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Petrographic Evaluation of Concrete Aggregates

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PREFACE

Petrographic examination of concrete aggregate was included in the three previous editions of ASTM Technical Publication, *ASTM STP 169*, *ASTM STP 169A*, and *ASTM STP 169B*, under the present authorship. The construction and content of this chapter is like that of the former presentations except that a substantial addition treats petrographic examination of recycled concrete for use as aggregate in new construction. The properties of recycled concrete are covered in some detail so as to aid the petrographer in decision on investigation of constructions to be demolished with intent to produce concrete for recycling and on observations that should be made as a part of the examination of the finished aggregate. Experience and literature pertinent to examination of all types of concrete aggregate are cited as appropriate.

INTRODUCTION

Petrographic examination of concrete aggregate is visual examination and analysis in terms of both lithology and properties of the individual particles. The procedure requires use of a hand lens and petrographic and stereoscopic microscopes. Less commonly, X-ray diffraction, differential thermal analysis, or electron microscopy is used to supplement the examination using optical microscopes. By petrographic examination, the relative abundance of specific types of rocks and minerals is established; the physical and chemical attributes of each, such as particle shape, surface texture, pore characteristics, hardness, and potential chemical reactivity, are described; coatings are identified and described; and the presence of contaminating substances is determined, each in relation to proposed or prospective conditions of service in concrete constructions.

As will be discussed subsequently, petrographic examination contributes in several ways to the investigation, selection, testing, and control of quality of aggregates. Consequently, the method is progressively being applied more widely. Since 1936, all aggregates used in concrete construction by the Bureau of Reclamation, United States Department of the Interior, have been examined petrographically as part of the basis for their selection [*1*,*2*]. The method has been applied similarly by the Corps of Engineers since before 1940 [*3*]. Coarse aggregates proposed for use in either portland-cement concrete or bituminous concrete are examined by petrographic methods in laboratories of the Ministry of Transportation–Ontario, and specifications governing acceptance are based upon the results [*4*]. Petrographic examination is performed also by several other agencies of the U.S. government and state departments of transportation, and may be obtained through some testing and engineering laboratories.

In 1952, ASTM Tentative Recommended Practice for Petrographic Examination of Aggregates for Concrete (C 295) was accepted, and was adopted as a standard in 1954. Minor modifications were made subsequently, most recently in 1985. The document has been published as the Guide for Petrographic Examination of Aggregates for Concrete in the *1991 Annual Book of ASTM Standards*. Petrographic examination is also cited in ASTM Specification for Concrete Aggregates (C 33).

The abundant data obtained and the rapidity with which petrographic examination can be completed justify more general use of the method in investigation, selection, manufacture, and use of concrete aggregates. However, in all cases, the petrographer should be supplied with available information on the conditions of service to which the concrete is to be exposed.

This paper summarizes the objectives and applications of petrographic examination of aggregates with reference to gravel, sand, crushed stone, blast-furnace slag, the most common types of lightweight aggregates, and aggregates produced by recycling of hardened concrete from constructions. Special attention has been given to developments in this field since publication of *ASTM STP 169B* in 1979. Techniques of the examination are treated briefly because instructions have been published [*3*–*11*] and are included in ASTM C 295.

PURPOSE OF THE PETROGRAPHIC EXAMINATION OF CONCRETE AGGREGATES

Preliminary Determination of Quality

Preliminary petrographic examination of concrete aggregate is performed either in the field or in the laboratory as an adjunct to geologic examination, exploration,

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mapping, and sampling. The examination assists the geologist or materials engineer in determining the extent to which consideration of an undeveloped deposit is justified. Also, the preliminary petrographic examination indicates the relative quality of aggregates from alternate sites. By revealing variations in the material, examination of exposures or cores from pilot drill holes establishes the minimum program of exploration and sampling necessary for acceptance or rejection of the deposit.

Establishing Properties and Probable Performance

Petrographic examination is primarily a supplement to the acceptance tests. Probable performance of concrete aggregate is estimated in two general ways by petrographic examination. First, the examination reveals the composition and physical and chemical characteristics of the constituents. From this information, the probable response of the aggregate to such phenomena as attack by cement alkalies, freezing-thawing, wetting-drying, heating-cooling, or high temperatures usually can be estimated. The rapidity with which the petrographic examination predicts potential alkali reactivity of aggregate is especially valuable because of the widespread occurrence of this condition and the long time commonly required by realistic tests of concrete or mortar.

Second, petrographic examination establishes the fundamental nature of aggregates so that aggregates from unfamiliar sources can be compared with aggregates upon which information is available. This application is discussed subsequently.

Correlation of Samples with Aggregates Previously Tested or Used

Detailed petrographic examination is the only procedure that permits comparison and correlation of samples with aggregates previously used or tested. Thus, data and experience previously obtained by use and long-time tests of similar aggregates can be applied in the selection of materials proposed for current work, even though the materials come from new sources.

By relating the sample to aggregates previously used in construction, aggregate indicated to be unsound by standard tests may be found adequate, or conversely, aggregate indicated to be sound in standard tests might be found unsatisfactory for the intended use.

For example, gravel in certain deposits near Jackson, Michigan, meets usual specification requirements for soundness, abrasion resistance, and content of soft particles, yet produces objectionable popouts in pavements after exposure for two winters (Fig. 1). Petrographic examination of the gravel and of individual particles producing popouts during service has identified the unsound rock types and the critical minimum size required for failure. Examination of proposed materials will demonstrate the presence or absence of such particles and will thus indicate, in the light of other data, whether the aggregate should be accepted, rejected, or subjected to special tests.

FIG. 1—Popouts produced by claystone, shale, and chert in concrete pavement near Jackson, Michigan (courtesy of Michigan Department of Transportation).

Petrographic examination of aggregate may be a part of an investigation of concrete constructions as described in the ASTM Practice for Examination and Sampling of Hardened Concrete in Constructions (C 823) and ASTM Practice for Petrographic Examination of Hardened Concrete (C 856). For example, the examination may be applied to determine the source of aggregate used in the constructions, such as whether it was obtained from an approved or not approved source.

Selecting and Interpreting Other Tests

All of the properties of aggregates influencing performance of concrete in service ordinarily are not evaluated by test before selection of the aggregate to be used in the work, primarily because of cost and time required. Such factors as thermal properties and volume change with wetting-drying rarely are determined. Other properties, such as chemical reactivity or effect of the aggregate on the freeze-thaw resistance of concrete, usually are not determined. Consequently, it is worthwhile to apply a procedure by which the relative significance of such properties can be determined and the need for supplementary quantitative tests indicated.

Petrographic examination aids interpretation of other tests. For example, are the particles identified as clay lumps in accordance with ASTM Test Method for Clay Lumps and Friable Particles in Aggregates (C 142) indeed clay lumps or are they merely friable or pulverulent particles of some other composition? What is the cause of unexpected failure of concrete specimens in freezing and thawing? Is it the presence of unsound particles that do not disintegrate in the sulfate soundness test, yet expand in freezing and thawing? Is it the result of an alkali-aggregate reaction? Is failure in the soundness or abrasion test the result of complete breakdown of a small proportion of unsound or soft particles or partial disintegration of the greater proportion of the aggregate?

Detection of Contamination

Petrographic examination is the best method by which potentially deleterious and extraneous substances can be detected and determined quantitatively. Inadvertent contamination with natural substances, industrial products, or wastes, such as overburden or from trucks or railroad cars not properly cleaned of previous cargo, may decrease the quality of aggregate markedly. Contamination by containers may invalidate samples. Such substances as clay, soil, coal, vegetable matter, chemical fertilizers, petroleum products, or refractories containing free calcium or magnesium oxides are especially important. Incomplete processing of synthetic aggregates may contaminate the finished product with raw or partly fired materials or coal.

Undesirable substances inherent in the material, such as coatings, clay, plant remains, coal, and soluble salts, are detected easily and can be determined quantitatively by petrographic methods or by other procedures that can be selected most definitively pursuant to petrographic identification.

Determining Effects of Processing

Petrographic examination aids in production and processing of aggregate. The relative merit of alternative processing methods and equipment can be determined quickly by comparison of the original material with the processed aggregate. Comparison can be based on particle shape, content of unsound or chemically reactive constituents, removal of coatings, or production of rock dust.

The feasibility of beneficiation by removal of unsound or deleterious constituents depends on the properties of the particles and their abundance. By petrographic examination, the undesirable particles can be identified and separated. Their properties can be evaluated and compared with properties of the remainder of the aggregate. If the undesirable particles are unusually soft, friable, dense, lightweight, or high in magnetic susceptibility, separation may be feasible on a commercial scale.

Petrographic examination can be used to control the manufacture of synthetic aggregate, such as expanded shale or clay, perlite, slag, and other types. Microscopical examination will reveal the presence of raw or underburned materials, alkali-reactive phases, and contaminants, such as coal (Fig. 2). X-ray diffraction analysis is the most dependable means to identify and determine quantitatively the proportion of crystalline phases, such as periclase (MgO), free lime (CaO), and clays whose crystal structure was not destroyed by the calcination. Differential thermal analysis can be used to estimate the effective temperature to which clays, shales, slate, and similar materials have been fired; the trace of the differential thermal curves for the raw and fired product will coincide above the effective temperature achieved in the firing operation.

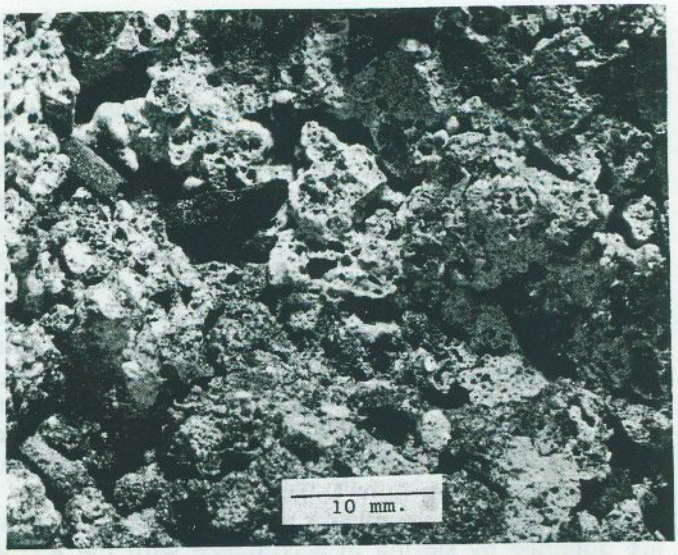


FIG. 2—Coal in sintered clay before crushing (courtesy of Bureau of Reclamation, U.S. Department of the Interior).

PERFORMANCE OF THE PETROGRAPHIC EXAMINATION

Samples for Petrographic Examination

Samples of aggregate for petrographic examination should be representative of the source. Recommended procedures for sampling and for preparation of the sample for analysis are covered by ASTM Practices for Sampling Aggregates (D 75), ASTM C 295, and technical literature [*12*].

Examination in the Field

Petrographic analysis of samples in the field is usually qualitative or only semiquantitative because lack of facilities makes detailed work difficult. However, detailed examination in the field may be warranted if aggregate retained on the 75-mm (3-in.) sieve is to be used in the work, inasmuch as a representative sample of this size fraction may weigh a hundred or more kilograms and transportation of the sample to the laboratory is costly. Chips from cobbles not adequately identified in the field should be taken to the laboratory for further study.

