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PETROGRAPHY IN THE EVALUATION OF AGGREGATES AND CONCRETE

JAMES A. SOLES

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PETROGRAPHY IN THE EVALUATION OF AGGREGATES AND CONCRETE

by

James A. Soles

SUMMARY

The stability of concrete depends on the quality of its constituents and on the environment in which it is placed. For long service life the components must be physically durable and chemically inert, but experiments and case histories are showing that many aggregate materials do not have the long-term stability expected of them. The petrographic examination of aggregates and concrete is therefore becoming increasingly valuable in concrete technology for indicating potential stability of components, controlling quality, and predicting the durability of concretes under the environmental conditions expected, particularly as the causes of alkali-aggregate reaction and the mechanisms of concrete deterioration become better understood.

This paper briefly reviews petrographic and related test procedures used in the study of aggregates and concrete, summarizes conditions and reaction processes which may cause their deterioration, describes characteristic features of known reactions, and discusses the problems faced and techniques employed to inhibit deterioration of concrete structures in various environments.

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LA PETROGRAPHIE DANS L'EVALUATION DES AGREGATS ET DU BETON

par

James A. Soles

SOMMAIRE

La stabilité du béton dépend dans une grande mesure de la qualité de ses éléments constitutifs et du milieu dans lequel il est placé. Pour assurer une longue durée du matériau, ses composantes doivent être résistantes du point de vue physique en plus d'être chimiquement inertes; cependant, les essais effectués et l'étude des antécédents démontrent que plusieurs agrégats ne possèdent pas la stabilité à long terme désirée. L'examen pétrographique des agrégats et du béton prend donc une importance toute particulière dans la technologie du béton pour déterminer la stabilité virtuelle des composantes, pour contrôler la qualité et pour prédire la durabilité des bétons soumis à des conditions environnementales prévues, particulièrement à mesure que les causes de réaction alcali-agrégat et les mécanismes de détérioration du béton deviennent mieux connus.

Le présent rapport passe brièvement en revue les méthodes d'essais pétrographiques et autres méthodes apparentées employées pour étudier les agrégats et le béton, résume les conditions et les méthodes de la réaction qui peuvent être cause de détérioration, décrit les caractéristiques des réactions connues, et discute des problèmes rencontrés et les techniques employées pour empêcher la détérioration des structures du béton dans divers milieux.

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INTRODUCTION

Petrographic study of concrete involves the application of petrographic and supportive techniques to describe the textural relations and distribution of constituent phases in the composite, and to determine the composition of aggregates and mortar and the causes and effects of concrete deterioration under different environmental conditions. In the concrete industry, such petrographic information is required at two critical periods: (1) before mixing, when a knowledge of aggregate composition and properties can guide the selection of materials for making concrete that will meet structural requirements and remain relatively stable under operating conditions and (2) after a concrete begins to show signs of deterioration, when the cause must be determined so that corrective measures can be taken to inhibit the process.

Long life is usually expected of concrete structures when they are built. Concrete deteriorates with time at rates depending on the composition of the materials used and on the environment in which it is placed. To estimate the durability and life span of an intended structure, as much as possible must be known about the stability of its proposed components under the conditions expected, otherwise problems may arise which are neither anticipated nor resolvable but which are increasingly considered engineering responsibilities (1). The concern of researchers with these problems in the past few decades is reflected in the 850-item bibliography compiled by Liu, O'Neill and MacDonald (2).

Many of the reactions associated with deterioration of concrete under different conditions are being identified by experiment and sophisticated analytical techniques. Such knowledge greatly increases the usefulness of petrographic study for predicting behaviour of concrete in particular environments and for defining causes of instability when the reactions are optically distinctive. A petrographic analysis cannot replace standard acceptance tests, which are intended to reveal inadequacies of concrete or its components

whatever the cause, but it can often indicate to the concrete engineer which aggregate materials may be deleterious under particular conditions, what tests would be most useful to determine durability, and how a given concrete may ultimately behave.

This paper briefly reviews petrographic and related test procedures used to study concrete materials, classify aggregates, characterize processes of deterioration which affect the stability of concrete, and provides information which will assist the engineer in controlling the quality of concrete or in extending its life.

