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Petrographic Examination

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PREFACE

Twenty-seven years have past since the publication of *ASTM STP 169A*, where this chapter was first published. Kay Mather, who wrote the previous version of this chapter in *ASTM STP 169A and 169B*, in her closure quoted from St. Paul, "Things which are seen"—concrete and mortar—"were not made of things which do appear." St. Paul is not with us—neither is Kay who died in 1991. The bulk of this paper is still her "quote" on petrography, but with modest changes and additions. The next version may be entirely different. But the emphasis will remain the same.

INTRODUCTION

Twenty-seven years have past since the inception of *ASTM STP 169A* and 15 years have past since the updated *ASTM STP 169B* was published. At that time, there was little reference material available on petrography of concrete. Today, there are literature references to petrographic examinations available where the theme is on petrography as a tool used to provide information about concrete instead of petrography that is incidental to the paper. Both approaches, however, are needed because doing petrography for the sake of solely providing information can be an exercise of futility, while doing petrography for the purpose of providing links connecting "activity" within the concrete to its behavior is indeed a fulfillment of the science.

Significant advances in petrography and petrographic methods have been published about petrographic examinations related to concrete. Once considered by many to principally revolve around light optical microscopes, the science has greatly expanded to include new types of instrumentation and techniques from light optical microscopy to specimen preparation, "wet" chemical analyses to infrared spectroscopy, X-ray diffractometry and spectroscopy, scanning electron microscopy with attendant elemental analysis, plus differential thermal analysis and other analytical tools.

In the history of petrography of concrete as we know it today, at least from published papers, was the work of Johnson in 1915 [*1*] who described and related microscopical observations of the composition and texture of deteriorated concrete to its performance. He further applied what he saw toward a philosophy of what makes inferior concrete inferior—and said that "even with the very best of materials, only concrete of inferior strength is commonly produced." There were trailblazers before Johnson, but his work was, perhaps, the first widespread enough so that it truly reached out to engineers. His work was published in a six-part series, from January through March in 1915 [*1*].

Subsequent and more recent informative documents include Refs *2* through *15*. The International Cement Microscopy Association (ICMA) was founded in 1978. That organization, whose main emphasis is on cement, provides publications of interest to concrete petrographers.

In June of 1989, the first symposium specifically directed toward presenting information on petrography of concrete and concrete aggregates was sponsored by ASTM. The papers presented at that symposium resulted in *ASTM STP 1061* [*16*].

The closing remarks of Kay Mather who authored the initial versions on petrographic examination of concrete in *ASTM STP 169A* and *ASTM STP 169B* foretold the potential advances in the science of petrography. Today, the imagination extends even further, and it is gratifying that her analytical visions are in use and being extended.

PETROGRAPHY

Within the realm of petrography, which includes the use of a broad variety of analytical and physical methods, is the scientific description of the composition and texture of materials, including the systematic classification of rocks. It also includes almost anything that can be said about a concrete, from its mineralogy to its strength and volume sensitivity.

Petrographic analysis of concrete—a man-made rock—is its examination by analytical techniques that will identify procedures and the sequence of its production, its composition and internal structure, and allow its classification as to type, original and existing conditions, and future serviceability.

The physical and chemical properties of concrete, especially immediately and shortly after it is made, is a physical wonder. Within a very short time measurable in terms of days, it becomes hard and strong and usually endures

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for long periods. Its strength originates within itself by complex chemical reactions. It is recreated "rock" akin to the rock conglomerate, which mother nature has made.

Like rocks and minerals, concrete is a "mirror" with a memory. Petrographic examinations allow us to interpret the concretes' past as it really was—to identify, beyond all of the obscurities essential facts about its manufacture and performance. Its makeup and past performance, in light of research and practical experiences, allows projections of its future serviceability.

Petrography is used, frequently, to assist in forensic evaluations, where it is vital for supplying factual information. That information can relate to mix proportions that include coarse and fine aggregates, portland cement and other cementitious materials, water-cement ratios, air contents, mixing, placing, bleeding, cement hydration, finishing, curing, cracking, scaling, spalling, low strength, excessive wear, blistering, delamination, and other features. To be effective, the petrographer should have a good understanding of all concrete-making materials, concrete manufacture, and the influence of environmental exposure on its stability and performance.