If the deposit or rock exposure is variable, samples should be selected from each zone, and detailed notes made at the site should relate each sample to a particular zone and portion of the deposit or rock ledge. The relative proportion of unsound, fractured, or chemically deleterious materials should be estimated from measurements made at exposures. These notes and the results of the tests on the samples will be the basis for operation of the deposit inasmuch as it may be desirable to waste or avoid zones or portions containing inferior, unsuitable, or alkali-reactive materials.

Examination in the Laboratory

Petrographic examination of aggregate in the laboratory may be brief or detailed. Brief examination indicates the relative merit of materials from alternate sources and supplies justification for abandonment or continued investigation of undeveloped deposits or other exposures. The preliminary examination should not replace the quantitative analysis included in the program of acceptance tests.

Samples supplied to the laboratory comprise: (*a*) granular materials, such as gravel, sand, crushed stone, slag, or synthetic aggregate; (*b*) stone in quarried blocks and irregularly shaped pieces or drilled cores; and (*c*) fragments, sawed pieces, or drilled cores of concrete that contain the aggregate (coarse, fine, or both) that is of interest. For fully graded granular materials, the examination should be performed on at least three size fractions included in the aggregate. The sample of each size fraction should comprise at least 150 particles. For natural sand and gravel and crushed stone, the minimum representative samples are shown in Table 1.

Samples of the aggregate for petrographic examination are obtained by sieving in accordance with the ASTM Method for Sieve Analysis of Fine and Coarse Aggregates (C 136) and ASTM Test Method for Material Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing (C 117). The fractions are quartered or, for fine aggregate, split repeatedly on an appropriate riffle.

Details of the procedure are outlined by K. Mather and B. Mather [*3*] and in ASTM C 295.

During the analysis, helpful information on identity and physical condition can be obtained by recording such features as: (1) friability or pulverulence in the fingers; (2) resonance when struck; (3) ease of fracturing; (4) nature of the fracture surface and fracture fillings; (5) odor on fresh fracture; (6) color and its variation; (7) internal structure, such as porosity, granularity, seams, and veinlets; (8) reaction to water, such as absorption of droplets on fresh fracture, evolution of air on immersion, capillary suction against the tongue, slaking, softening, or swelling; and (9) differential attack by acids or other media.

Fractions retained on the 600-µm (No. 30) sieve are best identified, examined, and counted under the stereoscopic microscope. The analysis can be made conveniently by traversing a representative portion of each fraction by means of a mechanical stage and microscope assembly like that employed in the point-count procedure according to ASTM Practice for Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete (C 457) (Fig. 3). The mineralogic composition of finer fractions usually is determined most easily and accurately in immersion oils or thin sections under the petrographic microscope. However, better continuity in description of physical characteristics of the particles is obtained if analysis of fractions passing the 600-µm (No. 30) sieve and retained on the 150-µm (No. 100) sieve is performed under the stereoscopic microscope.

FIG. 3—Performing petrographic examination of fine aggregate with stereoscopic microscope, mechanical stage, and tally counter.

TABLE 1—Minimum Representative Sample Size.

Size Fraction, mm (in.)	Weight of 150 Particles
90 to 38 (3 to $1^{1}/_{2}$)	13 kg (20 lb)
38 to 19 ($1^{1}/_{2}$ to $^{3}/_{4}$)	4.3 kg (9.5 lb)
19 to 9.5 ($^{3}/_{4}$ to $^{3}/_{8}$)	0.6 kg (1.3 lb)
9.5 to 4.7 ($^{3}/_{8}$ to $^{3}/_{16}$)	0.17 kg (0.38 lb)
4.75 to 2.36 (No. 4 to 8)	7.5 g
2.36 to 1.18 (No. 8 to 16)	1.1 g
1.18 to 0.60 (No. 16 to 30)	0.14 g
0.60 to 0.30 (No. 30 to 50)	0.017 g
0.30 to 0.15 (No. 50 to 100)	0.0033 g

Thin sections occasionally are necessary in examination of natural aggregate. They usually are employed in the study of quarried stone. However, preparation of plane sections by sawing and lapping, with or without etching or staining, commonly is preferable because of the large area made available for examination or analysis. Such examination should be supplemented by microscopical examination of grain mounts in immersion oils. Thin sections or polished surfaces, supplemented by use of oil immersion mounts of granular material, usually are used in the analysis of blast-furnace slag aggregates. X-ray diffraction and differential thermal analysis may be required to identify or determine quantitatively constituents that are very finely divided or dispersed through particles of the aggregate (Fig. 4).

Any of the previously noted types of coarse or fine aggregate can be examined while enclosed in hardened concrete, using broken fragments, sawed and lapped sections, and microscopical thin sections, as required and appropriate.

Ordinarily, petrographic analysis of concrete aggregates is performed on at least three coarse fractions and five fine fractions. The results may be used to compute the lithologic composition of the aggregate in any gradation comprising the analyzed size fraction. The bulk composition of a concrete sand may vary widely with fineness modulus. Occasionally, one analysis may be performed on a graded aggregate. For such analysis, the composition by count may differ greatly from the composition by mass.

Numerical results of the analysis may be expressed by mass or count of particles retained on the 600-µm (No. 30) sieve, but for the finer fractions, the results are based only upon count of grains unless a correction factor is applied. Consequently, consistent analyses of all fractions of fine aggregate and coarse aggregate can be reported

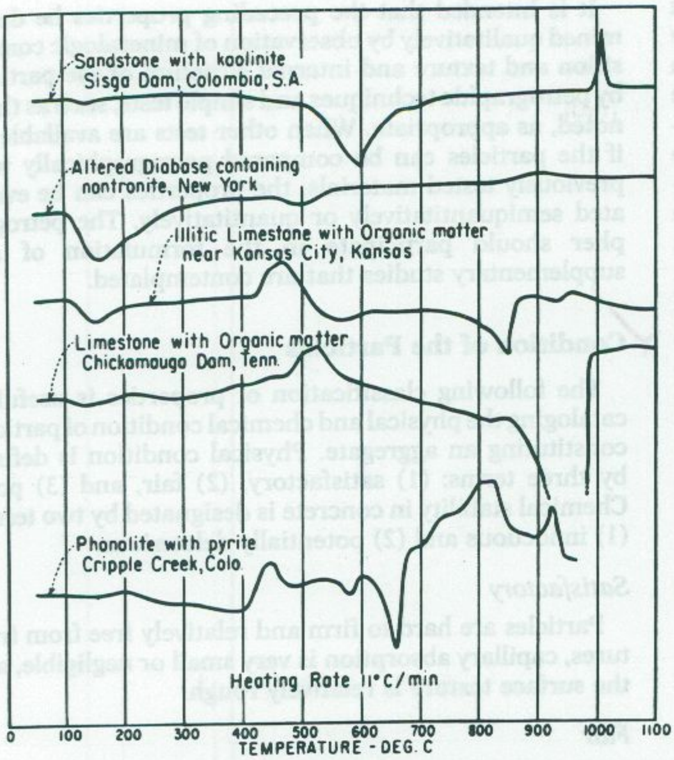


FIG. 4—Typical differential thermal analysis (DTA) records obtained on concrete aggregates. Kaolinite is indicated by the endotherm (downward shift) at 990 to 1025°C. Nontronite is revealed by endotherms at 100 to 350°C and 450 to 550°C. Illite produces the small endotherms at 100 to 200°C and 500 to 615°C. Organic matter produces large exotherms (upward shifts) at 430 to 500°C or 440 to 600°C. Pyrite (ferrous sulfide, FeS_2) develops a marked exotherm at 400 to 485°C (courtesy of the Bureau of Reclamation, U.S. Department of the Interior).

only by count. Analysis by count is the more appropriate determination technically because the influence of particles of given type upon performance of concrete in test or service depends primarily upon their frequency and distribution in the mass. When applied to coarse aggregate only, the petrographic analysis is more rapid if the relative proportion of the several rock types or facies is determined by mass. However, the accuracy and precision of analysis by mass are affected adversely by unavoidable loss of portions of the particles when they must be broken to allow identification of the composition and description of the physical condition. Specifications on lithologic composition preferably are expressed as percentage by count of particles.

Details of calculating and reporting of results of petrographic examination and analysis of concrete aggregates are summarized in ASTM C 295. The results of analysis of composition of aggregates enclosed in hardened concrete, such as by point-count analysis on sawed and lapped surfaces, are expressed as percent by volume of the concrete or percent by volume of total aggregate. Analysis of aggregate enclosed in concrete usually is confined to determination of the proportional volume of individual selected types of particles relative to the proportional volume of the total aggregate (see subsequent discussion).

Observations Included in the Petrographic Examination

In reporting the results of the petrographic examination, the petrographer should supply information on the following subjects as necessary for evaluation of the aggregate for service under the anticipated conditions of exposure in the concrete:

- Mineralogic and lithologic composition
- Particle shape
- Surface texture
- Internal fracturing
- Coatings
- Porosity, permeability, and absorption
- Volume change, softening, and disintegration with wetting-drying
- Thermal properties
- Strength and elasticity
- Density
- Hardness
- Chemical activity
  - Solubility
  - Oxidation
  - Hydration
  - Carbonation
  - Alkali-silica reactivity
  - Alkali-carbonate reactivity
  - Sulfate attack on cementitious matrix
  - Staining
  - Cation-exchange reactions
  - Reactions of organic substances
  - Effects of contaminants

The significance of these properties is discussed by Rhoades and Mielenz [*7,8*], Dolar-Mantuani [*11*], Swenson and Chaly [9], Hansen [*13*], Mielenz [*14*], and others [*15–19*]. Sarkar and Aitcin [*20*] emphasize the need for petrographic examination of aggregates for very high-strength concrete, especially regarding internal texture and structure of the particles.

A simple test to detect forms of pyrite and similar ferrous sulfides that are likely to oxidize while enclosed in concrete was devised by Midgley [*21*] and is discussed more generally by Mielenz [*14*]. Shayan [22] reported popout formation and deterioration of the surface of a concrete floor by oxidation and hydration of pyrite included in exposed particles of coarse aggregate.

Soles [*23*] found that pyritiferous dolomite used as coarse aggregate produces distress when the concrete was heated to about 150°C (300°F) but less than 300°C (575°F). The deterioration is a result of expansion of the particles as oxidation and hydration of the pyrite and crystallization of iron and calcium sulfates took place. The present author has observed similar effects when compact pyritiferous shales constitute appreciable proportions of gravel and sand coarse and fine aggregate. These observations are pertinent to the evaluation of aggregates to be incorporated in concrete that will be subjected to sustained high temperatures in the indicated range, such as structural members and slabs that are included in or support furnaces, kilns, and the like.

Stark and Bhatty [*24*] concluded that significant amounts of alkalies (sodium and potassium) can be released from certain alkali-bearing aggregates when in contact with a saturated solution of calcium hydroxide and that such released alkalies engage in expansive alkali-silica reaction in concrete. The release appears to involve ion-exchange phenomena and possibly dissolution of silicates within the aggregate. Sources of alkalies include glassy volcanic rocks, plagioclase feldspars, potassium feldspar (microcline), and feldspathic and quartzose sand. The release of potassium from phlogopite mica [*25*] and from particles of bentonite clay in natural sand [*26*] has been shown to promote an alkali-carbonate reaction in concrete. Similar effects can be produced by montmorillonite-type clays and zeolites from which sodium or potassium released by cation exchange may engage in alkali-silica reaction involving other siliceous constituents of the aggregate [*27*].