PETROGRAPHIC AND RELATED TEST PROCEDURES

Petrography is the description of rocks. It involves the study of their composition and texture, and their classification. The procedures used in petrographic analysis are well known and have been described in numerous texts (2,3,4). Concrete is an artificial rock, and the same basic techniques are used to prepare specimens and identify phases, but the petrographic examination of concrete and concrete materials demands more than simple modal analysis and classification of aggregate. By recognizing particular characteristics and making comparisons with similar materials of known behaviour, the petrographer is expected to provide information that is useful for predicting the behaviour of aggregates, for beneficiating them when necessary, and for identifying the causes of failure of concrete containing them. If he cannot draw conclusions from the petrographic study, then at least some test methods can be recommended which could provide answers.

Optical microscopy provides the most information most rapidly, but complete evaluation of an aggregate may require studies ranging from lithologic mapping to microchemical analysis of a grain boundary film. In the examination of concrete itself, the optical identification of phases involved in a specific reaction is often difficult, and supplementary analyses of reaction products may be required to confirm petrographic evidence of instability. X-ray diffraction and

electron microprobe techniques are the most useful for identifying phases, revealing fine morphology or textural relations, and tracing changes of composition, because only minute quantities are needed for analysis. Differential thermal and thermogravimetric analysis, infrared, and Raman spectroscopic techniques are also used occasionally to identify compounds when they are abundant. The use of these specialized analytical methods

requires time, expertise and costly equipment, however. Except for XRD analyses, they are avoided until particular information is sought.

The general procedures used for assessing different source materials and concrete products are standardized in specifications by the American Society for Testing and Materials (ASTM) and other national organizations. A selected list of standard practices are included in Table 1.

Table 1 - Selected ASTM standard procedures* applicable to studies of concrete aggregates

General	C 33	Standard specifications for concrete aggregates
	C 294	Nomenclature of constituents of natural mineral aggregates
	C 295	Petrographic examination of aggregates for concrete
	C 856	Petrographic examination of hardened concrete
Sampling physical tests	C 75	Sampling aggregates
	C 136	Sieve or screen analysis of fine and coarse aggregates
	C 702	Reducing field samples of aggregate to testing size
	C 131, C 535	Resistance to abrasion of coarse aggregate, Los Angeles machine
	C 127, C 128	Specific gravity and absorption, fine and coarse aggregates
	C 823	Examination and sampling of hardened concrete in construction
Aggregate analyses, tests	C 30	Voids in aggregate for concrete
	C 40	Organic impurities in sands for concrete
	C 88	Soundness of aggregate by use of sodium or magnesium sulphate
	C 123	Lightweight pieces in aggregate
	C 142	Clay lumps and friable particles in aggregate
	C 289	Potential reactivity of aggregates (chemical method)
	C 586, 586 _m	Potential alkali reactivity of carbonate rocks for concrete aggregate (rock cylinder or prism method)
Concrete stability, reactivity tests	C 227, 227 _m	Potential alkali reactivity of cement-aggregate combinations (mortar bar or concrete prism method)
	C 342	Potential volume change of cement-aggregate combinations
	C 457	Microscopical determination of air-void content and parameters of the air-void system in hardened concrete
	C 597	Pulse velocity through concrete
	C 642	Specific gravity, absorption, and voids in hardened concrete
	C 666	Resistance of concrete to rapid freezing and thawing
	C 682	Evaluation of frost resistance of coarse aggregates in air-entrained concrete by critical dilation procedures
	C 441	Effectiveness of admixtures in preventing excessive expansion of concrete due to alkali-aggregate reaction

*ASTM Book of Standards, pt 14, 1979 ed; m: modified to accelerate

CLASSIFICATION OF AGGREGATES

Petrographers may classify aggregate material in different ways according to preference, but what is important is that the information obtained will permit accurate evaluation of a material's usefulness and limitations, or will reveal the need of critical tests. Modern techniques have not changed the age-old requirement that the material be sound; they only enable soundness to be defined more positively with reference to the variables encountered.

Early work on petrographic classification of concrete aggregates has been reviewed and advanced by Meilenz and others (6). A useful work is that of Swenson and Chaly, who classified aggregate materials by those physical and chemical characteristics that could cause deterioration of concrete (7). Their tabulation, reproduced in Table 2 with few modifications, lists most of the factors which affect aggregate stability and, therefore, concrete durability and strength. These characteristics are sought and recorded during the petrographic analysis of aggregate materials and form the basis for assessing their quality. The general procedures are given in ASTM recommended practice C-295, Canadian Standard CSA-3:A23.1-M77, and other modifications (8).