This chapter provides insight into aspects of petrographic examinations by giving information about its usefulness in evaluating hardened concrete, noting problems inherent in its applications, outlining what it involves, describing the kinds of information that it can produce, and showing how this information can be applied.

The questions that materials testing and evaluation tries to answer are: (*a*) Does the concrete conform to specification requirements; (*b*) How will it behave in use? (*c*) Why did it behave the way it did? and (*d*) What can be anticipated in the future? The most useful method for developing practical information from which to answer these questions is to study the concrete in the field and in the laboratory.

Testers of materials try to compress time and to anticipate and reproduce the environment that the material will experience. Generally, they use standardized procedures not directly related to the specific environment or that do not determine the particular properties relevant to performance in the specific instance. Thus, the testing of construction materials amounts to obtaining various kinds of information about certain samples in specified conditions and extrapolating to the conditions of use insofar as they can be predicted.

Petrographic examination of hardened concrete is included among the subjects in this volume because it helps to improve the extrapolation from test results to performance. It offers direct observational information on what is being tested and what is in the concrete structure, giving another way of appraising the relationship between samples being tested and materials in service by judging how similar the two are.

COMMUNICATIONS

A petrographic examination of concrete ordinarily begins with communication between the person who requests the examination and the petrographer. Unless the two succeed in producing a clear mutually understood statement of the problem, they cannot expect a clear useful answer to be obtained economically. In nearly all cases, whoever asks for an examination knows that the concrete is unusual as reflected by its performance; the more clearly he defines the features prompting his interest, the more he directs the petrographer toward the important aspects. The person may not be familiar with the techniques that the petrographer may use or with his approach; conversely, the petrographer may not realize the individual's responsibility for a decision or action, may not have all the background information that could help him better understand the concrete and the problem, and may not realize which petrographic findings are useful and relevant.

The petrographer should not expect petrographic results to be taken on faith; the rationality of the techniques producing them should be demonstrable. Both should remember that the essentials of petrographic examination of concrete are practiced anytime anyone looks intelligently at concrete either in a structure or as a specimen and tries to relate and project what he sees to the past or future performance of the concrete. On this basis, useful "petrographic information" can come from inspectors, engineers, chemists, physicists—anyone concerned with the production and laboratory examination or use of concrete. No one should hesitate to examine concrete with all available means. Anyone, from novice to expert, is entitled to question data and conclusions and verify them in as many ways possible.

METHODS—STANDARDIZATION AND DESCRIPTION

The recommended practice for petrographic examination of aggregates, ASTM Guide for Petrographic Examination of Aggregates for Concrete (C 295) was published in 1952. ASTM Practice for Examination and Sampling of Hardened Concrete in Constructions (C 823) was adopted in 1975. It gives guidance for both the field examination of concrete in constructions and the petrographic examination of the samples taken. Steps to be taken before examination and preliminary investigations are outlined and include: (1) the desirability of assembling reports and legal documents concerning the construction, and (2) the usefulness of interviews with contractors and others connected with the construction and with the owners, occupants, and users of the constructions. Procedures for detailed investigations of the concrete in place in constructions are described. Sampling hardened concrete is discussed along with the preparation of appropriate sampling plans and selection of the number and size of samples. Information needed to accompany samples is described. ASTM C 823 was prepared to be useful not only to petrographers but also to engineers and others who have reason to examine constructions.

ASTM Practice for Petrographic Examination of Hardened Concrete (C 856) was adopted in 1977. It turned out to be a more complicated document than was expected, because there may be different purposes for examining concrete specimens including: constructions, specimens after periods of field exposure, specimens in simulated service, specimens from laboratory tests, and specimens after initial laboratory preparation and curing. What may be recognized as concrete features produced in field exposures, simulated service, laboratory tests, and laboratory curing may be features interesting and revealing in themselves in laboratory experiments. The laboratory observations may also make similar or related features of concrete from constructions more comprehensible. ASTM C 856 (1) serves those who buy a petrographic examination and want more understanding of what they are getting and why, (2) serves petrographers approaching the examination of concrete, and (3) reminds concrete petrographers of things they may have forgotten or neglected.

