

PETROGRAPHIC INVESTIGATION OF ALKALI-REACTIVE
SILICATE ROCKS IN SEVERAL STRUCTURES

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ABSTRACT

The identification of potentially reactive aggregates is a very responsible and one of the most difficult task of a petrographer. To establish the alkali reactivity of silicate rocks proves to be especially complicated because of the great number of rocks which may be reactive. Three examples of alkali reactive rocks from deteriorated concrete structures are described. The aggregates are: quartz arenite, quartz wacke and argillaceous quartz wacke, and distinctly deformed dacite. The problems in identifying the reactive varieties of these rocks especially in bulk aggregate samples are emphasized.

Petrographic examination is one of the important techniques for identifying rocks that are potentially alkali reactive when used in portland cement concrete. The petrographic identification of alkali reactive rocks is based on a knowledge of, or direct comparison with, rocks that are proven to be alkali reactive. It is generally recognized that the petrographer cannot predict that a rock will be reactive if there is no previous record of reactivity for that particular type of rock. It is well to understand that a petrographic examination by itself is not an absolute assurance against the inclusion of alkali reactive material in portland cement concrete.

The petrographic identification of alkali reactive rocks and varieties suspected of being alkali reactive is based on examination to determine the composition and texture of rocks and on the identification of the products of alkali-aggregate reactions. For the siliceous reactive rocks, the reaction products are the rims and silica gel which are formed when reactive aggregates are incorporated in concrete. The presence of alkali reactive aggregates in concrete can also be confirmed by identification of physical effects associated with reactivity; the expansion primarily of the aggregates and subsequently of the concrete. The closing of joints, disalignment of structural elements, misalignment of machine sets, cracking of the aggregates and the cement paste, pattern cracking of the concrete surface and general disintegration of the concrete are evidence of the expansion.

This paper is a discussion of the difficulties and uncertainties faced by the petrographer in identifying alkali-reactive silicate rocks or silicate rocks suspected of being alkali reactive. The purpose of emphasizing the problems and difficulties is to encourage further work and perhaps help to point out the direction in which further work and answers are urgently needed.

Methods of "Routine" Petrographic Analysis

The main petrographic method for identifying alkali reactive rocks is by careful examination of the composition and texture of the rocks and by comparing rocks with others that are known to be alkali reactive. The basic guidelines for petrographic examinations are given in the ASTM Designation C295. The new proposed "Standard Recommended Practice for Petrographic Examination of Hardened Concrete" ASTM Designation C (?) provides a method for the examination of aggregates in concrete. Many

excellent papers by various authors such as K. and B. Mather (e.g.11) and R. Mielenz (e.g.12) describe detailed petrographic methods applicable to concrete aggregates and concrete. Detailed petrographic examinations of alkali reactive rocks in Canada was made by Gillott, Swenson and Duncan (16, 17, 7).

Difficulties in Identification of Reactive Silicate

Aggregates in Concrete

As mentioned, the basis for petrographic identification of reactive aggregates are concrete structures which show distress typical for alkali reactive aggregates: dark rims on crushed aggregate particles are frequently the first features observed, gel as the product of reactivity, characteristic expansion cracks in the reactive particle extending into the cement paste and pattern cracking on the surface of a concrete. In addition, proof of reactivity requires that the aggregate has been used with high alkali cement in a concrete exposed to a moist environment. If these conditions were not fulfilled, an erroneous conclusion could be made that an aggregate is not reactive. Although cracking and reactive expansion are typical signs of reactivity, similar cracking may be caused by other factors such as freezing and thawing.

When examining single aggregate particles, the weathering rims that occur in natural sands and gravels may be mistaken for the secondary dark rims that are a positive indication of alkali-aggregate reaction. If both gravel and crushed rock have been used together in a concrete, then it is necessary to examine the rims on crushed particles only.