INVESTIGATION OF AGGREGATE SOURCE MATERIALS

A petrographic analysis of material from a deposit intended for use as concrete aggregate

will not be meaningful unless the sample truly represents the mass. Selection of distinctive specimens for qualitative study is usually not difficult, but determining the proportions of different phases accurately may be, if they are optically similar or compositionally gradational with respect to a harmful component. Examples are: dolostone with indistinctive portions that contain expansive clay enveloped by dolomite crystals; aphanitic rock that may be sound or unsound; and sandstone with intergranular material that may be either innocuous or alkali-reactive. Also, phases which would deteriorate only over long periods or in unusual conditions may not be classified as unstable. For these reasons, petrographic examinations cannot replace durability tests.

The ability to distinguish phases in the field and to classify them there according to their potential stability in use would greatly expedite the petrographic investigation of an aggregate deposit and minimize the number of acceptance tests required for its development. The advantage of being able to recognize innocuous rock types, unstable components and undesirable physical properties is therefore obvious. When it is difficult to do so or if the petrographer is not experienced, then the recommended practices for sampling and estimating proportions would be applied, and classification of the different materials would follow testing of their stability in the laboratory.

The general procedures used in the assessment of concrete aggregate source materials

Table 2 - Deleterious characteristics of concrete aggregate material

PHYSICAL		CHEMICAL	
External	Internal	Cement reactions	Other
Encrustations	Undesirable pore characteristics	Alkali reactivity	Oxidation
Weathered surfaces	High volume change;	Organic impurities	Hydration
Polished surfaces	wetting-drying or	Salt impurities	Entrained
Undesirable shape	freezing-thawing	Base exchange	impurities
Extreme fineness	Lamination, cleavage		Soluble
	Soft, weak particles		material

Reference: Swenson and Chaly

are summarized in Table 3 along with applicable test specifications. Others may also be required, depending on the characteristics of the aggregate and the analyses needed to reveal its potential behaviour under the conditions expected with the cement to be used.

Many investigators have summarized details of petrographic examination of aggregates and have noted various useful procedures (8,9).

Others have compared laboratory procedures for testing aggregates to determine which may be the best, but no single test was found to be clearly superior for defining rock quality. Only the petrographic examination appeared to be consistently dependable (10); nevertheless, it should be used principally for monitoring aggregates and guiding empirical testing.

Table 3 - General procedures for investigating aggregate source materials

Source material	Procedures	ASTM Std or other method
Gravel sands	1. Map deposit or consult map showing distribution of materials	
	2. Obtain representative sample of deposit by channeling, drilling, or multiple random sampling	D 75
	3. Reduce volume by splitting or quartering	C 702
	4. Grade sample into required size fractions	C 136
	5. Classify and describe rock types ⁺ , determine proportions in each fraction and calculate totals or P.N.*, if desired, for the deposit	C 294, C 295 CSA:A23.2
	6. Select specimens for qualitative analyses and samples for durability testing of rock types that require it	C 40, C 88
	7. Test questionable rock, using the most rapid, most informative methods	C 131, C 342
Ledge rock	1. Map exposures or consult detailed geological map	
	2. Classify, describe, and determine proportions of different rock types in exposed sections, drill cores, or representative aggregate supply	C 295
	3. Select specimens for qualitative analyses or durability tests considered necessary on questionable rock types	C 88, C 131 C 289, C 227 _m
	4. Delineate sections of potentially durable and unsound rock to guide selective quarrying, pending results of tests	C 342, C 586 _m
	5. Test selected samples for soundness and possible rejection of type	Fr-Th cycling
Artificial aggregates	1. Consult results of any durability tests to assist preliminary classification of particle types	
	2. Examine general sample or graded fractions, describe and separate different types of particles	C 295
	3. Select samples of different types for thin section study and durability tests	C 88, C 131 C 289, C 342
	4. Test durability of particle types, correlate with petrography	Fr-Th cycling

⁺ Or mineral particles, if material is fine

* Petrographic Number. See Ref. (9) or Canadian Standards Association, A23.2-15B

DETERIORATION OF CONCRETE

The observation of deterioration in concrete structures poses many questions, the first being why it should occur at all when so much is known to prevent it. Concrete should last indefinitely if all known precautions are exercised during its manufacture, i.e., using only high quality cement of the proper type, applying proper concreting procedures, and ensuring that aggregates are sound and chemically stable in all environments to which the concrete will be subjected. Unfortunately, liberties are commonly taken with the first two, the latter is never certain, and some flexibility in choice of aggregate is usually necessary. With concrete, problems arise with compromise.