In 1976, Ref *17* was published. It provides help in (1) identifying alite and belite residues in paste, and (2) examining paste by X-ray diffraction, differential thermal analysis, and infrared absorption spectroscopy. Pastes of three cements, that is, a Type I, a white cement, and a cement containing no tricalcium aluminate (C_3A), were examined at different ages up to one year and a number of pure phases were synthesized and examined by these methods. Another publication for help in petrographic examination of hardened concrete is Ref *18*. Other publications of interest are in volumes of the Fifth International Symposium on the Chemistry of Cement [*19*] and those of the Sixth International Symposium on the Chemistry of Cement [*20*]. A stimulating publication originating in 1971 [*21*] covers a wide field of cement and concrete topics and has the advantage of being truly international because the editorial board and the contributing authors come from centers in various parts of the world where cement and concrete research is carried out.

Before ASTM C 856 was published, petrographic techniques for the examination of hardened concrete had been described and discussed but were not standardized. In 1966, Kay Mather wrote:

> At present I know of no laboratory where petrographic examinations of concrete are made that is equipped to use all the methods that have yielded useful information and no one person who has digested the available approaches and developed the ability to choose the particular combination of techniques best suited to each problem encountered. Concretes are more complex than most rocks used as aggregates; their constituents are less well known; concretes change through time more rapidly than most aggregates. All of these circumstances combine to make each petrographic examination of concrete unique and thus to make the methods harder to generalize and standardize. Each examination presents some new facet for the petrographer who is willing to learn.

Today, in 1994, sophisticated equipment is available in many laboratories that is bringing about a breakthrough by orders of magnitude in our ability to decipher and to interpret the composition and performance aspects of concrete in constructions. These methods can bring with them the danger of losing touch with the primary purposes of an examination, that is, due to great ranges in scale such as constructions with dimensions in hundreds of metres (kilometres in the case of pavements); core samples with dimensions in hundreds of millimetres that can be examined with great advantage using low-power stereomicroscopes; thin sections with scales ordinarily about 800 mm^2 by 15- to 30- μm thick examined using petrographic microscopes; X-ray diffraction samples that may be milligrams of material hand-picked under the stereomicroscope or a few grams of material concentrated by hand-picking paste or aggregate from carefully broken concrete; scanning electron microscope specimens that may be 200 mm^3 or much smaller and thinner; single crystals a few angstroms cubed that are examined using microprobes; and the nanometer-sized material examined using transmission electron microscopes. Few cases will be found in which all of these steps in scale will be used. The preliminary important steps are (1) looking at the construction itself and (2) observing the samples from it with the naked eye and the low-power stereomicroscope. Then the petrographer can form one or more working hypotheses for best making the transition from the macroscale to the microscale so that knowledge gained from each unit of effort, preferably using more than one method, provides independent and complimentary verification. Care is needed to ensure that proper sampling is done at all levels of scale. For example, field samples should include cracks, specimens for detailed laboratory analysis should be taken from deposits in cracks and voids in several samples, and paste concentrates should be made from several samples so that a sensible sampling plan is carried out from the macro to the microscale.

"The straw that broke the camel's back" theory of concrete deterioration is archaic. Unless the concrete was hit by a truck or a large object from outer space, it is highly probable that evidence of more than one deteriorative mechanism (or what appears to be such evidence) will be present in any sample of deteriorated concrete. Sorting out the major cause or causes from the minor causes or secondary effects of deterioration requires the exercise of an experienced petrographer's best judgment.

The history of the concrete construction and its subsequent behavior may be of great importance, and for this kind of information the petrographer should consult engineers, inspectors, and contractor's personnel who have been present during construction and those who have later inspected or occupied the construction.