Schmitt [*28*] recently summarized information on micas as constituents of fine aggregate in concrete, citing work done in England whereby it was concluded that for each 1% of mica in fine aggregate by mass of total aggregate, the compressive strength of the concrete is reduced as much as 5%. Frost resistance is reduced and drying shrinkage is increased by increasing content of biotite. He commented also on applicable specifications on allowable quantities of mica in coarse and fine aggregate. Occurrence of mica in concrete sands from numerous sources in the continental United States is reported by Gaynor and Meininger [*29*].

Higgs [*30*] reported a correlation of methylene blue adsorption and the amount of smectite (montmorillonite-type) clay in natural sand that was the cause of undue slump loss and increased drying shrinkage of concrete, citing work by Davis et al. [*31*]. Elsewhere, he described the effect of chlorite in aggregate relative to its effect on the freeze-thaw durability of concrete [*32*]. The critical criteria required for poor durability were found to be chlorite content of volcanic rocks in excess of 20% and distribution of the mineral in seams, clots, and fissures in contrast to a disseminated condition in the rock.

Petrographic criteria useful in detecting dolomitic rocks that are potentially susceptible to a deleterious degree of the alkali-carbonate reaction in concrete are described by Dolar-Mantuani [*11*], Hadley [*33*], Gillott [*34*], and others [*35–38*]. Dolar-Mantuani [*39*] described the alkali-silica reactivity of argillites and graywackes. Bachiorrini and Montanaro [*40*] reported the occurrence of alkali-silica reaction in non-dolomitic carbonate rocks containing disseminated, finely divided silicate minerals. The alkali reactivity of strained quartz and quartzose rocks has been described and discussed by Buck [*41*] and others [*6,11,42*]. Investigators of concrete affected by alkali-silica reaction in many structures in Nova Scotia have concluded that alkali-silica reaction in which strained quartz is the primary alkali-reactive constituent has been augmented substantially by an alkali-aggregate reaction involving vermiculite that is present in phyllites, argillites, and graywackes that are widespread in natural aggregates of that region [*43*].

It is intended that the preceding properties be determined qualitatively by observation of mineralogic composition and texture and internal structure of the particles by petrographic techniques and simple tests, such as those noted, as appropriate. When other tests are available, or if the particles can be compared petrographically with previously tested materials, the properties can be evaluated semiquantitatively or quantitatively. The petrographer should participate in the formulation of any supplementary studies that are contemplated.

Condition of the Particles

The following classification of properties is useful in cataloging the physical and chemical condition of particles constituting an aggregate. Physical condition is defined by three terms: (1) satisfactory, (2) fair, and (3) poor. Chemical stability in concrete is designated by two terms: (1) innocuous and (2) potentially deleterious.

Satisfactory

Particles are hard to firm and relatively free from fractures, capillary absorption is very small or negligible, and the surface texture is relatively rough.

Fair

Particles exhibit one or two of the following qualities: firm to friable, moderately fractured, capillary absorption small to moderate, surface relatively smooth and impermeable, very low compressibility, coefficient of thermal expansion approaching zero or being negative in one or more directions.

Poor

Particles exhibit one or more of the following qualities: friable to soft or pulverulent, slake when wetted and dried, highly fractured, capillary absorption high, marked volume change with wetting and drying, combine three or more qualities listed under "fair."

Innocuous

Particles contain no constituents that will dissolve or react chemically to a significant extent with constituents of the atmosphere, water, or hydrating portland cement while enclosed in concrete or mortar under ordinary conditions of service in constructions. Particles are stable at high temperature or decompose without expansion.

Potentially Deleterious

Particles contain one or more constituents in significant proportion that are known either to react chemically under conditions ordinarily prevailing (or applicable in the present instance) in portland-cement concrete or mortar in such a manner as to produce significant expansion, interfere with the normal course of hydration of portland cement, or supply substances that might produce harmful effects upon mortar or concrete. By extrapolation, this category is extended to include individual constituents that produce notable expansion under conditions that are expected in the proposed work, such as in concrete to be exposed to high temperatures as a part of the planned service regimen, of which a prime example is quartz and highly quartzose rock types that are subject to disruption as the quartz crystal expands about 2.4% by volume while inversion takes place from the α- to the β-polymorph at 573°C (1063°F) [*44*].

Coatings should be reported and evaluated separately because coatings usually are confined to portions of a deposit and, for crushed stone, the nature and abundance of coatings vary with processing methods and equipment. Schmitt [*28*] recently summarized information concerning petrographic features of aggregate coatings and their significance.

Similarly, particle shape should be considered apart from other aspects of physical quality because particle shape commonly is subject to control or modification by processing of the aggregate. Unless otherwise defined by applicable specifications, particles whose length is five or more times their width should be designated as "elongated pieces," and those having a ratio of width to thickness greater than five should be designated as "flat pieces." The measurement should be made in accordance with definitions of these terms as they appear in ASTM Terminology Relating to Concrete and Concrete Aggregates (C 125). Particle shape relative to coarse aggregate is discussed by Sarker and Aitcin [*20*], noting in particular the unfavorable effect of elongated or flaky pieces on workability of concrete. See Gaynor and Meininger [*29*] and Mass [*45*] for helpful discussions of the significance of the particle shape of concrete sands.

Petrographic Examination of Aggregates in Hardened Concrete

General

Aggregates enclosed in hardened concrete from structures or pavements in service or from test specimens can be subjected to petrographic examination for any of many reasons, such as initially to identify the nature of the aggregates in older structures under investigation or to determine the involvement of the aggregates in either satisfactory performance or deleterious activity. The following features can be investigated during such examination:

1. Analysis of composition
    - Identification and qualitative or quantitative determination of proportions of constituents
    - Proportions of physically unsound or chemically reactive constituents
    - Contamination by foreign substances
    - Identification of sources of coarse and fine aggregate
    - Proportioning of blended aggregates
2. Proportions of coarse and fine aggregates
    - Sand-aggregate ratio
3. Segregation
    - Homogeneity of distribution of coarse and fine aggregates
    - Differential distribution of lightweight and heavyweight particles; coarse and fine aggregates
    - Concentration of unsound particles at exterior surfaces
4. Effects of attrition during handling of aggregates and mixing of concrete
    - Rounding of edges and corners
    - Coatings of dust of fracture
    - Aggregate fines within the cement-paste matrix
5. Coatings on aggregate particles
    - Composition and physical characteristics
    - Frequency and extent
    - Deleterious effects
6. Unsoundness of constituents during service or test exposure
    - Relationship of lithology and particle size to popouts
    - Involvement in scaling, *D*-cracking
    - Thermal expansion at high temperature in service exposure or fire
    - Decarbonation of carbonate aggregates in high-temperature service or fire
7. Chemical reactivity of constituents during service or test exposure
    - Alkali-silica reaction
    - Alkali-carbonate reaction
    - Dissolution of soluble constituents
    - Oxidation and hydration of ferrous sulfides in normal service
    - Oxidation and hydration of ferrous sulfides in high-temperature service
    - Hydration of free lime (CaO) or magnesia (MgO) in slag aggregates or contaminants
    - Staining of cement paste matrix by organic matter, sulfides, or other substances

Proportions of Coarse and Fine Aggregates

The proportions of coarse and fine aggregates within hardened concrete can be determined fairly readily on sawed and lapped sections by means of the microscopical point-count method or the linear-traverse method in general accord with the requirements of ASTM C 457. The task is straightforward if the lithology of the coarse and fine aggregates are unambiguously distinctive such that no mutually common constituents are included in the respective materials. The particles of coarse or fine aggregates are accordingly identified by composition and relegated to the appropriate category, regardless of particle size. The area to be traversed should be at least three times that shown in Table 1 of ASTM C 457 for the respective nominal maximum size of aggregate; the method is of doubtful practicality for concrete containing aggregate whose nominal maximum size is larger than 37.5 mm (1½ in.) [*46*].

For concrete containing natural or crushed gravel coarse aggregate and manufactured sand or natural sand or a crushed stone coarse aggregate and a natural sand, wherein one or more constituents are found in both the coarse and fine aggregates, other considerations are required. For example, in southern Michigan, gravels and sands contain high proportions of dolomites and calcitic dolomites originating in geologic formations that are operated as sources of crushed stone coarse aggregate for use in structural concrete and pavements. Although the natural aggregates characteristically are rounded because of the only moderate hardness of the rock, the particles of crushed stone typically are rounded at edges and corners by attrition incidental to processing and handling of the aggregate and mixing of concrete. In this instance, the distinction of coarse and fine particles can be approximated by classifying as coarse aggregate all particles whose cross section on sawed and lapped surfaces include one or more dimensions greater than 3/16 in., the opening of the U.S. Sieve No. 4 (4.75-μm), the remainder being classified as fine aggregate.

The measurement is made conveniently if the reticle of one eyepiece of the stereoscopic microscope includes a scale which, when calibrated, will demark the 4.75-μm (3/16-in.) dimension in the field of view. Of course, the dimensions of the cross section so revealed are not a measure of the size of the particle. Sections of coarse aggregate adjacent to edges and corners of the particle may be less than 4.75 μm (3/16 in.) in diameter and the maximum dimension of flat or elongated particles of fine aggregate may be greater than 4.75 μm (3/16 in.). However, these effects tend to be self-compensating. Completely angular and irregularly shaped particles of requisite lithology whose size is less than 4.75 μm (3/16 in.) would appropriately be relegated to the coarse-aggregate fraction if the aggregate is a combination of a crushed stone and natural sand.

These determinations permit estimation of the sand-aggregate ratio, an important factor in proportioning of concrete for optimum workability.

Alkali Reactivity of Aggregate Constituents

Examination of hardened concrete from service or test exposure allows determination of alkali reactivity of siliceous or dolomitic rock types through observations made on sawed and lapped sections or fracture surfaces. The manifestations of reactivity include such features as rim formation, microcracking within the particles and adjacent cement-paste matrix, and the presence of secondary deposits. Darkened or clarified rims within the peripheral border of aggregate particles are the initial and most frequent indication of cement-aggregate reaction. The presence of such rims requires determination that the rims are, in fact, a consequence of processes occurring within the concrete rather than a result of prior weathering.

A decision on this matter is made readily if a bonafide sample of the unused aggregate is available for separate study. Peripheral rims occurring adjacent to fractured faces of crushed stone or crushed natural aggregate can be taken as being a product of cement-aggregate reaction. Also, rims produced by cement-aggregate reaction will be seen to thin or disappear where the aggregate particle is bordered by a void space [47]. A condition that is more frequent and more readily discovered than the relationship between peripheral rims and adjacent void space is the thinning or disappearance of the peripheral reaction rim along the bottom side of the aggregate particle as cast in the concrete, a circumstance related to bleeding and settlement of the fresh concrete, presumably producing a real or incipient separation at this location or a more dilute cement paste of higher water-cement ratio and lower alkalinity.

Summarizing the Petrographic Examination

Tables 2 through 6 exemplify a variety of forms in which the petrographic analysis may be reported. All are based upon samples received as a part of engineering investigations. The tabulations always are accompanied by appropriate discussions and supplementary descriptions. Table 2 is in the form that has been employed by the Bureau of Reclamation [48]. It departs somewhat from the format recommended in ASTM C 295, but the inclusion of pertinent descriptions facilitates interpretation of the analysis. The tabulation could be simplified by cataloging the rock types into major and secondary classifications, such as "granite: fresh, moderately weathered and internally fractured, and deeply weathered." The summary of physical and chemical quality is included in a separate tabulation.

Table 3 is the analysis of the sand produced with the gravel whose composition is summarized in Table 2. The format conforms with ASTM C 295. Table 4 is similar except that the designations of quality are not used because they are inappropriate for the description of synthetic lightweight aggregates.