In natural environments the deterioration of concrete usually results from positive physical actions involving: (1) degradation of the mortar bonds, resulting in piecemeal destruction of the concrete matrix and (2) expansion of aggregate

particles, from which sufficient stress is generated to exceed the tensile strength of the mortar and cause the familiar surface map-cracking. The processes which produce these actions are numerous; moreover, they seldom occur independently, which compounds the problem of identifying the underlying causes.

Some of the principal causes of concrete deterioration are discussed below with examples and useful references. A summary of causes and effects is included in Table 4.

DEGRADATION OF MORTAR

Mortar deterioration is invariably related to low bond strength, which may be a primary feature or result from reactions in place. It is revealed by routine strength tests, particularly tensile, and often by surficial weathering which leaves the coarse aggregate exposed and clean (Fig. 1). The principal causes of low bond strength are: a. improper concrete procedures, b. improper cement or poor mix proportions, c.

Table 4 - Common features and causes of concrete deterioration

Distress mechanism	Features	Causes, activities
Degradation of mortar	Weakly bonded matrix; friable, low strength mortar Aggregate clean of mortar	a. Original strength low: excessive water, low cement content; incomplete hydration b. Green state freezing; over-working damage c. Hydration bonds destruction: acid or salt attack; moist freeze-thaw cycling
Physical expansion of aggregate	Disruption of particles; popouts; mortar cracks Dilation of concrete	a. Water absorption and adsorption by clay minerals or other high surface area materials; increased volume ruptures mortar b. Freezing of adsorbed water in permeable aggregate
Cement-aggregate reactions	Physical expansion of concrete Random cracks on exposed surfaces; inter-crack mortar strong unless mortar deterioration advanced Gel and limy deposition on fractured aggregate or in pores Reaction rims on aggregates	a. Alkali-silica gels form in hydrous environment, effect expansion of aggregates, rupturing mortar; reaction continued as alkalis recycled or replenished from cement or salts b. Finely divided phyllosilicates imbibe water, or react with alkalis and expand c. Unstable phases react to form a higher-volume solid (e.g., ettringite)

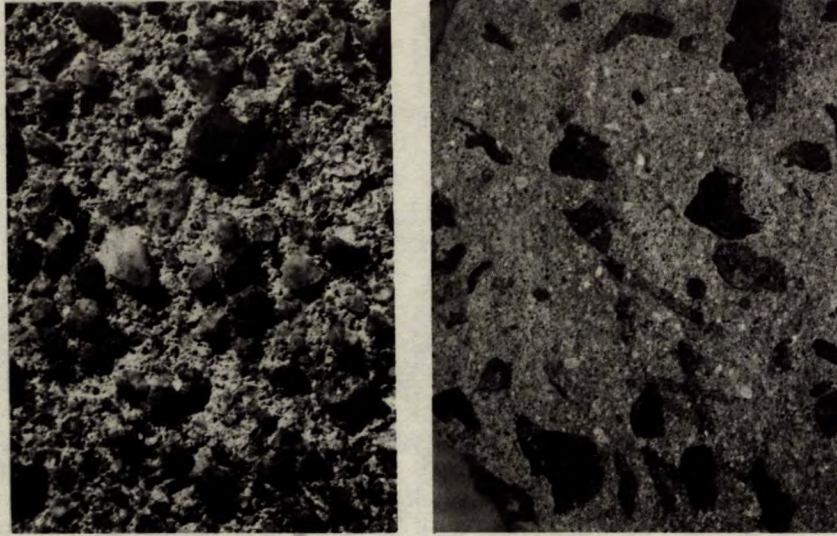


Fig. 1 - Deterioration of mortar in 2-year concrete pavement frozen after emplacement (left), compared with durable 70-year pavement (right). Mortar of the former erodes easily, that of the latter has worn evenly with the coarse aggregate. Mag 0.6x.

aggressive environments and d. sub-standard fine aggregates. Some examples of each are worth emphasizing:

- a. Placing concrete in freezing conditions without adequate protection slows hydration and unreacted water may freeze, destroying early-set bonds. Overworking the paste and attack by corrosive solutions can produce a similar effect at the surface.
- b. Using improper cement can have devastating effects, such as that produced by expansion or polymorphic inversion of primary aluminosilicate hydrates in unfavourable conditions (8, 11). Aggregated cement particles, inhomogeneous mixes and excessive water can all yield concrete with poor bonding and durability, at least locally, because of low cement content.
- c. Aggressive environments which destroy cement bonds are common. Well known examples are: aerobic sections of sewage lines where sulphurous acids are produced; pure or carbonatic water; acidic water, e.g., from swamp lands (12); alkaline and sulphatic soils or treatment plant solutions (Fig. 2); roadways treated with de-icing salts; and marine sites.