The newer analytical techniques offer an opportunity to understand internal chemical reactions in much more details so that it is possible to characterize the hydration and reaction products more clearly. Consequently, the chemical reactions of normal hydration or abnormal deterioration, or both, in concrete can be evaluated with much more clarity and certainty. The relative roles of chemical attack and physical attack in producing deterioration can then be better understood. The goal of relating better-established and more-familiar techniques in petrographic examination of hardened concrete to the more intimate and detailed insights that are made possible by the newer techniques remains to be achieved completely. While progress has been considerable, the task is still far from complete.

PURPOSE AND APPROACH

Purpose

A petrographic examination of concrete attempts to answer three general objective questions: (1) What is the concrete composition? (2) How is it put together? and (3) What chemical or physical features are present now that were not present when it was made? The first question refers to the recognizable individual constituents present on the scale at which they are seen. The second question refers to structural fabric, that is, the articulation or packing in space of the component elements making up any sort of external form [22] or heterogeneous solid body. The third question refers to those forces, chemical or physical, that have altered the original concrete. These questions may be answered on any useful scale by choosing the technique or techniques of appropriate resolving power. The resolving power needed differs depending on the specific questions to be answered.

Approach

Step one, in any case, is to define the problem in order to find and ask the right questions—those that need to be answered to solve the problem that caused the examination to be requested. These questions should be answered as long as they are in the context, limited as it may be, of money, time, instrumentation, and the state of the art. The best petrographic examination is the one that answers the questions with maximum economy in minimum time, with a demonstration clear to all concerned that the right questions were answered with all necessary and no superfluous detail. The approach to this ideal varies depending on the problem, the skill with which the questions are asked, and the skill of the petrographer. One measure of the petrographer's skill is knowing when to stop, either because the problem is adequately solved, or, in some cases, because it has been shown to be unsolvable under the circumstances. The petrographers skill includes not only deftness in obtaining data, but also in putting the data together. Knowing when to stop the petrographic examination is not easy because of a synergism of phenomena sometimes encountered, or when two phenomena occur concurrently. If the petrographer has too little skill and understanding about concrete and the concrete-making materials, he may stop short or dwell too long on the examination. If there is a choice, the latter is preferred.

FABRIC AND COMPOSITION

Fabric is the packing and relationship of components and is the textural and compositional heterogeneity obvious on a weathered concrete surface or a broken or sawed surface of concrete. Fabric includes all of the structural elements, ranging in scale from gross to atomic, and comprises both structure and texture as those terms are used in rock description. The fabric is reflected on the magnitude and scale of the concrete lift or batch, the structural crack, the coarse aggregate, the sand grains, the air voids, the microcracks, the residual (unhydrated) cement, the calcium hydroxide crystals, the hydrous calcium aluminates, the almost amorphous crystalline hydrous calcium silicates in the hydrated cement paste, and the atomic structure of any crystal forming a part of any of the structural components. The closest naturally occurring analogue among rocks to the fabric of concrete is greywacke conglomerate with an abundant matrix. The closest naturally occurring analogue to hardened cement paste is silty clay.

Fabric and composition together define, characterize, and form the basis for descriptive classification of solid multicomponent substances. Composition and fabric are so closely interrelated in concrete that they cannot be clearly separated.

One important aspect to be derived from petrographic examinations is the determination of whether problems were created by the physical structure of the concrete or because of its chemical composition. For example, problems arising from the physical structure or fabric include inadequacies in mixing or consolidation and inadequacy of the air-void system to provide frost resistance. Problems arising from the chemical composition include those resulting from errors in batching, reactions between cement and aggregate or cement and admixtures, reactions between a contaminant and cement paste, and reactions between cement paste and solutions from external sources.

The petrographic examinations can be used to evaluate whether (1) construction practices were suitable for producing concrete capable of giving satisfactory service in the particular environment and exposure; (2) the concrete-making materials were susceptible to chemical reactions that have deleterious consequences; and (3) there was a failure to modify the environment, for instance, by improving the drainage so as to increase the ability of the concrete to survive the chemical or physical character of the environment. Usually, several causes have interacted, but one is probably the originator. If the originating cause can be identified before the petrographic studies, the most direct and appropriate techniques for the studies can be used.