Table 5 is an analysis of a sample representing a commercial crushed stone coarse aggregate passing the 37.5-mm (1½-in.) sieve. The analysis was obtained because the aggregate apparently delayed or prevented development of specified strength by the concrete under certain conditions. In the tabulation, the denotation of "innocuous" and "deleterious" is restricted to potential deleterious alkali-silica reactivity because the significance of the sulfides and organic matter in the stone was not evaluated.

Table 6 is an example of petrographic analysis of aggregates in hardened concrete, namely, a crushed stone coarse aggregate and a natural sand containing particles of shale.

PETROGRAPHIC EXAMINATION OF NATURAL AGGREGATES

Examination of Natural Aggregates in the Field

Sand and gravel result from weathering, natural abrasion, and impacting of rock and the deposition of the resulting particles along streams, in lakes or marine basins, or by wind or glaciers on the earth's surface. Consequently, sand and gravel are more or less complex mixtures of different kinds of rocks and minerals. Moreover, deposits of sand and gravel usually vary vertically by stratification and laterally because of the lenticular nature of zones or strata. The concrete-making qualities of the aggregate are influenced by these changes. Examination in the field also should reveal the variability of the sand and gravel with reference to unsound or deleterious particles, interstitial clay, and organic matter.

Deposits of sand and gravel commonly are changed by deposition of mineral matter from ground water or by weathering of particles. Examination in the field should indicate the lateral and vertical extent and the physical nature and composition of the coatings. Areas of the deposit that are free from coatings and zones that are

TABLE 2—Example of Tabulation of a Petrographic Analysis of Gravel.
____________ Plant, ____________ Company, Near Denver, Colorado
Sample No. ____________

Rock Types	Size Fraction, % by weight[a]			Description of Rock Types	Physical Quality	Chemical Quality
	$1\frac{1}{2}$ to $\frac{3}{4}$ in.	$\frac{3}{4}$ to $\frac{3}{8}$ in.	$\frac{3}{8}$ to $\frac{3}{16}$ in.			
Granite	29.5	40.0	48.6	medium- to fine-grained, rounded to fragmental	satisfactory	innocuous
Weathered granite	12.0	17.7	17.2	fractured, weathered, rounded to fragmental	fair	innocuous
Deeply weathered granite	...	0.5	...	fractured, slightly friable, rounded to fragmental	poor	innocuous
Coarse-grained granite	6.4	6.1	8.4	pink, rounded, includes some free quartz	satisfactory	innocuous
Fractured coarse-grained granite	...	0.9	...	pink, rounded, includes some free quartz	fair	innocuous
Rhyolite porphyry	0.8	0.2	1.1	microcrystalline, porphyritic, white to brown	satisfactory	innocuous
Andesite porphyry	2.2	1.2	0.1	microcrystalline, porphyritic, tan, to green	satisfactory	innocuous
Weathered andesite porphyry	...	0.3	...	as above, fractured and weathered	fair	innocuous
Basalt	0.2	...	0.6	weathered, fractured, black, microcrystalline	fair	innocuous
Diorite	0.4	0.4	0.1	medium- to fine-grained, hard, massive	satisfactory	innocuous
Granite gneiss	32.2	14.3	15.8	hard, banded, fine- to medium-grained	satisfactory	innocuous
Weathered gneiss	10.3	7.8	2.7	as above, fractured to slightly friable	fair	innocuous
Deeply weathered gneiss	0.2	...	...	as above, intensely fractured to friable	poor	innocuous
Schist	2.2	2.3	2.2	hornblende schists, hard, rounded	satisfactory	innocuous
Fractured schist	...	0.4	0.2	as above, fractured	fair	innocuous
Quartzite	2.8	6.2	2.0	fine-grained, hard, massive to schistose	satisfactory	innocuous
Milky quartz	0.6	1.0	0.5	massive, hard, brittle, dense, smooth	fair	innocuous
Quartzose sandstone	...	0.1	...	fine-grained, massive, firm to hard	satisfactory	innocuous
Ferruginous sandstone	...	0.4	...	porous, brown, platy, quartzose	fair	innocuous
Shale	...	0.2	0.5	soft, absorptive, rounded, gray	poor	innocuous
Rhyolite	0.2	...	...	cryptocrystalline, porphyritic, pink to gray	satisfactory	deleterious

NOTE—Conversion factors—1 in. = 25.4 mm and 1 lb = 0.45 kg.

[a] Based upon analysis of 19.0 lb of $1\frac{1}{2}$ to $\frac{3}{4}$-in., 2.7 lb of $\frac{3}{4}$ to $\frac{3}{8}$-in., and 0.80 lb of $\frac{3}{8}$ to $\frac{3}{16}$-in. aggregate.

so heavily coated as to preclude processing as aggregate should be delineated.

Weathering of gravel and sand after formation of the deposit is common on terraces and at lower levels along existing stream channels, glacial deposits, and outwash. The examination should define the extent and distribution of such weathering.

Close observation of gravel and sand exposed on the surface of the deposit commonly will reveal unsound particles that slake or fracture with freezing-thawing or wetting-drying (Fig. 5). Identification of such particles will aid evaluation of the petrographic examination performed in the laboratory. In interpreting the effects of natural freezing and thawing, the consequences of particle size should be evaluated [*49*]. Representative specimens of particles affected by freezing and thawing should be packaged separately and transmitted to the laboratory with samples of the gravel and sand. Water-soluble salts in coatings or ground water also may be revealed by efflorescence at or near the surface of the deposit. Their presence forewarns of the need for their identification and quantitative determination of their concentration in the aggregate.

Examination of Natural Aggregates in the Laboratory

Samples and data from the field should be examined to determine: (1) the abundance of individual lithologic or mineralogic types; (2) the abundance of particles in various conditions of alteration and internal texture and structure and degrees of chemical reactivity; (3) the composition, frequency, abundance, and physical nature of

TABLE 3—Example of Tabulation of a Petrographic Analysis of Natural Sand.
____________ Plant, ____________ Company Near Denver, Colorado
Sample No. ____________

	Amount, as Number of Particles, %												
	In Size Fractions Indicated[a]							In Whole Sample[b]					
								Physical Quality			Chemical Quality		
Constituents	No. 4–8	No. 8–16	No. 16–30	No. 30–50	No. 50–100	No. 100–200	Passing No. 200	S[c]	F[c]	P[c]	I[c]	D[c]	T[c]
Granite and granite gneiss	34.9	33.6	21.0	4.8	...	...	...	13.5	1.0	0.6	15.1	...	15.1
Pegmatite	34.2	28.7	2.0	...	...	...	...	8.2	0.8	0.2	9.2	...	9.2
Rhyolite tuff	0.8	0.9	0.3	...	...	...	...	0.3	...	...	...	0.3	0.3
Basalt	...	1.0	...	...	...	...	...	0.2	...	...	0.2	...	0.2
Sericite schist	2.4	0.7	...	9.5	11.2	1.1	...	4.7	...	...	4.7	...	4.7
Quartz and quartzite	24.6	41.2	59.2	65.0	43.0	48.8	28.8	51.6	...	...	51.6	...	51.6
Feldspar	2.6	3.3	16.7	11.1	18.7	23.8	10.5	...	11.4	...	11.4	...	11.4
Claystone	0.5	...	...	...	...	1.2	...	...	...	0.2	0.2	...	0.2
Chalcedonic chert	...	0.6	...	3.3	...	...	...	1.2	...	...	...	1.2	1.2
Mica	...	...	0.8	6.3	10.2	8.3	51.1	...	3.8	...	3.8	...	3.8
Hornblende, garnet, zircon, etc.	...	...	...	...	16.9	16.8	9.6	2.3	...	...	2.3	...	2.3
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	82.0	17.0	1.0	98.5	1.5	100.0

[a] Based on count of 500 particles in each sieve fraction.
[b] Based on gradation of the sample received and on the distribution of constituents by size fractions shown at the left above.
[c] S = satisfactory; F = fair; P = poor; I = chemically innocuous; D = potentially chemically deleterious; T = total of constituent in whole sample.

TABLE 4—Example of Tabulation of a Petrographic Analysis of Expanded Clay Aggregate.
____________ Plant, ____________ Company
Sample No. ____________

	Amount, as Number of Particles, percent									
	In Size Fractions Indicated[a]									
Constituent	$^3/_4$ to $^3/_8$ in.	$^3/_8$ to $^3/_{16}$ in.	No. 4–8	No. 8–16	No. 16–30	No. 30–50	No. 50–100	Passing No. 100	In Whole Sample[b]	Remarks
Black to gray, vesicular particles	44.6	30.2	36.2	44.1	46.5	55.0	62.2	64.4	42.4	vesicular, hard
Black to gray, vesicular particles	13.1	1.7	...	...	...	...	...	...	1.2	vesicular, friable
Red to tan, vesicular particles	26.1	29.5	20.2	25.0	15.4	24.0	21.8	20.6	23.5	vesicular, hard
Red to tan, vesicular particles	7.7	1.8	...	...	...	...	...	...	0.8	vesicular, friable
Red to brown, brick-like particles	4.9	23.6	32.3	22.0	25.6	12.4	7.8	4.9	21.3	not vesicular, firm to fragile
Gray to pink, brick-like particles	2.8	9.8	7.7	8.8	9.2	3.0	1.6	1.1	7.1	not vesicular, fragile, many slake in water
Gray to pink, brick-like particles	0.6	1.0	0.4	...	...	...	...	...	0.4	not vesicular, friable, many slake in water
Gray to black, friable particles	...	1.7	2.0	...	0.8	0.3	...	...	1.0	not vesicular, contain coal
Granite	0.2	0.4	0.4	...	1.4	2.8	4.7	7.0	1.4	hard, dense
Sandstone	...	0.2	...	...	...	...	...	...	0.1	hard, fine-grained
Coal	...	0.1	0.8	0.1	1.1	2.5	1.9	2.0	0.8	hard to friable
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	

NOTE—1 in. = 25.4 mm.
[a] Based on count of 500 particles in each size fraction.
[b] Based on gradation of the sample received, and on the distribution of constituents by size fractions shown at left above.

coatings; (4) particle shape and surface texture; and (5) the possible qualitative contribution of particles of the several types to properties of concrete (Tables 1 and 2).

Natural aggregate may contain more than 20 rock and mineral types. Consequently, petrographic examination commonly is time consuming. Based upon the similarity in composition and the probable performance in concrete, two or more rock types commonly can be combined into a single category with considerable savings in time and without loss in the validity of the analysis. For example, granites, quartz diorites, granodiorites, and quartz monzonites—or rhyolites, dacites, and latites—of similar composition and physical condition might be combined, thus eliminating the need for tedious examination sufficient to effect a separation.

Soft, friable, and altered particles may be original constituents of sand and gravel, or may be developed by weathering in the deposit. Weathering in the deposit is

TABLE 5—Example of Tabulation of a Petrographic Analysis of Crushed Stone Coarse Aggregate.[a] ______________ Plant, ______________ Company
Sample No. ______________

		Amount, % by weight[b]					
		Physical Quality			Chemical Quality		
Rock Type or Facies	Description of the Rock Type or Facies	S[c]	F[c]	P[c]	I[c]	D[c]	T[c]
Dense dolomitic limestone	gray to buff, contains sparse organic matter with pyrite and marcasite	56.2	...	...	56.2	...	56.2
Soft dolomitic limestone	gray to buff, soft to friable, slightly porous, sparse organic matter with pyrite and marcasite	...	33.9	...	33.9	...	33.9
Soft, organic dolomitic limestone	same as above except containing one or more seams of iron sulfides and organic matter	...	4.2	...	4.2	...	4.2
Limestone	white to gray, coarse- to medium-grained	2.4	...	...	2.4	...	2.4
Laminated limestone	laminated, fine-grained, iron sulfides and organic matter abundant	...	2.1	...	2.1	...	2.1
Chalcedonic limestone	white to gray, particles of zones of chalcedony evident	1.0	...	...	...	1.0	1.0
Chalcedonic chert	conchoidal fracture, dense	...	0.1	...	...	0.1	0.1
Sandstone	includes also grains of quartz and feldspar	0.1	...	...	0.1	...	0.1
Total		59.7	40.3	...	98.9	1.1	100.0

[a] Sample graded in accordance with specifications of the ______________ State Highway Dept. for 1½ in. to No. 4 aggregate for concrete highway pavement (1 in. = 25.4 mm).