Freezing and thawing always accelerate destruction.

Potentially aggressive environments must be recognized in advance so that durable materials and protective methods can be used. Appropriate cement, sound aggregates and shielding with unreactive coatings will minimize destructive reactions (13).

- d. Low quality fine aggregate may be used inadvertently or from necessity, despite rigid specifications (ASTM C-33). Poor materials are those containing salts, clays and reactive silicates, which decrease the total bond strength because of interference with hydration, poor cement-mortar adhesion or harmful reactions with cement. The mechanisms are discussed later.

EXPANSION OF AGGREGATE

Aggregate expands for three principal reasons: a. free absorbed water freezes, increasing the total aggregate volume; b. water is adsorbed by hygroscopic phases, increasing their volume; and c. cement-aggregate reactions produce compounds which are themselves hygroscopic.



Fig. 2 - Deterioration of portland cement mortar in the concrete footings of a Na_2SO_4 plant, after 6 years. The aggregate rubble is sound, except for minor damage of schistose material. A protective concrete shielding (right) slowed the reaction greatly for a time.

Absorption of Water with Subsequent Freezing

This cause of failure is common with permeable rocks of fine grain size, fine porosity and weak intergranular bonding, such as shale, siltstone and poorly indurated, impure sandstone. Such rocks may often be suspect from their colour, friability and mineralogy, but resistance to freezing and thawing is more dependably judged from standard tests of absorption (ASTM C-127, C-128), sulphate soundness (ASTM C-88) and abrasion resistance (ASTM C-131, C-535). For ledge rock, a most useful rapid test is to measure the dilation of cylinders or prisms during accelerated freezing and thawing or immersion in NaOH solution (14,15). Slaking loss from aggregate particles in freeze-thaw cycling or wetting-drying can also quickly indicate potential soundness of aggregate (16).

A high pore volume does not necessarily mean that a rock would deteriorate in moist freeze-thaw environments; e.g., a coarsely porous recrystallized dolostone or a well-bloated artificial aggregate can be highly durable because the interpore bonding is strong and relatively impermeable. Having a wide range of pore sizes also seems to improve resistance to freezing, perhaps because unfilled larger pores permit the release

of hydraulic pressures resulting from water freezing in finer conduits, as do the pores in air-entrained concrete (16).

Adsorption of Water

Phases which strongly adsorb water are undesirable in aggregate because migrant moisture will cause expansion and possible rupturing of the concrete matrix. In natural aggregates they are usually recognizable as weak materials (ASTM C-142, etc.) or are revealed by the standard absorption and soundness tests. Most of them are clay minerals, perhaps having an expandable layer such as in sodium montmorillonoid, but at least having a large surface area and ligands to which the water molecule can attach and decrease the surface free energy or strength of bonding so that expansion occurs. The water literally becomes part of the structure and, unlike the water in larger capillaries, is not freezable as a liquid mass; nevertheless, the expansive force can be highly destructive (18).

Chemical Reactions

Reactions involving aggressive solutions which cause rapid surficial destruction of concrete mortar, such as the acid and sulphate attack

mentioned earlier, are of less concern than those arising from the interaction of cement and aggregate components, because the latter's destructive ability may not be predictable. In the last three decades, many combinations once considered stable have been found unstable when exposed to unfavourable conditions over long periods.

The major unstable phases in concrete are alkali hydroxides present in the cement and constituents of the aggregate which react with them. Many minerals and rocks are known to be alkali-reactive, but judging from their appearance and alteration products they react in different ways. Three types of reactions are now recognized: (1) alkali-silica reactions, in which hydrated amorphous silica, finely divided or chalcedonic quartz, and glassy to cryptocrystalline volcanic rocks are the unstable phases; (2) alkali-carbonate reactions, involving certain dolomitic limestones containing dispersed argillaceous material; and (3) alkali-silicate reactions, in which layered silicate minerals of metamorphosed sedimentary and other rocks appear to be the unstable phases. The characteristics and products of the different types of reaction have been described in detail and the mechanisms of deterioration debated by many authors as field occurrences were recognized and examined (19,20,21). All types may show evidence of aggregate expansion, such as closure of joints, buckling or stress of structures, fracturing of mortar surrounding aggregates and map cracking on exposed surfaces. The destructive mechanisms are often not obvious, but the problems generated are; they range from loss of aesthetic appearance to failure of the structure.