Investigating composition and fabric provides a specific, unique definition of what is being examined. The standard tests do not always supply information that permits discrimination between one piece of concrete and another, but direct observation on the relevant scale does. For example, there are *n* possible concretes all having 50-mm (2-in.) slumps, with air contents of 5%, with 31-MPa (4500-psi) compressive strengths at 28 days, but the No. 2 cylinder in the set of three broken on Day A in Laboratory B is unique and different, perceptibly, from Nos. 1 and 3 and from all the members of the other possible sets, and its top is different from its bottom as cast. A petrographic study of this unique cylinder and a "normal" cylinder will define their differences. The salient lesson from this study of composition and fabric is the individuality and uniqueness of this cylinder, or of each structure or part of a structure, or of each specimen and each thin section. This individual combination of fabric and composition reflects a part of the history of the concrete and can be used to understand past performance and to forecast future performance of the concrete. What is investigated at any time is a particular concrete, not concrete in general. Each concrete and each part of a concrete is unique in terms of composition, fabric, history, and exposure.

COMPARISONS

To say that each structure and specimen is unique does not mean that comparisons are useless or impossible. They are essential, and concretes can be grouped rationally and compared usefully within classes and between classes, if the basis for the grouping is objective. Each comparison may leave out some characteristics of the things compared, so that any evaluations should consider the accidentally or deliberately omitted factors that may prove to be important.

Paste, mortar, or concrete of known proportions, materials, age, and curing history offer the logical basis for comparison and extrapolation; laboratory specimens made to be examined or salvaged after having been tested for strength provide a good source of such comparative material. Specimens exposed to laboratory air outside the moist room or curing tank for more than a few hours are much less suitable, because pastes of specimens that are cracked or that have slender cross sections sometimes carbonate very rapidly. Specimens exposed to simulated weathering tests, or wetting and drying cycles, or prolonged drying are not to be considered as representative of normally cured or naturally weathered concretes, but nevertheless, may be instructive. Natural weathering differs from part to part of a structure, as well as from climate to climate, elevation to elevation, and subgrade to subgrade.

However, based on field and laboratory data, there are expectations of what will happen to concrete after it is made, handled, tested, or exposed. With an understanding of what can happen, an experienced petrographer can separate the expected features from the artifacts.

INTERPRETATION OF OBSERVATIONS

Normal Concrete

"Normal" constituents and fabrics are here defined as those in serviceable concrete of the class and age in the region. "Serviceable" is used here instead of "undeteriorated," because it is possible to tell whether concrete in a structure is serving as it was intended. However, criteria that distinguish inevitable chemical and physical changes from deterioration in concrete 20 or 50 years old have not been well established.

Very valuable information that can be obtained by petrographic methods comes from the examination of normal concrete. By comparing the range of constituents and fabrics in the normal satisfactory concrete, differences from the normal can be identified and specifically defined. Unless it can be demonstrated that the constituents, or the proportions of constituents or the fabric, depart from those found in serviceable concrete of the age and class in the region, there is no logical basis for assuming any connection between constituents, or proportions or fabric, and service behavior. When petrographic studies reveal that a concrete has a peculiar service record and some unique feature or features not shared by others of comparable class, age, and provenance, the unique feature(s) can be evaluated in light of the peculiar service record, and a cause-and-effect relationship established.

Class of Concrete

Proper comparisons of different kinds of concretes is necessary because changes in cement content, water/cement ratio (w/c), and maximum size of aggregate can entail major changes in specified properties so that no close comparison will be significant. If, for example, the criteria for paving concrete are applied to mass concrete, all mass concrete appears very inferior, which it is not for the purpose it is intended to serve. The class of concrete is important because it implies relative homogeneity in mixture proportions, particularly in w/c, cement content, and maximum size of aggregate. It is possible by petrographic methods to identify concretes that differ in cement content and w/c ratio regardless of age, and it is possible to identify concretes fairly homogeneous in age having different cement contents. The ability to evaluate cement contents and w/c can be in the range of ± 30 kg/m^3 (50 lb/yd^3), and about ± 0.05 in w/c.