[b] Based upon analysis of 25.9 lb of aggregate split from the sample (1 lb = 0.45 kg).

[c] S = satisfactory; F = fair; P = poor; I = not deleteriously alkali reactive; D = potentially deleteriously alkali reactive; T = total of constituent in the sample.

TABLE 6—Microscopical Analysis of Aggregate in Hardened Concrete[a]

Core No. 1—Street pavement in front of ______________. Washington Street, ______________, Michigan

Core No. 2—Sidewalk, SW corner of ______________ Street and ______________ Street, ______________, Michigan

Item	Core No. 1	Core No. 2
Coarse aggregate, % by volume of total aggregate	54.99	54.70
Sand fine aggregate, % by volume of total aggregate	45.01	45.30
Shale particles, % by volume of sand fine aggregate	11.35	8.96

[a] Microscopical point-count method, ASTM C 457, based on the following criteria:

Core No.	Number of Counts	Area Traversed, in.[2b]
1	1944	35.9
2	2838	24.9

[b] Maximum area available in submitted samples (1 in. = 25.4 mm).

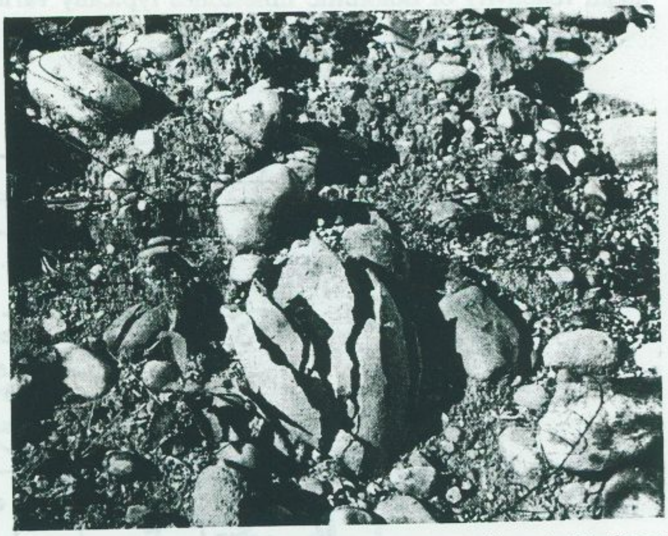


FIG. 5—Cobbles of argillaceous limestone disrupted by freezing-thawing in the deposit, near Charlesvoix, Michigan. Observation of natural disintegration forewarns of possible difficulty in service as concrete aggregate (courtesy of Michigan Department of Transportation).

especially significant because the alteration affects most or all particles, possibly causing softening and absorptivity in the superficial portion of the particles. This action decreases both the bond with the cementitious matrix and the strength, durability, and volume stability of the concrete.

Coatings on gravel and sand vary from minute spots and films to a cement that produces zones of sandstone or conglomerate in the deposit. Coatings usually are composed of fine sand, silt, clay, and calcium carbonate; but organic matter, iron oxides, opal, manganiferous substances, alkali- and alkali-earth sulfates, and soluble phosphates have been identified [8,28]. The petrographic examination should reveal the composition, abundance, physical properties, probable potential chemical reactivity, and the ease with which the coatings are removed by impact and abrasion.

Gravel and sand potentially susceptible to the alkali-silica reaction occur along many important rivers in the United States and have been responsible for serious distress in many concrete structures of all types, including highway pavements (Fig. 6). The location of many known deposits of alkali-reactive natural aggregate in the western United States was reported by Holland and Cook [*50*]. The known alkali-reactive substances are the silica minerals, opal, chalcedony, tridymite, cristobalite, and strained or very finely divided quartz; glassy to cryptocrystalline rhyolites, dacites, latites, and andesites, and their tuffs; at least certain artificial siliceous glasses; and certain phyllites, slates, argillites, and graywackes (Fig. 7). Occasional basalts contain glass whose index of refraction is less than 1.535 and palagonite may be partly altered to opal; such types are potentially alkali reactive. Fraser et al. [*51*] have provided a detailed study of composition of chalcedonic cherts in relation to their reactivity with alkaline solutions. Alkali-reactive dolomitic rocks may occur as constituents of natural aggregates. Any aggregate containing a significant proportion of these substances is potentially deleteriously alkali reactive in concrete in service.

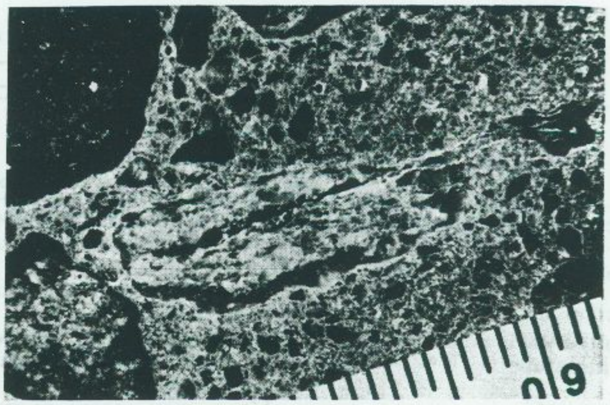


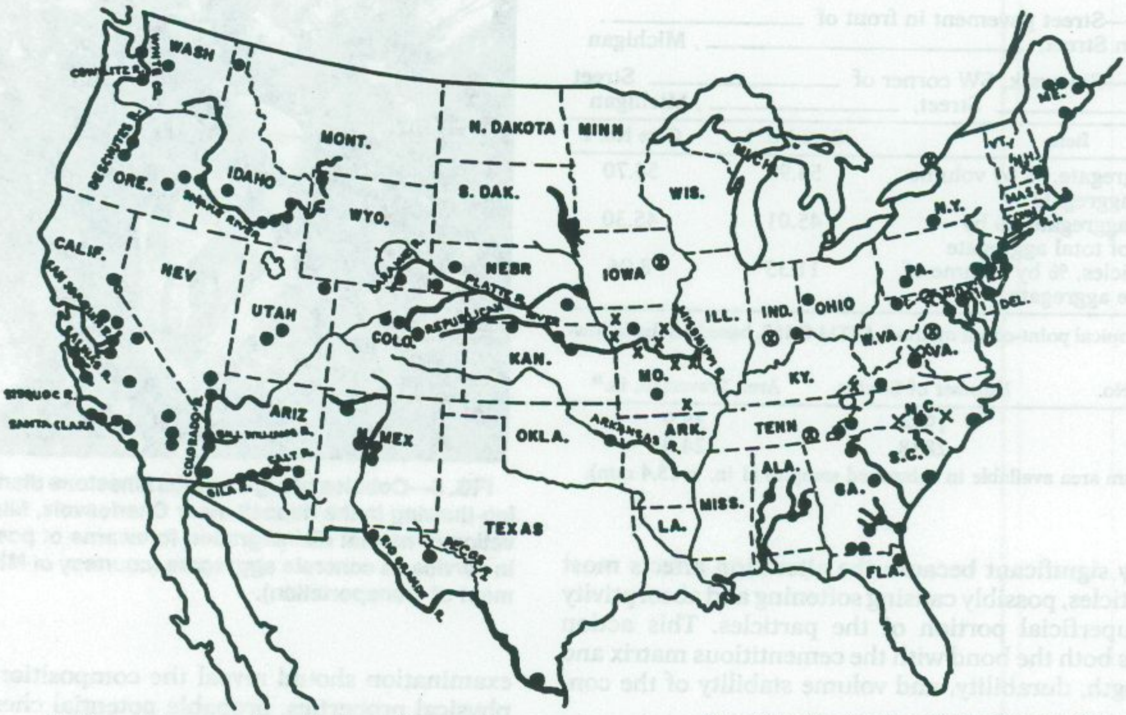
FIG. 7—Metasubgraywacke exhibiting advanced alkali-silica reaction in mass concrete, including darkened peripheral rim, internal microcracking, and radial cracking of enclosing mortar matrix. The internal microcracks are characteristically open in the interior of the particle and closed at the periphery. Note white deposits in external microcracks. A millimetre scale is shown.

PETROGRAPHIC EXAMINATION OF CRUSHED STONE

Examination of Stone in the Field

Rock formations are massive or stratified; the strata can occur in any attitude relative to the horizontal; and rock may vary widely in porosity, hardness, toughness, degree of fracturing, or chemical reactivity. For example, the alkali reactivity of dolomitic limestones typically varies widely even within the same quarry when deleterious facies are present [*33,34*].

Rock formations commonly contain zones of faulting, jointing, or local shearing, within which the materials are fractured or chemically decomposed. Certain zones may contain deleterious or unsound substances, such as chal-



——— Section of river carrying alkali-reactive sand or gravel.
X Source of alkali-reactive crushed stone.
● Structure affected by alkali-silica reaction.
⊗ Structure affected by alkali-carbonate reaction.

FIG. 6—Location of structures in the United States (other than Alaska and Hawaii) known to be affected by alkali-aggregate reaction in concrete, sources of sand or gravel subject to alkali-silica reaction, and sources of crushed stone subject to alkali-carbonate reaction.

cedonic or opaline chert and clay or shale in limestone or dolomite, or zones of hydrothermal alteration in igneous or metamorphic formations in which sulfides, zeolites, clays, or clay-like minerals are prominent. Especially in warm and humid areas, rock formations commonly are fractured, leached, and partially decomposed by weathering near the surface to varying depths, depending on localized differences in fracture, porosity, or lithology.

These features should be discovered by geologic and petrographic examination of natural exposures, quarried faces or other excavations, and drilled core. Petrographic examination in the field should include exposures of geologic formations and stone used in the area for fill, ballast, riprap, and masonry. Excavation of trenches or test pits may be required. This survey may reveal lithologic varieties that have failed during the natural exposure to freezing-thawing or wetting-drying or to oxidation and hydration (Fig. 8). The significance of the size of fragments should be recognized in any evaluation of such observations [*49*]. Disintegration of rock on natural exposures commonly does not coincide with results of the sulfate soundness test, ASTM Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate (C 88) [*52*].

Shale, claystone, and argillaceous rocks, including deeply altered basalts and diabases (traprock) containing nontronite, may slake and fracture during brief exposure even though they appear sound when excavated. Similar effects occur if the zeolites leonardite-laumontite constitute a significant proportion of the rock or occur as seams or veinlets in the formation; they are especially common in granodiorites, quartz diorites, quartz gabbros, and anorthosites. Soluble salts usually will be revealed by efflorescence at exposed surfaces.

Note that the term "crushed stone" covers aggregates produced by processing of boulders, cobbles, and the like as they may be derived from deposits of gravel and sand, where substantially all of the faces of the particles have resulted from the crushing operation (ASTM C 125). Field examination of such sources is analogous to that applied to natural aggregates as discussed previously.