The presence of silica gel is usually considered to be the best proof that alkali-silica reactive aggregate is present in a concrete. Difficulty in detecting and identifying silica gel may occur for various reasons such as (a) unsatisfactory sampling of the concrete, (b) the silica gel may be partially crystallized and complex due to repeated gel formation, (c) it may be "contaminated" with various oxides and therefore may not have the same appearance as the classical isotropic gel, (d) it may be coated with other products, (e) it may be leached out. In thin sections, gel may be lost during the preparation of the thin section if insufficient care has been taken to preserve it.

Incorrect sampling may cause difficulty in determining the most reactive rock or variety in an aggregate; this applies especially for

multilithic aggregates. It is frequently difficult to establish which particle originated the gel on the surface of a crack. Secondary products such as calcite or ettringite or both, which may also be developed on cracks opened and enlarged by reactive aggregates, may cover the silica gel. Calcite may be present as a crust on the gel, as small prisms or as minute rhombohedrons. Ettringite may be present as long fibres indicating that it developed in a fairly open crack. Gel is not always easily identifiable and many mounted sections of the secondary products may have to be examined to make an appropriate judgement about the extent of alkali reactivity.

Examples of Alkali Reactive Silicate Rocks in Concrete

Silicate rocks which are alkali reactive may occur in various compositional or textural varieties or both. Precise determination of the variety of a rock that is reactive is often difficult because it has been proven that for most rocks, similar or petrographically equal varieties may be either innocuous or reactive to varying degrees. This has been experienced with silicate rocks from the Canadian Shield (5) and it can be assumed that it applies to varieties of sandstones and an acid volcanic rock which were examined recently. These rocks were used as aggregates in large concrete structures which required repeated extensive repair. Parts of the structures showed pattern cracking varying in intensity at different locations. Distinct cracking parallel to the edges and outer surfaces indicated deterioration due to frost action. The concrete in each structure contained gel and additional secondary products consisting of abundant calcite and various amounts of ettringite. The three aggregates are described in the following detail.

Example 1

Coarse and fine aggregates consist of quartz arenite (ortho-quartzite), very subordinate calcitic quartz wacke and some blending sand (?).

Concrete containing these aggregates was used in a lift bridge, in a hydraulic lock and in a hydro-electric generating station. Of the three aggregates discussed in this paper, this aggregate causes the greatest problems. Disalignment necessitates repeated repair. The concrete shows pattern cracking, in some areas with a well developed large pattern of wider cracks enclosing a smaller pattern with narrower cracks.

Example 1: Quartz Arenite

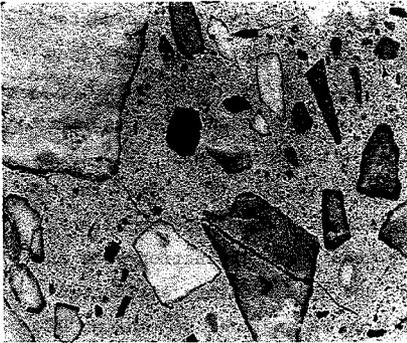


FIG. 1

Cracked coarse, fine aggregates
and cement past (1.1x)

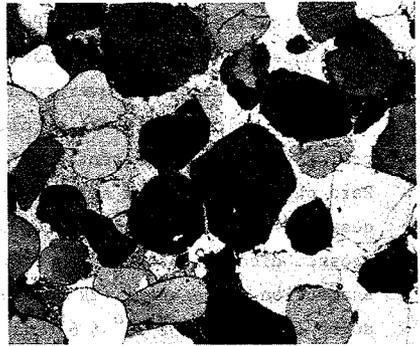


FIG. 2

Quartz wacke with calcitic cement
(65x), T.S. crossed nicols

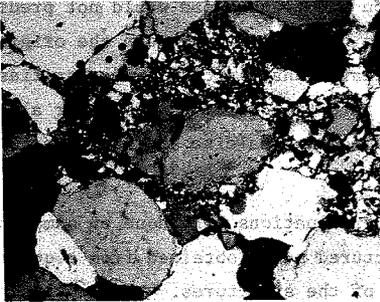


FIG. 3

Quartz arenite with fine-
grained quartz and clay inter-
stices (62x), T.S. crossed nicols