AGE OF CONCRETE

The age of the concrete may be important for judging the significance of observations. For example, calcium sulfoaluminate (ettringite) found in many voids as far as 130 mm (5 in.) from the outer surfaces of a concrete pavement of unknown age and of high flexural and compressive strength may be of importance relative to projected service. That observation is of particular importance when in other 15-year-old, similarly exposed, field concretes from the region calcium sulfoaluminate is not abundant. If the concrete of unknown age is in fact five or seven years old and it differs conspicuously, the difference probably justifies some concern about its future; if it is 15 years old, it is peculiar, but the peculiarity is probably of less practical importance.

SOURCES OF CONCRETE

Restriction of an investigation to one region assists in rational comparison from several points of view. The aggregates economically available in an area are determined by the regional geology and consequently show some homogeneity of composition resulting from similarity of origin and history. In a particular region, cements and aggregates economically available are used in making concrete exposed to the climate characteristic of the region—the prevailing temperature range and temperature frequency distribution and the characteristic amount and sequence of precipitation.

The extent of a region may vary from a few square miles to many thousands, depending on variations in:

(*a*) regional geology—as it determines quantity and uniformity of aggregates;

(*b*) topography—a region of low relief and generally uniform slope, such as the Great Plains, or the Atlantic or Gulf Coastal Plain, that has widespread comparable range and distribution of temperature and precipitation. In a region of high relief and broken slopes, temperature varies considerably with altitude, and precipitation varies with orientation to prevailing winds, making important differences in exposure over short distances; and

(*c*) patterns of distribution of aggregates and cement from different sources—in some areas, only one type of natural sand and gravel is available, no manufactured aggregate is produced, and synthetic aggregate sources are not common. Metropolitan marketing areas served by water transportation usually have available a selection of natural coarse and fine aggregates, manufactured coarse aggregates, and synthetic aggregates.

All variations between these extremes can be found.

There currently are 119 portland-cement plants in the United States [*23*] of which three produce white portland cement and eight are used only for grinding clinker. Twelve states have no producing plants, and the largest number of plants, ten, are in Pennsylvania. Foreign imports of portland cement amount to about 9% of the U.S. production, and serve costal and Great Lakes ports.

An additional influence that may appear is a prevailing engineering opinion within an organization placing concrete in different regional areas on what is desirable in proportions of components or methods of placing or consolidation. The existence of satisfactory structures built in many different ways underlines the need to define "normal" concrete in objective and regionally restricted terms.

NORMAL AND UNUSUAL CONCRETE

Although petrographic examinations of normal concrete is important, usually the concrete that a petrographer is asked to examine has behaved in an unexpected way. Before and during the early stages of the petrographic examination, the petrographer should seek background information about the history and behavior of the concrete. He can compare what he finds to the manufacturing processes used for making the concrete, and by secondary features present, evaluate interactions within the concrete and between the concrete and its environment.

Among the questions he should answer are: (1) What process or processes could produce the described results? (2) What observable traces could the process or processes leave in the concrete? and (3) Would such traces be unique and specific evidence of what is supposed to have happened?

RECONSTRUCTION OF HISTORY OF FIELD CONCRETE

To progress from consideration of simple petrographic examination to the petrographic examination of concrete that has aged and perhaps deteriorated in service introduces two important new unknowns—time and the precise environment of the structure. The effects of the passage of relatively short periods of time on the constituents present in several cement pastes of known w/c stored under laboratory conditions have been investigated. However, anomalies remain in the results, even though compositions of pastes and nature of the environments were known and controlled far more thoroughly than the composition and environment of any field concrete. Today, where there is extensive use of fly ash, silica fume, and slag, there are even more anomalies.

COMPOSITION

If the changes in composition of cement paste with time in laboratory conditions were known for a representative number of cement compositions and water cement ratios, effects of both cement-aggregate interactions and of environmental influences would be easier to recognize and could be interpreted more usefully.