Examination of Crushed Stone in the Laboratory

As is indicated earlier, crushed stone aggregates commonly are complex petrographically and not only when they are derived by crushing of boulders and cobbles recovered from gravel. Consequently, they should be examined in the same detail as required for natural aggregates (Table 5).

Petrographic examination of stone in the form of quarried blocks or irregularly shaped pieces should include inspection of the entire sample. The examination should establish the relative abundance of individual rock types or facies (Fig. 9). Specimens representative of each type should be obtained by sawing or coring of typical pieces; these specimens provide for special tests, detailed petrographic examination, and reference. Procedures for obtaining representative samples are described by Abdun-Nur [*12*].

Quantitative petrographic analysis can be made on calcareous rocks by preparing plane surfaces by sawing and lapping, followed by etching. Thirty seconds of immersion in 10% hydrochloric acid (HCl) will provide adequate differential attack on calcite and dolomite and will expose noncalcareous constituents, such as clay, chert, pyrite or marcasite, and siliceous sand or silt. The etched surface can be analyzed by point-count or linear traverse in general accordance with procedures given in ASTM C 457. This technique can be applied to calcareous aggregates in hardened concrete (Fig. 10).

Quantitative analysis can be made similarly on prepared surfaces of quartzose and feldspathic rocks following etching by 1½ to 2 min immersion in hydrofluoric acid (HF) (Fig. 11).

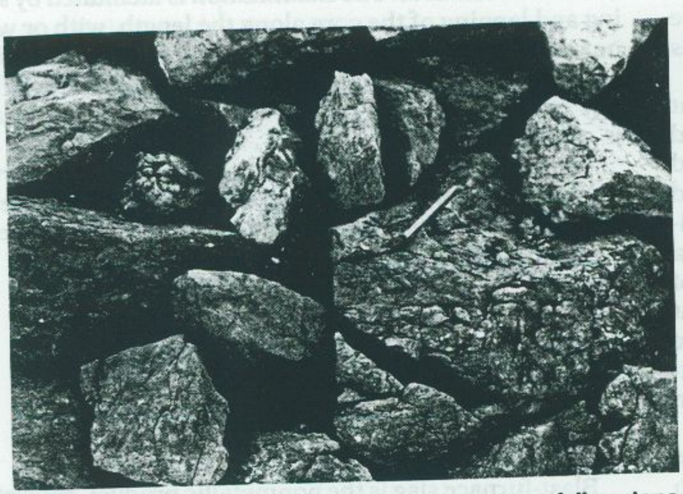


FIG. 8—Disintegration of argillaceous facies of limestone used as riprap at Chickamauga Dam, Tennessee. Observation of such disintegration indicates unsoundness of stone in at least portions of a quarry (courtesy of the Bureau of Reclamation, U.S. Department of the Interior).

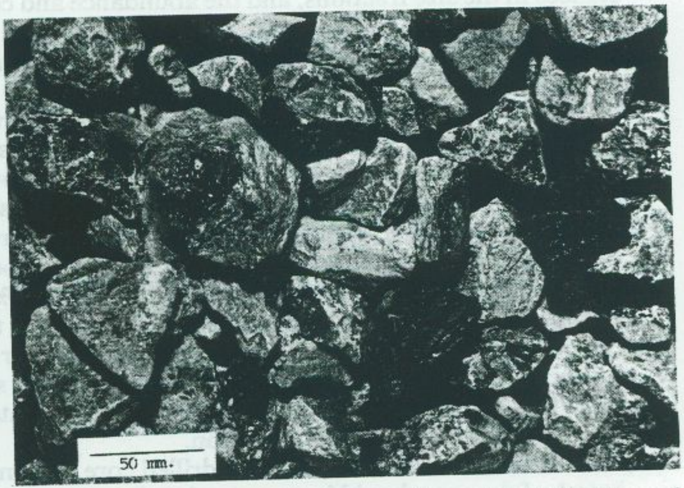


FIG. 9—Crushed limestone aggregate containing seams and pieces of illite shale, Webster Dam, Kansas. The physical quality was indicated as follows: satisfactory, 61%; fair, 34%; poor, 5% by mass (courtesy of the Bureau of Reclamation, U.S. Department of the Interior).

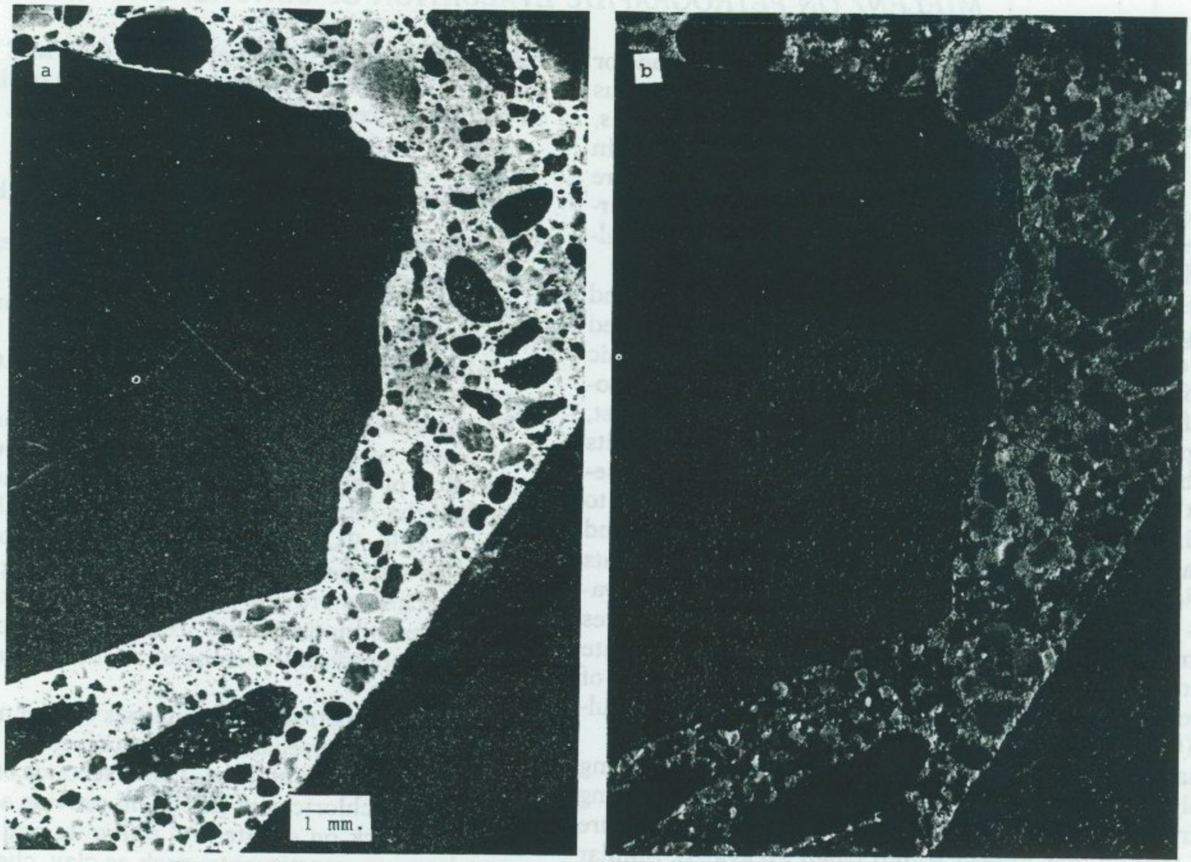


FIG. 10—Concrete containing dolomitic limestone coarse aggregate (*a*) before and (*b*) after etching for 30 s in 10% HCl. Scattered crystals in the etched areas on the lapped surface of the aggregate particles are dolomite.

If the sample of stone was submitted for crushing tests in the laboratory, the manufactured aggregate produced should be examined to determine the effects of natural fracturing, jointing, and internal texture on particle size and shape; frequency of fractures and seams within the particles; distribution of unsound or deleterious substances in the size fractions; and the abundance and composition of crusher dust. These features should be correlated with the processing equipment and methods employed.

Inspection of the stone prior to processing is important because only thus can the examination of the finished aggregate be interpreted fully. For example, if unsound or deleterious particles constitute 10% of the finished aggregate, was this proportion derived from approximately one piece in ten of the original sample or does a typical piece of the stone contain approximately 10% of unsound material? The former possibility suggests that the quarry should be examined to determine whether the unsound zones can be avoided or wasted; the latter suggests that the material should not be used as aggregate in concrete for permanent construction.

If the samples are in the form of drilled core, the entire length of the core should be examined and compared with logs available from the driller and geologist. Special attention must be given to sections in which core loss was high or complete, inasmuch as such zones commonly represent fractured, altered, or otherwise unsound rock. The core should be examined by means of the hand lens, stereoscopic microscope, and petrographic microscope, as necessary, to establish variations in lithology; frequency and intensity of fracturing; content of clay or other soft materials, regardless of rock type; and presence of chemically reactive substances. The examination is facilitated by sawing and lapping of the core along the length, with or without etching or staining. These observations should be correlated from hole to hole so that the variation in lithology or quality of the rock, both in depth and laterally, is established.

The quality of the rock to be expected from the formation represented by the cores also will be revealed by petrographic examination of aggregate produced from cores in the laboratory.

PETROGRAPHIC EXAMINATION OF BLAST-FURNACE SLAG

Blast-Furnace Slag

Blast-furnace slag is the nonmetallic product, consisting essentially of silicates and aluminosilicates of calcium and other cations, that is developed simultaneously with iron in a blast furnace (see ASTM C 125). Properties of blast-

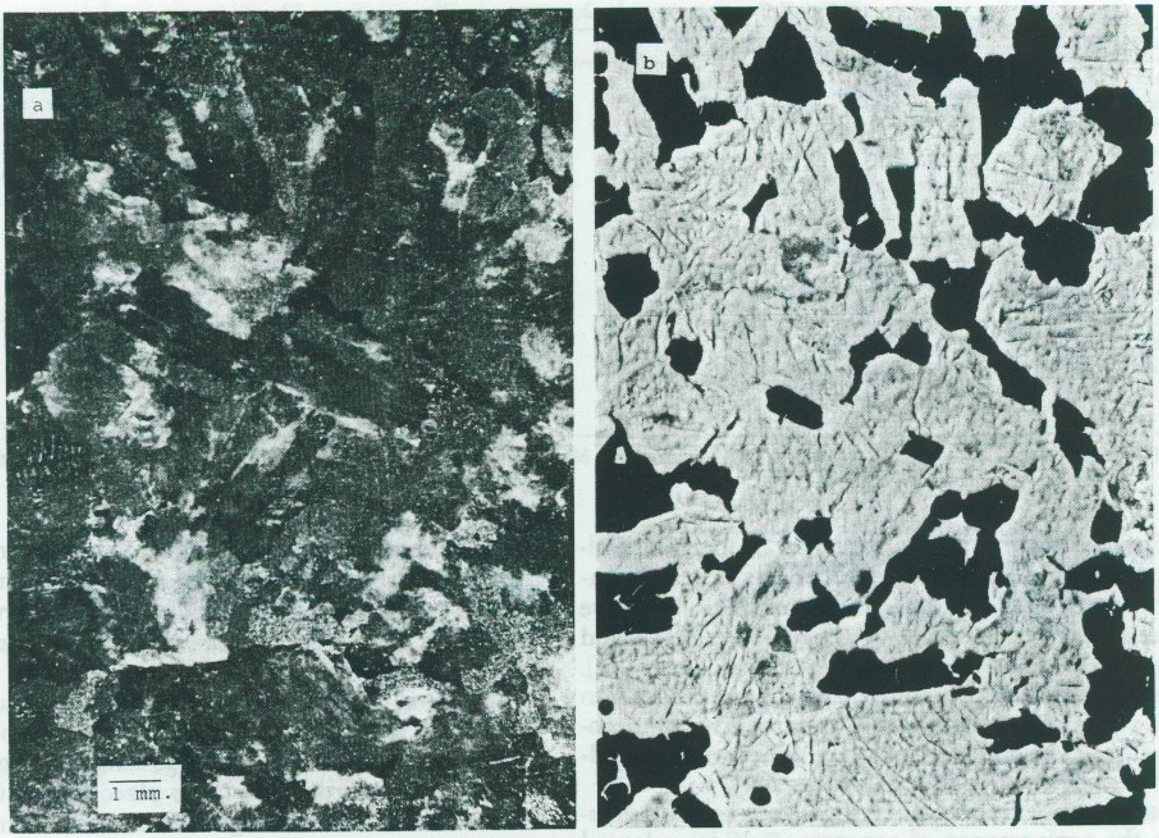


FIG. 11—Augite gabbro (*a*) before and (*b*) after 1½ min etching in concentrated HF. White areas are plagioclase feldspar, dark areas are augite in the etched surface.

furnace slag as concrete aggregate have been reported by Gutt et al. [*53*]. Three general types of blast-furnace slag are used for concrete aggregate; namely, air-cooled slag, granulated slag, and lightweight slag [*54*]. Petrographic examination of lightweight or expanded slag will be discussed in a later section.