The alkali-silica reaction is probably known best. Its principal products of alteration are distinctive gelatinous hydrates which form when the Na and K alkalis in solution, either from the cement or introduced with de-icers, attack unstable silica in aggregates. These gels expand as water is imbibed and exert pressure on the surrounding mortar (22). If the gel viscosity is high, the stress may exceed the tensile strength of the mortar and fractures will develop. If the viscosity is low and the permeability high, the

gel will migrate through the mortar and along fracture systems, relieving expansive pressure. Characteristic features of reaction are "clarified" rims on permeable particles, layered deposits of opalescent alkali-silica hydrates in voids, and a weakened aggregate-mortar bond. The classic example of reactive aggregate is the well known opaline chert of California; a different type, shown in Fig. 3, 4 and 5, is the permeable calcitic Potsdam orthoquartzite from Valleyfield, Quebec, which contains chert particles and siliceous intergranular films that appear to be reactive (23).

The alkali-carbonate reaction is less common, is normally slower, and the destructive mechanism is less evident than in the alkali-silica type. The most abundant alteration products present are calcite and films of Ca-Mg hydroxides and silicates; gels are rarely observed. Extensive studies have suggested that the reaction involves destruction of dolomite crystals by the alkaline solutions, which releases entrapped active clay minerals that adsorb water directly and swell, or perhaps adsorb sodium to form a hygroscopic, montmorillonite-like material that imbibes water (24).

The alkali-silicate reaction, now being recognized in several localities, is even less easily explained. The reaction rate is slow, which has long delayed diagnosis and will always cause uncertainty as to the potential soundness of similar types of aggregate. Many different rocks are responsive, including greywackes, shales, phyllites, other metamorphosed sedimentary and possibly volcanic rocks (25). Constituents common to all of these are phyllosilicate minerals, some of which appear to react with the cement alkalis in solution, exfoliate, imbibe water and expand. However, the total volume affected often seems inadequate to cause destructive expansion. Gels have been observed in concretes containing the aggregates, but the typical opalescent alkali-silica deposits are not abundant in voids. Dark rims do appear on permeable aggregates and the adjacent mortar may be discoloured but such features need not indicate expansion (Fig. 6,7). Other features are also notable: radial fractures,



Fig. 3 - A fracture through 45-year old concrete, from a river pier, containing reactive calcitic Potsdam sandstone aggregate. Translucent siliceous gel (with desiccation cracks) migrated along the fracture from reacting aggregate. The porcellaneous deposit lying within the dark clarified rim contains much calcium, either derived from the calcite or transported. Mag 3x.

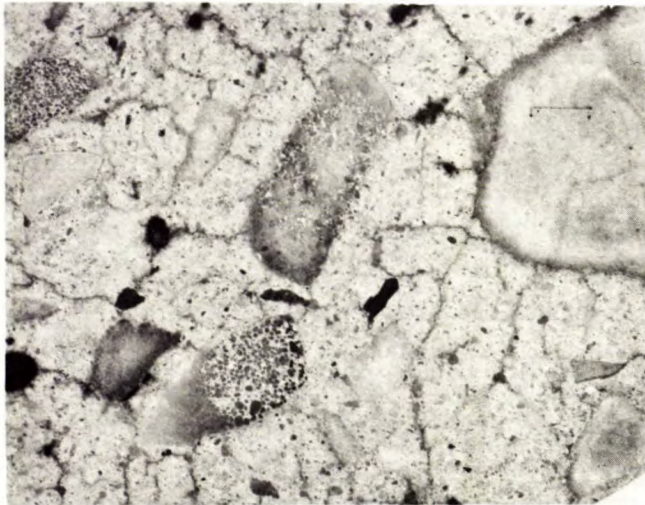


Fig. 4 - "Reaction" rims on polished surface of the same permeable Potsdam sandstone aggregate of Fig. 3. A typical amorphous alkali-silica reaction product deposited elsewhere in voids is unidentifiable here; but the gel or sol is believed to have migrated along quartz grain boundaries and fractures, wetting them and reducing light reflection. Radiating fractures suggest aggregate has expanded. Mag 3x.