Environment

Why do exposed vertical walls of chert-gravel concrete in the vicinity of St. Louis, Missouri, generally have fewer popouts than similar walls in the vicinity of Memphis, Tennessee? The winters are colder in St. Louis, but the mean annual rainfall is lower; in Memphis, a larger proportion of the higher mean annual rainfall occurs in winter. The difference probably is that the chert gravel in the Memphis walls is more likely to be critically saturated when it freezes. The Weather Bureau's climatological data for the location are a valuable source of information that can assist in interpreting the data from many petrographic examinations of hardened concrete. In Mississippi, several highway pavements and associated structures were affected by sulfate attack and by combined sulfate and acid attack [*24*]. The petrographic examinations can reveal the cause of the problem. Available information on the ground-water environment can tie the cause and effect together.

The examination of samples of field concrete after extended service involves an increase in analytical complexity, a decrease in available information, and, to a certain extent, a decrease in the confidence that may be placed in the answer, as compared to examinations of new concrete or laboratory test specimens of concrete.

Sometimes the petrographer must admit that he cannot find an answer to the questions posed—neither may the chemist, the physicist, nor the engineer. Sometimes the petrographer can recover evidence not accessible by other approaches. There may be difficulty in reconstructing the history of field concretes. Yet, the results of a petrographic study can be used to eliminate certain factors or direct attention to others.

Deteriorated field concrete submitted to a laboratory or to a petrographer may have performed abnormally because of more than one cause. Simple cases can sometimes be explained on the spot to the satisfaction of those concerned. Usually, the cases are more complex. The field concrete examined by a petrographer is concrete that has worried some responsible person enough to make the effort and expense of sampling and testing appear justified. There is thus a built-in bias in the sampling process. Normally concrete that a petrographer sees as part of his assigned duties is controversial concrete sent in by organizations with alert conscientious concrete technologists or concrete that has become the subject of controversy under other situations. In practice, this generally means that he usually sees only the poor concrete produced under conditions where a degree of control was intended, unless samples representing all conditions are included. Concrete produced where there was little intent for control to be exercised, that is, the worst concrete, rarely is sampled and sent to a petrographer; good concrete is rarely controversial.

Furthermore, the older the concrete the less information is likely to be available about materials, proportions, conditions of placing, and the characteristics that undeteriorated comparable concrete would have.

Although it can be deduced from concrete that the w/c was high or low, that cement content was high or low or medium, and general quality of workmanship, the alkali content of the cement can usually not be reconstructed. Aggregate sources, particularly of natural sand and gravel, can be located from their composition—the constituents present and their size distribution are usually diagnostic of the region and sometimes of the particular source.

Finally, deteriorated field concrete usually shows superimposed traces of several processes, with at least one in an advanced stage. The most advanced process may conceal evidence of others that were more important in effect.

Laboratory test exposures are simple compared to natural exposures because some factors are excluded and those that are retained and often regulated or "accelerated" by altering some factor so as to remove it from the range possible in nature. Consequently, a laboratory procedure often results in symptoms different from symptoms encountered in a field example of the process that the test is intended to simulate.

Samples of field concrete, when examined using light microscopy, are frequently found to contain secondary calcium carbonate near their outer surfaces, along old cracks, and sometimes in the interior. Such calcium carbonate, when examined by optical methods, is generally found to be calcite rarely aragonite, and almost never vaterite, in the form—birefringent spherulitic calcite with interstitial water. Vaterite, however, was found by optical methods to be common on mortar bars that had been tested according to ASTM Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method) (C 227) and had been found on concrete specimens tested for resistance to freezing and thawing according to ASTM Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666). The use of X-ray diffraction to examine cement-paste concentrates from field concrete has revealed that vaterite, not recognized by optical methods, is frequently a major constituent of the secondary calcium carbonate [*25*], especially on samples from seawater exposures or from other wet environments. Vaterite is known to persist for several months in laboratory specimens stored in room conditions. The sequence from poorly crystallized vaterite, calcite, and aragonite to well-crystallized calcite in the carbonation of pastes and mortars has been clarified [*26*], and vaterite is now known as a natural mineral [*27*].