FIG. 4

Cracked quartz grains in arenite
(65x), T.S. crossed nicols

Figure 1 shows the coarse and fine aggregate particles in the concrete with cracks crossing the aggregates and extending along the aggregate-cement paste paste interfaces into the cement paste. The aggregate rock is whitish to greyish, less frequently slightly brownish. A narrow rim (0.3 mm in the average), usually one or two quartz grains deep, is developed in most particles. The border of the rim toward the inside of the aggregate is gradational. Gel occurs in cracks but is lost

during thin section preparation.

The aggregate is a uniform quartz arenite according to the classification by Pettijohn, Potter and Siever (14), with rounded to subrounded, well sorted to moderately well sorted quartz grains. They are mostly cemented by overgrown silica, far less frequently with secondary calcite (FIG. 2) or clayey material. The size of the quartz grains varies in different particles, the most frequent size is 0.25 mm. Rare particles contain stripes of much smaller grains (FIG. 3). The quartz grains are usually homogeneous (see FIG. 2 and 3 taken with crossed nicols). Few grains show slight undulatory extinction with an extinction range angle (ER angle) of 13° and an undulatory extinction angle (UE angle) of 30° (6); grains with an ER angle of 26° and an UE angle of 53° are exceptions. Cracking of larger quartz grains is frequent in some areas (FIG. 4) but few are broken into smaller pieces or are separated into small grains by the calcite cement.

In general petrographic terms, the rock is uniform as are most of the quartz grains. Based on the composition and texture one would not predict this to be a highly expansive rock. The border lines between the original quartz grains and the later growth indicates that lattice irregularities may occur there. Calcite indentations into the quartz grains occur along portions of the interface between the cementing calcite and many quartz grains.

About 20 years ago, petrographic examinations were done on samples of crushed coarse aggregate and manufactured sand, obtained from a quarry which supplied aggregate for a portion of the structures. Megascopic and microscopic examinations showed that the aggregates were of the same kind as those in the concrete examined recently. The quartz arenite consisted mostly of fine to medium quartz grains and a few varieties contained layers rich in coarse sand. The cement, 10 to 20 percent, was formed by secondary overgrowth of quartz, in patches it was calcitic or consisted of clayey material. In 25 thin sections used in the previous and recent examinations, the clayey material did not amount to 5 percent of the rock by estimation. The carbonates amounted to 1.1 percent in the fractions of manufactured sand indicating that calcitic cement was rare. At this time, the alkali reactivity of the rock was not recognized and there was no obvious cracking in the concrete which, at that time, was about 20 years old. This would indicate that the quartz arenite belongs to the group of slow expanders.

Example 2

The coarse concrete aggregate consists of crushed sandstones grading to siltstone and shale or orthoquartzite, and gravel consisting predominately of these rocks and subordinately carbonate rocks. The fine aggregate is a natural sand of the same composition as the gravel with monomineral grains prevailing in the finer fractions.

Example 2: Sandstones

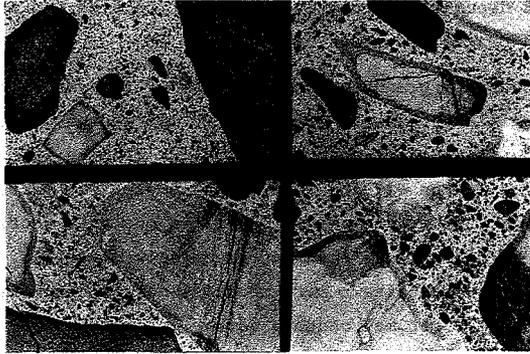


FIG. 5

Red argillaceous wacke and greenish quartz wacke both with rims and cracks (0.94x)

0.64



FIG. 6

Argillaceous wacke with dark argillaceous concentrations showing crack (65x) T.S. crossed nicols

