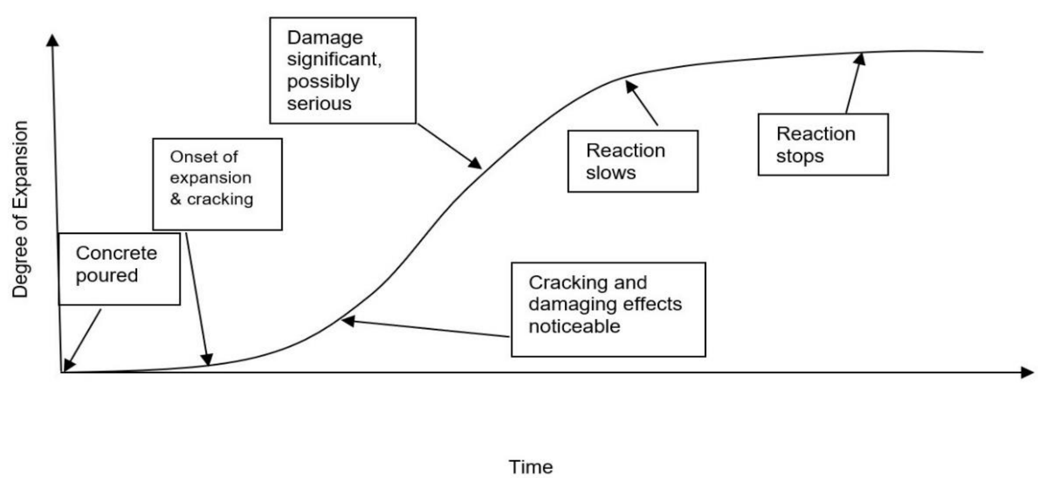


Figure 15: Schematic illustrating the progression of concrete damage from ASR.

What is often desired by Owners of concrete infrastructure and their engineers and management staff is to understand on what part of the curve shown above is the concrete of concern? When certain types of deterioration are taking place, the answer to that question can range widely, and although physical test data is highly relevant, it may not be able to provide the answer/s that are required in order to most efficiently and economically address those concerns.

CONCLUDING REMARKS

Petrography applied to concrete can provide powerful and important insights in the assessment of the nature and quality of concrete, at various points in its service life. From provision of a general condition survey to analysis of a perceived or actual dire situation, the information that can be provided as output from petrographic of examination of concrete can make the difference between sound decision-making for concrete and ill-informed planning.

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