Accelerated freezing and thawing in water according to ASTM C 666, Procedure A, produces a characteristic loss of surface skin and loss of mortar, which is not like the condition of specimens exposed on the mean-tide rack at Eastport, Maine [*28*]. Field concrete that is not air-entrained and is deteriorated by natural freezing and thawing develops sets of subparallel cracks normal to the placing direction of the concrete or deteriorated regions parallel to the nearest free surface. These phenomena may not be reproduced in accelerated freezing and thawing in water.

Field concrete that has deteriorated because of alkali-silica reactions usually has much more advanced and conspicuous internal symptoms of this reaction than are found in mortar bars of expansive combinations examined after they are tested according to ASTM C 227. On the other hand, some field concrete regarded as undeteriorated has shown a range of evidence of alkali-silica reaction.

Alkali-carbonate and alkali-silica reactions exist together in varying degrees of development in some concretes, and inconspicuous degrees of reaction may be the only recognizable peculiarities in cases of unsatisfactory service with possibly expensive consequences. Alkali-carbonate and alkali-silica reactions are described in other papers in this publication.

CONCLUSION

The kinds of information about hardened concrete that petrographic examinations reveal can be used to identify, for example; unsound aspects of portland cement that have lead to bulk concrete expansion [*29*]; improprieties of aggregates that can cause low concrete strength [*30*]; stray naturally occurring organic chemicals in aggregates that can cause variable concrete air contents [*8*]; the causes of concrete failure to set; rapid slump loss; poor proportioning and batching; factors resulting in large concrete shrinkage; early and late concrete instability due to a variety of causes; conformance to specifications; malperformance due to chemical reactions of aggregate; surface distress due to improper finishing, curing, and inadequate air entrainment; and poor performance due to composition, manufacture, and exposure to aggressive environments for which it is not designed.

Before the petrographic trail was blazed, during its early adventuresome period, and even today where new and exciting methods and techniques are constantly developed, we still have some ignorance about the factors that lead to good or poor concrete performance. However, there is no need to view our analytical level of understanding as insignificant.

It makes no difference if the concrete is a 10-ton cherry pie 14 ft (4.2 m) in diameter and 2 ft (0.6 m) deep constructed in Charlevoix, Michigan, to commemorate the birthday of George Washington, or a dam, nuclear reactor facility, bridge, foundation, wall, pavement, sidewalk, electrical insulator, or bank safe liner anywhere in the world; the basic constituents are similar at any age. Petrographic methods are ideal for evaluating how they have been put together and changes that have occurred, and provide an understanding of performance.

Petrography of concrete is flourishing. Like in other sciences, the development of new methods and techniques of examination, more sophisticated equipment, more people and laboratories available to complete work, and better understanding of the physical and chemical make-up of concrete, now make possible better interpretations for the causes of concrete performance and malperformance.

Along with improvements in analytical methods and equipment comes a new problem—the development of petrographers who are able to obtain the right analytical data, but also have the background to interpret the data. There is a need for hands-on appreciation of mixtures of portland cements; blended cements; mineral and chemical admixtures; water; varieties of coarse and fine aggregates; methods of mixing, placing, and consolidation; the physics and chemistry of what happens to and within plastic and hardened concrete; and the effects of time and environmental exposure on performance. Too frequently, the analyst becomes a specialist who operates in a narrow walkway of self- or organization-imposed semi-isolationism.

In this day of specialization, the techniques, and particularly the analytical equipment, are very expensive. The cost of getting petrographic information dramatically increases as the size and scale of what is analyzed progressively decreases. However, there is still a lot of information obtainable at moderate and justifiable costs.

Kay Mather included in her closure to this chapter in *ASTM STP 169B* a quote from St. Paul, "Things which are seen"—concrete and mortar—"were not made of things which do appear." St. Paul is not with us—neither is Kay who died in 1991. The bulk of this paper is still her "quote" on petrography, but with modest changes and additions. The next version may be entirely different. But the emphasis will remain the same.

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