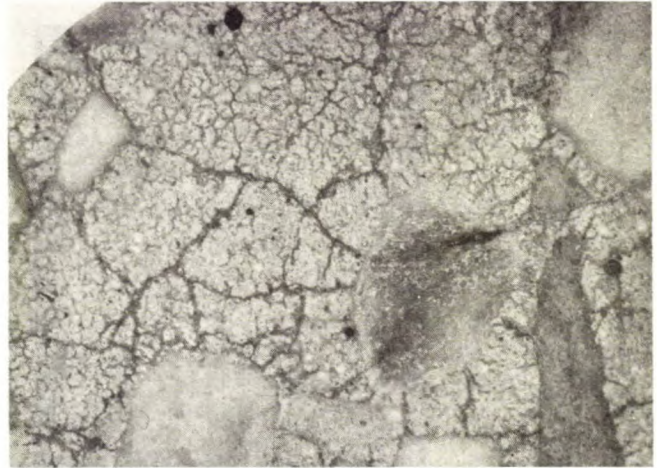


Fig. 5 - Advanced alkali-silica deterioration of the concrete shown in Fig. 4, in which the sol appears to have anastomosed into the concrete matrix from the radial fractures surrounding aggregate. Trypan dye; Mag 3x.

have rarely developed around aggregate, the aggregate-mortar bonding is invariably weak, the major fractures follow the aggregate boundaries, and siliceous limy films often coat the fracture faces. Possibly, shrinkage after reaction rather than expansion, followed by invasion of saline solutions and freeze-thaw cycling, was the most active process of destruction. Further detailed chemical and strength analyses of boundary phases may provide information for a different theory.

METHODS OF CONTROLLING ALKALI-AGGREGATE REACTION

The control of concrete quality is truly becoming a problem even in those countries endowed with abundant raw materials. It is often an exercise in economics, in which the costs of producing low alkali cement, transporting high quality aggregate, or beneficiating poorer local materials are compared relative to the rising price of fuel (26). More important is the fact that aggregates of lower quality must increasingly be accepted out of necessity, with the result that rejection of concrete materials now often depends on how much they will increase the potential rate of concrete deterioration in the ambient conditions. The principal means of controlling undesirable reactions are discussed below.

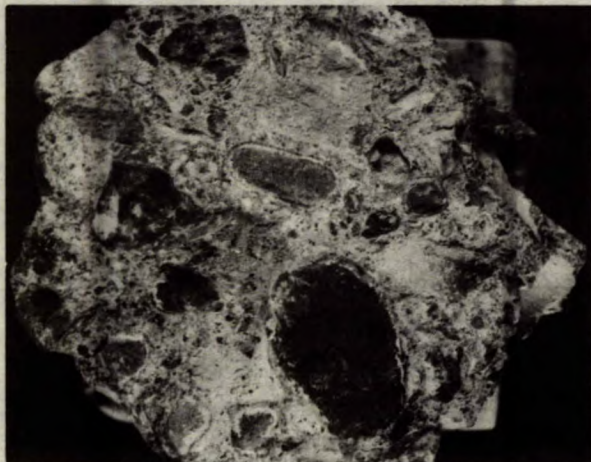


Fig. 6 - Fracture surface of concrete from a New Brunswick highway bridge, incorporating heterogeneous metasedimentary, metavolcanic and igneous rock aggregate. The surface is coated partly with a calcitic veneer containing silica presumably hydrous and derived from alkali-silicate reactions. Note limy rims on broken metasediment particles.

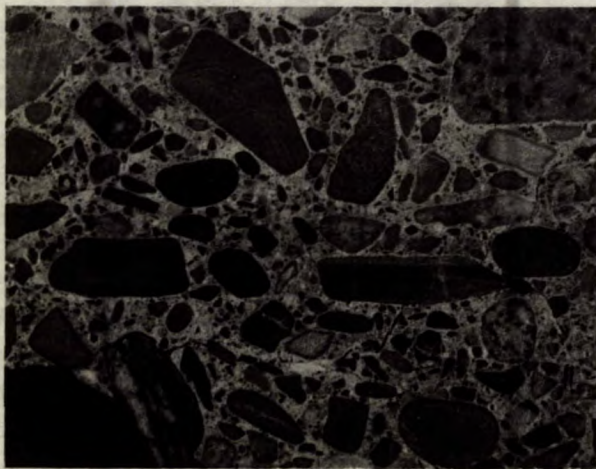


Fig. 7 - Polished surface of the same concrete, revealing reaction features. Igneous particles (speckled) and most volcanics (dark, smooth) are unaffected; most metasediments and sandstone contain dark rims. Mortar at grain boundaries may be whitened and is weakened so that fractures mostly follow the boundaries. No radial cracks have developed around aggregate particles to suggest they have expanded.