Performance of the Petrographic Examination of Blast-Furnace Slag

The procedure for petrographic examination of blast-furnace slag is not included specifically in ASTM C 295. However, the instructions provided for examination of ledge rock, crushed stone, and manufactured sand are applicable. In addition to the indicated microscopical methods, examination of polished and etched surfaces in reflected light is a valuable technique, being preferred by some petrographers because the surfaces are easy to prepare in sizes larger than standard thin sections, the two-dimensional aspect simplifies quantitative estimation of composition, and microchemical tests can be used to identify various phases in the surface under study.

Air-cooled slag is more or less well-crystallized, depending primarily upon the method of disposal employed at the steel plant. Such slag crushes to angular and approximately equidimensional pieces, the surface texture of which is pitted, rough, or conchoidal. Crystals range from submicroscopic to several millimetres in size. Abrasion resistance relates to glass content and the condition of internal stress [*54*].

Well-granulated slag is substantially all glass. Crystals occur individually or in clusters scattered through the glass matrix. Incipient crystallization produces brown or opaque areas in thin sections (Fig. 12).

The petrographic examination of blast-furnace slag aggregate should include description of the various types of slag as well as of contaminating substances. The slag constituent usually can be segregated into two or more varieties, depending upon particle shape, surface texture, color, vesicularity, crystallinity, or the presence of products of weathering. Evaluation of effects of weathering is especially important when old pits or deposits or fill are being exploited. Each type should be studied in sufficient detail to assure identification of potentially deleterious compounds.

More than 20 compounds have been identified in blast-furnace slag (Table 7), but even well-crystallized slag rarely contains more than five compounds (Table 8). The typical constituent of blast-furnace slag is melilite, a compound of variable composition between akermanite ($2CaO \cdot MgO \cdot 2SiO_2$) and gehlenite ($2CaO \cdot Al_2O_3 \cdot SiO_2$). Pseudowollastonite and anorthite are of common occurrence. High-lime blast-furnace slags usually contain one or more forms of dicalcium silicate (α, β, or γ forms of $2CaO \cdot SiO_2$). Magnesium-containing blast-furnace slags commonly include monticellite, forsterite, or merwinite. Calcium sulfide

TABLE 7—Compounds Occurring in Blast-Furnace Slag.[a]

Compound	Chemical Formula	Compound	Chemical Formula
Gehlenite	$2CaO \cdot Al_2O_3 \cdot SiO_2$	oldhamite	CaS
Akermanite	$2CaO \cdot MgO \cdot 2SiO_2$	ferrous sulfide	FeS
Pseudowollastonite	$\alpha CaO \cdot SiO_2$	manganous sulfide	MnS
Wollastonite	$\beta CaO \cdot SiO_2$	spinel	$(Mg, Fe)O \cdot Al_2O_3$
Bredigite	$\alpha' 2CaO \cdot SiO_2$	anorthite	$CaO \cdot Al_2O_3 \cdot 2SiO_2$
Larnite	$\beta 2CaO \cdot SiO_2$	periclase	MgO
γ-dicalcium silicate	$\gamma 2CaO \cdot SiO_2$	lime	CaO
Olivine	$2(Mg, Fe)O \cdot SiO_2$		
Merwinite	$3CaO \cdot MgO \cdot 2SiO_2$	cristobalite	SiO_2
Rankinite	$3CaO \cdot 2SiO_2$	calcium aluminate	$CaO \cdot Al_2O_3$
Monticellite	$CaO \cdot MgO \cdot SiO_2$	cordierite	$2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$
Pyroxene			
Diopside	$CaO \cdot (Mg, Fe)O \cdot 2SiO_2$	sillimanite	$Al_2O_3 \cdot SiO_2$
Enstatite	$MgO \cdot SiO_2$	mullite	$3Al_2O_3 \cdot 2SiO_2$
Clinoenstatite	$MgO \cdot SiO_2$	madisonite	$2CaO \cdot 2MgO \cdot Al_2O_3 \cdot 3SiO_2$

[a] Compiled from several sources, primarily Nurse and Midgley [56], McCaffery et al. [62], and American Concrete Institute Committee 201 [60].

(CaS) almost always is present in small proportion. Sulfides of manganous manganese and ferrous iron are common. Properties and techniques for identification of these compounds are summarized by Rigby [55], Nurse and Midgley [56], Insley and Frechette [57], and Snow [58], and in standard works on mineralogy. X-ray diffraction methods are necessary if crystalline phases are submicroscopic and are a great aid to a petrographer who is developing experience independently in this field.

Several constituents of blast-furnace slag may be deleterious to the performance of concrete. Sulfides released into the cement-paste matrix produce innocuous green staining of the interior of the concrete. Occasionally, a mottled aspect is produced on the surface of damp concrete [14], but the coloration fades to a homogeneous shade of gray on drying and exposure to the atmosphere. Presence of colloidal sulfides is suggested by yellow or brown coloration of the glass phase [53]. Gypsum (calcium sulfate dihydrate, $CaSO_4 \cdot 2H_2O$) commonly forms in blast-furnace slag by weathering and may result in sulfate attack on the cement-paste matrix of concrete in service. Granulated slag is most susceptible to the formation of gypsum during weathering exposure.

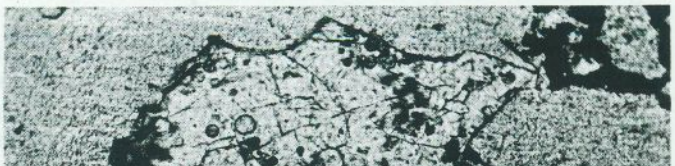

300 μm

FIG. 12—Photomicrograph of granulated blast-furnace slag. Note the vesicles (bubbles) in glass phase (white). The dark areas are concentrations of microcrystalline melilite and merwinite (courtesy of the Bureau of Reclamation, U.S. Department of the Interior).

Inversion of β-dicalcium silicate to the γ-dicalcium silicate, with accompanying 10% increase in volume of the crystal, causes "dusting" or "blowing" of slag [54,59,60]. The inversion ordinarily takes place before the slag has cooled, and the disintegrated material is removed by screening during the production of coarse aggregate. In less severe occurrences, the disintegration takes place slowly, producing pieces that are partly or wholly weak and friable, and thus unsuitable for concrete aggregate. This action of dicalcium silicate can be avoided by maintaining a ratio of CaO to SiO_2 in the slag sufficiently low to prevent formation of the compound, or by chilling the molten slag so that the compound does not crystallize [53]. If air-cooled slag is poured in thin layers, rapid cooling ordinarily arrests the compound in the β-modification. Dicalcium silicate can be identified microscopically in slag by special techniques [59]. Scattered crystals of β-dicalcium silicate commonly are stable in blast-furnace slag and therefore are innocuous.

Free lime (CaO) and magnesia (MgO) are extremely rare as constituents of air-cooled blast-furnace slag and are not likely to form either as a primary phase or devitrification product in granulated blast-furnace slag [56,61].[2] Nevertheless, their absence or presence and abundance should be established by petrographic examination. These compounds are deleterious because of the increase in solid volume resulting from hydration and carbonation in place.

Cristobalite (SiO_2) has been reported as a constituent of blast-furnace slag [62]. This compound is potentially subject to the alkali-silica reaction in portland-cement

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[2] Unlike blast-furnace slags, basic open-hearth slags commonly contain free oxides that are subject to hydration and carbonation in portland-cement concrete, namely, free lime (CaO) and magnesiowustite, a solid solution of magnesium oxide (MgO), manganese oxide (MnO), and ferrous oxide (FeO).

TABLE 8—Most Frequently Occurring Combinations of Compounds of $CaO \cdot MgO \cdot Al_2O_3 \cdot SiO_2$ Produced by Crystallization of Blast-Furnace Slag.[a]

	Combination of Compounds[b]												
Flux Stone	C_2AS	C_2MS_2	C_2S	CS	C_3S_2	C_3MS_2	MA	CMS_2	CMS	CAS_2	M_2S	MS	MgO
Limestone	X	X	X		X								
	X	X	X			X							
	X	X				X	X						
	X	X					X			X			
	X	X		X						X			
Dolomite		X		X				X		X			
		X						X		X	X		
		X					X			X	X		
		X					X		X		X		
		X				X	X		X				
						X	X		X				X
								X		X	X	X	

[a] After Nurse and Midgley [*56*].

[b] Key:
C_2AS = gehlenite } melilite
C_2MS_2 = akermanite } melilite
C_2S = dicalcium silicate
CS = wollastonite or pseudowollastonite
C_3S_2 = rankinite
C_3MS_2 = merwinite
MA = spinel
CMS_2 = diopside
CMS = monticellite
CAS_2 = anorthite
M_2S = forsterite
MS = enstatite
MgO = periclase

concrete; if identified, its abundance should be determined.

The glass phase of blast-furnace slag is not deleteriously reactive with cement alkalies.

Contaminating substances whose presence or absence should be determined by petrographic methods are metallic iron, iron carbide, coke, and incompletely fused fluxstone. The last is important because hydration and carbonation of free lime and magnesia may produce expansion of the concrete and popouts. Metallic iron and iron carbides rust by oxidation and hydration if exposed at the surface of the concrete.

PETROGRAPHIC EXAMINATION OF LIGHTWEIGHT CONCRETE AGGREGATES

Expanded Clay, Shale, and Slate

Petrographic examination of lightweight aggregate should include segregation of the particles into as many categories as required to describe the sample adequately (Table 4). Particles of expanded material may be segregated on the basis of particle shape, surface texture, development of a coating or "skin," and vesicularity. Incompletely expanded particles and particles not expanded should be distinguished from vesicular ones. Such particles usually represent sandstone or siltstone that was intercalated within the clay, shale, or slate. They should be separated on the basis of porosity, absorptivity, density, friability, softness, occurrence of efflorescence, and reaction to water (softening, slaking, or swelling). The petrographic examination supplements standard tests in distinguishing clayey particles from "clay lumps" determined in accordance with ASTM C 142. Other materials to be identified and determined quantitatively are underburned or raw material, coal, and miscellaneous rock particles. The composition and content of raw materials commonly can be established most easily and accurately by X-ray diffraction or differential thermal analysis.