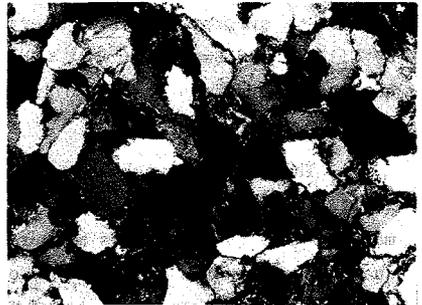


FIG. 7

Quartz wacke grading to arenite with mica scales at quartz borders (65x) T.S. crossed nicols

The 40 year old concrete used in hydraulic locks and bridges show extensive cracking, scaling and spalling and typical pattern cracking in some locations. Many coarse aggregate and several particles of the coarse sand fraction show dark rims measuring 1 to 4 mm. in width with little variation in a given particle (FIG. 5).

Secondary products are very abundant in the outer areas of the concrete but decrease toward the inner ends of the 3 to 8 foot long drill cores which were examined in detail. The products consist of silica gel and abundant deposits of relatively compact calcite and fluffy ettringite developed in cracks and voids.

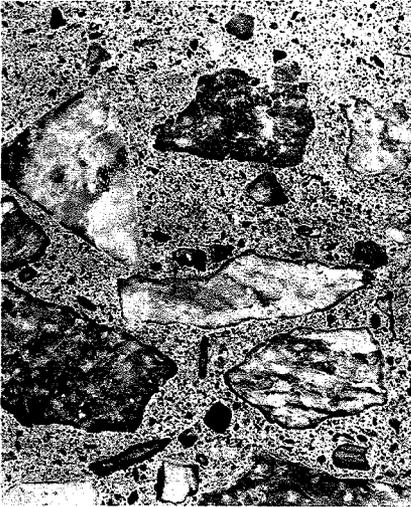
The coarse aggregate consists mainly of two varieties of sandstones, a reddish argillaceous wacke grading into siltstones and even shales and a somewhat less frequent greenish quartz wacke grading into quartz arenite. Both varieties may be developed in the same concrete particle. The reddish wacke is usually finer grained (0.07 mm. in one thin section), the grains are angular to subangular, than the greenish wackes (FIG. 6 and 7). The reddish rock also contains a more abundant matrix consisting of hematite and clay minerals. It may contain narrow layers richer in the clayey matrix or even small argillaceous lenses. Particles of the reddish distinctly argillaceous sandstone and especially the argillaceous lenses are prone to cracking parallel to the layering (see FIG. 6). The rims and gel deposits along the rims in the wacke show that the variety is definitely reactive. Although no data of the exact amount of clay-grade constituents are available, the rock seems to have some similarity to the alkali reactive subgraywacke from Alert, Ellesmere Island, examined in detail by Gillott and Swenson (8). The presence of gel in this rock seems however to indicate that also in this wacke quartz is involved in the reaction.

The greenish wacke consists of angular to subrounded uniform quartz grains, much less abundant feldspar grains and a scarce clayey matrix. The quartz grains measure about 0.20 mm. in size and show frequent quartz overgrowth. This variety of the sandstones with some similarity to quartz arenites is also reactive forming reaction rims with gel deposits.

Example 3

Coarse aggregate crushed distinctly deformed dacite. Fine aggregate natural sand with fragments of the crushed volcanic rock in the

Example 3: Distinctly Deformed Dacite



0.68X

FIG. 8

Segregation of cracked aggregates and cement paste. Life size.



FIG. 10

Uniform plagioclase and strained quartz in fine grained groundmass (35x) T.S. crossed nicols.

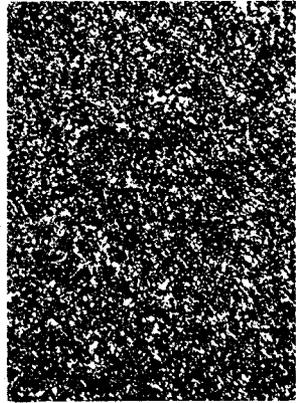


FIG. 9

Uniform cryptocrystalline groundmass (65x). T.S. crossed nicols.