Protective Shielding

As water is the medium through which all harmful chemical reactions occur in concrete, its exclusion from the system following hydration of the cement would largely prevent deterioration. Rendering concrete impermeable to water and water vapour would therefore be the most effective method of preventing reactions except that impermeability is rarely obtained or maintained. A coating may be slightly penetrable or cracks will develop; an impregnant may not seal the permeable components completely because of poor bonding or instability (27,28), and surface reactions and cyclical thermal or freeze-thaw activity may ultimately destroy an effective shielding.

Such a method of protection will always slow the rate of deterioration, however, and particular circumstances may favour its application, such as the resurfacing of a bridge deck. More important, perhaps, is that shielding a concrete may increase the potential durability of an aggregate sufficiently to permit its being used in a normally hostile environment.

Selecting Sound Aggregate

Second to maintaining a dry environment, using sound aggregate is the most effective way of reducing cement-aggregate reactions. In many countries it is not readily available, however, and in others with an abundance, the supply of better quality aggregate is decreasing steadily in high-demand areas. Beneficiation by removing deleterious materials, selective quarrying to obtain the soundest rock types, and proper firing of raw materials with selected additives to obtain durable artificial aggregate are all methods used to improve the quality of aggregate and minimize its potential reactivity.

Reducing the Alkali Content of Cement

It has been shown frequently that reducing the alkali content (Na_2O equivalent) of cement markedly decreases the rate of alkali-induced reactions in concrete, therefore with reactive aggregate the cement content should be reduced to the minimum obtainable. The amount tolerated will vary greatly with the proportion and type of dele-

terious aggregate present and with the environment (19,29). For example, in dry or cold regions a high-alkali cement might be used safely with relatively reactive aggregate, whereas in warmer wet conditions it could not.

The modern cement plant is designed to give the maximum output at minimum cost using a dry process involving preheating and recycling of feed at lowered temperatures to conserve fuel. As a result, the calcine contains most of the alkalis present in the feed, which may give far more than the 0.6 % limit for low-alkali cement. Their removal would require elevating the calcining temperature to volatilize them and then precipitating the added dust from the flue gases to prevent contamination of the environment. Both processes are costly and plant efficiency would drop appreciably with their introduction (30).

Some researchers now question whether an excess of alkali will cause destructive expansion, as the water absorption of the gel increases and a less rigid sol is formed which moves through the matrix without developing high pressures (31). The durability of such a modified matrix, well illustrated in Fig. 5, might also be questioned, however, so the assurance of less reaction with a low-alkali cement would recommend its use when possible, pending results of durability tests.

Mineral Admixtures

If the alkali content and proportions of reactive aggregate cannot be reduced in the concrete mix and water cannot be excluded from the structure, the alkali-aggregate reactivity can at least be greatly inhibited by adding low-alkali pozzolans such as fly ash to fix the reactive alkalis (32), or replacing a proportion of the cement with cementitious material such as blast furnace slag to reduce permeability (Fig. 8). These preventive measures are well known or are being investigated and their use can be expected to increase as inhibitors are improved or found to be effective (33,34).

DISCUSSION

Concrete is a composite of hydrated cement and aggregate materials often placed in chemically active environments. Under such circumstances, few of the phases should be viewed independently because they are often mutually unstable. The types of reactions, their rates and effects will differ greatly, depending on ambient conditions and the composition and texture of aggregates, cement and mortar.

The petrographer must take these factors into account when investigating concrete or concrete materials. Predicting the potential behaviour of a concrete in advance or determining the causes of failure after emplacement is his ultimate objective, which can be achieved only if stability of the materials used is known under all the conditions expected or to which it is subjected. The information is accumulating steadily as theory, experimental work and case histories reveal the behaviour of petrographically similar materials in different environments (35,36). The usefulness of petrographic analysis in the con-



Fig. 8 - A comparison of the stability of portland cement mortar cubes submerged 5 months in 2% Na_2SO_4 solution. Left: 100% cement; Right: 40% cement and 60% blast furnace slag, which apparently decreased mortar permeability remarkably. (E.E. Berry, unpublished data.)

struction industry is therefore increasing.

When conclusions are drawn using petrographic information alone, caution is advisable because, to quote Mather (37), "Each examination presents some new facet for the petrographer...". That is an accurate and sobering statement, for it means we do not have all the factors at hand to predict or resolve all the problems that may

arise with concrete during its use. Nevertheless, concrete that is acceptably durable can be produced by using materials that are relatively stable in the environments expected. Petrographic examination assists in their selection and, coupled with an improved understanding of deterioration mechanisms, provides a sound basis for solving unexpected problems.

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