FIG. 11

Branching crack with gel and desiccating cracks in microcrystalline groundmass (78x) T.S. polar. light.

coarse "sand" fractions.

The concrete is used in a bridge which shows distinct cracking in the piers and typical pattern cracking in the sidewalks. The coarse aggregate particles showed narrow rims, 0.1 to 0.9 mm. in thickness (FIG. 8). Gel and calcite deposits were abundant on cracks and in air voids in some concrete pieces but were scarce in other pieces that were available for examination.

The coarse particles are very heterogeneous but consist of one rock type only which is a dacite with well developed large phenocrysts twinned plagioclase (subordinate potash feldspars) and quartz.

The groundmass consists of quartz, feldspar, mica and locally of chlorite scales. The micas are aligned in some areas giving the rock a slightly schistose appearance. The size of the constituents varies greatly. It is most frequently microcrystalline, in small areas homogeneous cryptocrystalline, with an average grain size less than 0.01 mm. (FIG. 9), in other areas it is fine crystalline.

The most characteristic feature of the rock is the distinct deformation, which increases its heterogeneity. It is least evident in the feldspar phenocrysts which show a patchy extinction or they are broken into several pieces. The cracks do not always follow cleavage planes. Quartz phenocrysts show a distinct wavy extinction (FIG. 10) and cracks separating them into smaller grains. The average ER angle is 7° and the UE angle 30° . Shearing planes and microfolding are visible in the groundmass. Lenses and accumulations of muscovite scales represent what seems to be former mafics. Aggregations of quartz coarser than the groundmass are developed in the shadows of the feldspar and quartz phenocrysts. Some quartz may have been introduced later as were pyrite grains which are disseminated in some particles. Calcite occurs in rare patches. Distinct cracks are developed in the concrete aggregates. They follow the mica rows but also cross the groundmass irregularly. In two thin sections gel was preserved in the cracks, in both instances in areas of the groundmass (FIG. 11).

Unsolved Problems

Detailed examination with the petrographic microscope and some x-ray analysis left many pertinent questions unanswered. Rims were not easily detectable under the petrographic microscope. Normal optical methods did not show identifiable signs of reaction such as surface

indentation on medium or coarse quartz grains. In the quartz arenite, it could not be determined if only the small quartz grains and the portions of quartz overgrowth were alkali reactive or if the medium and coarse quartz grains were also reactive. It is hard not to assume the latter, although signs of lattice disturbance were rare and no imperfections were evident. It was not determined whether the rare calcitic quartz wacke varieties were reactive. Alkali reactive quartzites (quartz arenites) involving coarsely crystalline quartz have been reported from other areas (3 , 7).

In the second example of wackes and arenite, it could not be determined if the quartz grains or the matrix are reactive or both. The amount of argillaceous material that must be present in sandstones (wackes) and siltstones to make them unreactive was not determined. The silty shales present in the concrete areas where gel occurred on sandstones showed only cracks parallel to the fissility and no development of gel although the silt grains were apparently minute quartz grains.

The distinctly deformed and devitrified dacite presents special problems. It is known that a devitrified groundmass of acid volcanics is alkali reactive. Cracks in the cryptocrystalline (grain size less than 0.01 mm (13)) and microcrystalline groundmass are filled with gel. Some cracks occur within mica-rich lenses but traverse the mica lineation in areas with fewer micas. This rock is secondarily altered but judging from the presence of cracks and gel the alteration has not significantly diminished the reaction, if it has influenced it at all. The extent to which this would apply to other rocks is not known.

Some of these questions might be answered by modern scanning electron methods which provide micrographs (16,8) and by x-ray element distribution photographs (19). The former is more and more widely used in investigations of alkali reactive aggregates.

Examination of Rock Specimens and

Bulk Aggregate Samples

It is much easier to determine the reactive silicate rocks in concrete petrographically than to assess the potential reactivity of an outcrop or a quarry. It is even more difficult to determine the reactivity of bulk aggregate samples from multilithic pits. An exceptionally large number of particles would have to be examined in thin sections or mounted

powder sections to establish reactivity if only about 2 percent of the rocks were reactive. Some rocks cause deterioration of concrete at this concentration.

Far too little experience is yet available to identify in bulk aggregate samples reactive granitic rocks, charnokites and granite gneisses (19,9) a few of which are described as being alkali reactive although strained quartz may give some indication (18,6). It would be unjustifiable to classify all granitic rocks and granitic gneisses as suspected of being alkali reactive on the basis of the few reported alkali reactive examples when the same rocks have been widely used in concrete without causing distress. The examples from India indicate that the concrete was exposed to higher temperatures than are normal in moderate climates.

It has to be repeated that without examination of concrete structures containing similar aggregate and/or adequate laboratory tests petrographic examinations cannot establish whether an aggregate without a service record is potentially alkali reactive. Concrete structures made with an aggregate which can be identified with sufficient degree of exactness must be available. There are newly developed areas in which no concrete structures are yet built. The same or identical rocks submitted for petrographic examination have to be tested for expansion before it can be concluded that the aggregate source contains potentially reactive material. The examination of expansion in rock cylinders ASTM C586 gives an important clue to which varieties are expansive. The test of rocks in easily prepared small prisms (1-1/8" by 1/8" by 1/4" or approximately 30 x 3 x 6 mm) proposed by Grattan-Bellew and Litvan (10) is promising. Relatively small gravel pieces could be tested.

General Petrographic Questions Regarding Alkali Reactive

Silicate Rocks

There are many basic questions of general petrographic interest which cannot be resolved using the normal methods and equipment available to a petrographer. The main problems are connected with medium to coarse grained quartz-rich rocks. It has to be assumed that minute quartz grains are probably developed on the surfaces of larger quartz grains, in interstices, along channel ways into which alkali solutions can penetrate, and on microcracks. Are these minute quartz grains causing alkali reactions or it is correct to assume that even coarse quartz grains are alkali

reactive? What is the role of an argillaceous matrix containing quartz in silt or clay size? In these cases, are the amounts too low to influence the degree of reactivity of the main constituent of a silicate or carbonate rock? Should it be assumed that quartz is the most important and abundant constituent in devitrified volcanic glass? How coarse must be the groundmass in an acid porphyritic rock, a type of felsite, to prevent it from being reactive? How does metamorphic alteration influence volcanics? What is the influence of chalcedonic chert inclusions on the reactivity of carbonate rocks? These are some of the questions connected with the aggregate rocks discussed in this paper.

Conclusion

The petrographer when examining concrete aggregates for alkali reactivity deals with two different problems:

- 1) to determine whether a concrete is prematurely deteriorated because it contains alkali reactive aggregates and
- 2) to determine whether an aggregate source is potentially alkali reactive.

Detailed examination of deteriorated concrete containing alkali reactive aggregates helps to become better acquainted with some varieties of the numerous silicate rocks which are alkali reactive.

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CONTRIBUTIONS TO DISCUSSION

Mr. D. St. John

My experience has been similar in that while I have seen reaction rims around aggregates in fracture surface I have not always been able to see the same rims in thin section. In one particular case, of a pyroxene andesite which consisted of more than 60% reactive glass, I considered that such a large area of surface was available for reaction that at any one point on the surface of the aggregate reaction had not proceeded to the point where it was visible in thin section.

Mrs. K. Mather

Evidence of alkali silica reaction is sometimes visible only as rims on crushed stone and as "main cracks" as described by Gunnar Idorn and excellently illustrated in two diagrams in his book. These illustrations are of great value to all petrographers.

Dr. P. Grattan-Bellew

I would like to add further comments to the discussion by K. Mather on the problem of observing gel in sections and polished slabs, etc., the point was made that during the course of time gel may get washed out. My comment is that gel may get washed out as one tests a gel extracted from concrete made with reactive aggregate and high alkali cement have shown. At least 50% of the gel is readily soluble in water, the bulk of the remainder being soluble in dilute HCl.