The individual types of particles also should be analyzed petrographically to establish the presence of free lime or magnesia. These compounds result mainly from decomposition of calcium and magnesium carbonates in the feed during firing. They may produce distress or popouts in concrete or concrete products unless the aggregate is water- or steam-cured prior to use [*63*]. Hard-burned magnesia may not be accommodated by such treatment.

Petrographic examination also assists in the selection of raw materials, development of manufacturing equipment and methods, and process control.

Industrial Cinders

Industrial cinders used as concrete aggregate are the residue from high-temperature combustion of coal and coke in industrial furnaces. Petrographic examination should determine the physical nature of the cinder particles on the basis of composition, friability, softness, particle shape, and surface texture. Particular attention should be given to identification of sulfides, sulfates, coal, and coke.

Expanded Blast-Furnace Slag

Expanded blast-furnace slag is produced by carefully controlled intermingling of molten slag and water or steam in one of several ways [*54*]. The petrographic examination should describe the aggregate in terms of the nature of the expanded particles, including their particle shape, surface texture, friability or softness, effects of weathering in stockpiles, and content of contaminating substances, such as dense slag. The petrographic examination is especially important when fill or waste deposits are later contemplated for use as a source of concrete aggregate.

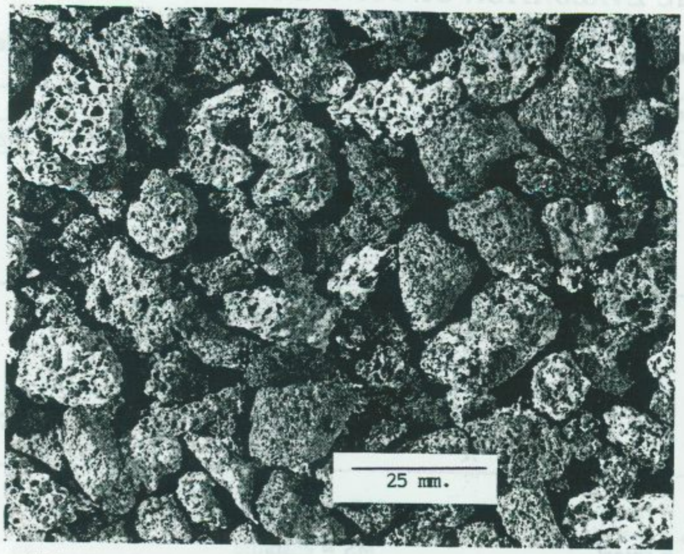

FIG. 13—Typical basaltic scoria aggregate. The pieces are black, gray, and reddish brown. Note the rounded vesicles (courtesy of the Bureau of Reclamation, U.S. Department of the Interior).

Pumice, Scoria, Tuff, and Volcanic Cinders

Pumice, scoria, tuff, and volcanic cinders used for lightweight aggregate are naturally occurring porous or vesicular lava and ash. Pumice is a very highly porous and vesicular rock composed largely of natural glass drawn into approximately parallel or loosely intertwined fibers and tubes. Scoria is a highly porous and vesicular rock in which the vesicles typically are rounded or elliptical in cross section, the interstitial glass occurring as thin films (Fig. 13). Tuff is a general term designating consolidated volcanic ash of any lithologic type or physical character. Volcanic cinder is a loose accumulation of highly vesicular (scoriaceous) fragments of lava, predominantly ranging from 4 to 32 mm (0.16 to 1.26 in.) in diameter.

Petrographic examination of these types of aggregate includes segregation of the particles on the basis of particle shape, surface texture, porosity or vesicularity, fracturing, friability or softness, weathering, specific gravity, secondary deposits in voids, coatings, and potential alkali reactivity. Extraneous or contaminating substances are primarily dense particles of volcanic rock and organic matter. In production of lightweight aggregate, two types of volcanic materials occasionally are intermixed for economy or to control gradation or unit weight. The type and relative proportion of the materials can be established by petrographic examination.

Volcanic glass with an index of refraction less than 1.535 is potentially deleteriously reactive with cement alkalies; glass whose index of refraction is in the range of 1.535 to 1.570 probably is alkali reactive. Opal, chalcedony, tridymite, and cristobalite are also common alkali-reactive constituents of volcanic aggregates. These minerals are especially common as alteration products of volcanic rocks of acidic to intermediate composition. However, opal may occur as an alteration product of palagonite in basaltic lavas.

In spite of alkali-silica reaction and formation of alkalic silica gel in highly porous vesicular lavas and tuffs, expansion and cracking of the enclosing concrete usually is prevented by the abundant voids into which the hydrating gel can escape without development of excessive stress in the mortar. For example, a highly porous rhyolite tuff from Hideaway Park, Colorado, containing abundant tridymite caused only 0.041% expansion of a high-alkali cement mortar during one year of moist storage in accordance with ASTM Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method) (C 227), yet the specimen contained abundant alkalic silica gel [*64*]. A similar but dense rhyolite tuff from near Castle Rock, Colorado, produced an expansion of 0.400% under the same conditions.

Perlite

When heated rapidly to fusion, certain obsidians and pitchstones release gases that, being trapped within the molten glass, vesiculate the rock and cause disruption into small pieces. The product is known commercially as perlite.

Petrographic examination should indicate the composition of the aggregate in terms of particle shape, surface texture, rock classification, density, friability or fragility, and potential alkali reactivity. Perlite may contain particles of dense volcanic rock or individual crystals.

Being composed of rhyolitic volcanic glass, typical perlite is potentially reactive with cement alkalies, although significant expansion may not occur because of the porosity of the particles. However, laboratory tests demonstrate that certain perlites produce significant expansion of mortar stored in accordance with ASTM C 227 in combination with either high-alkali or low-alkali cement [*65,66*]. Such volume change will not necessarily cause structural distress if appropriately accommodated in the design of the constructions or concrete product, such as masonry units or precast panels.

Exfoliated Vermiculite

Exfoliated vermiculite is produced by rapid heating of the micaceous mineral, vermiculite. Release of combined water expands the crystals—like an accordion—increasing the volume to as much as 30 times its original size. The degree of expansion varies widely, depending upon mineralogic properties and purity and the conditions of firing.

During petrographic examination, the particles of vermiculite are segregated by degree of expansion, elasticity or brittleness of the flakes, and fragility of the expanded crystals. These differ significantly within individual samples from some sources, especially from marginal deposits where the vermiculite grades into hydrobiotite or biotite. Also to be reported is the intermixture of the vermiculite with particles of rocks and minerals occurring with the vermiculite in the ore deposit.

Diatomite

Crushed and sized natural diatomite typically is soft, porous, absorptive, and ranges from firm to pulverulent.

Finely divided opal and opaline skeletons of diatoms are the predominant constituents. Fine sand, silt, clay, and volcanic ash are present in widely differing proportions. At least certain diatomites produce significant expansion of mortars stored in accordance with ASTM C 227, with both high- and low-alkali cement [*65,66*].

PETROGRAPHIC EXAMINATION OF RECYCLED CONCRETE FOR USE AS CONCRETE AGGREGATE

Recycled Concrete

Recycled concrete is defined in the report of the American Concrete Institute (ACI) Committee 117 on Cement and Concrete Terminology [*67*] as "hardened concrete that has been processed for reuse, usually as aggregate," and in ASTM C 33 as "crushed hydraulic-cement concrete." Such reclaimed concrete from structures and pavements was used widely in Great Britain and Germany following World War II and, more recently, it has been investigated in the United States, Great Britain, Canada, and elsewhere as a partial or complete replacement for conventional aggregates for purposes of economy, substitution for natural or crushed stone aggregates in short supply, and environmental benefits.

Buck [*68*] concluded that use of recycled concrete as aggregate in new concrete is feasible and may become routine. Forster [*69*] reported on extensive studies of such applications by state departments of transportation. Committee 37-DRC, Reunion Internationale des Laboratoires D'Essais at de Recherches sur les Materiaux et les Constructions (RILEM), reported on the state-of-the-art in this technology for the period of 1945 to 1985 [*70*].

The following summary of the properties of concrete containing recycled concrete as aggregate may assist the petrographer in decisions on: (1) features to be considered in examination of constructions to be demolished with the intent that the concrete will be reclaimed for production of concrete aggregate, and (2) observations that should be included in petrographic examination of samples of such materials.

Compressive Strength

Hansen and Narud [*71*] concluded that the compressive strength of concrete containing recycled concrete is controlled largely by the water-cement ratio of the original concrete when other conditions are essentially identical. When the water-cement ratio of the original concrete is equal to or lower than that of the new concrete containing the recycled aggregate as coarse aggregate only, they observed that the strength of the new concrete is equal to or higher than that of the original concrete, and vice versa, provided the fine aggregate is a natural sand or manufactured sand of suitable quality.

In evaluating the probable influence of recycled concrete from a given source on the strength of new concrete, the compressive strength of the concrete to be recycled is a more practical measure of quality than is the water-cement ratio because the water-cement ratio usually is not known and is not readily determined in practice.

A substantial reduction in compressive strength may result when the conventional fine aggregate is replaced in whole or in part by fine aggregate derived from the recycled concrete. The RILEM report [*70*] concludes that all material below 2 mm in recycled concrete should be screened out and wasted.

Water Requirement

Use of recycled concrete decreases workability of fresh concrete, increases the water requirement for a given consistency, increases drying shrinkage at a given water content, and reduces the modulus of elasticity at a given water-cement ratio [72]. These effects are greatest when the recycled concrete is used as both coarse and fine aggregate.

Freeze-Thaw Resistance

Widely varying results have been obtained in tests of freeze-thaw resistance of concrete containing recycled concrete as aggregate. The results relate to many factors, including use of recycled concrete as coarse aggregate alone or as both coarse and fine aggregate, the quality of the original concrete in terms of water-cement ratio and parameters of the air-void system, frost resistance of the aggregates included in the recycled concrete, and presence or absence of purposeful air entrainment in the new concrete containing the recycled concrete. In any event, there is no reason to believe that the recycled concrete should not be required to meet generally accepted standards for quality of the cementitious matrix, air entrainment, and soundness of aggregates when the new concrete is to be exposed to severe conditions of weathering.

Presence of Chemical or Air-Entraining Admixtures

Available data [73] indicate that, when used at generally recommended rates in the original concrete, plasticizing, set-retarding, or air-entraining admixtures in recycled concrete have no significant effect on slump, air content, or setting time of the new concrete or compressive strength of the new concrete after hardening. High concentrations of water-soluble chloride ion in recycled concrete have been shown to contribute to accelerated corrosion of steel embedments included in the new concrete. It is not expected that the chloride-containing admixtures used at ordinary rates as normal-setting or accelerating admixtures in the recycled concrete will influence the setting time of the new concrete.

Presence of Mineral Admixtures

Mineral admixtures, such as fly ash, natural pozzolans (raw or calcined), or silica fume, included in recycled concrete are unlikely to modify the properties of the new concrete.

Unsound Recycled Concrete

Prospective sources of recycled concrete may be unsound or have been rendered unsound in service, namely, presence of finely porous aggregate that is susceptible to disruption by freezing and thawing, deterioration by sulfate attack, damage by fire or service at high temperatures, presence of alkali-silica or alkali-carbonate reaction, and so on. Tests and experience show that concrete disrupted by *D*-cracking can be successfully recycled as concrete aggregate, presumably in part because of the reduction in maximum size of the offending coarse aggregate, use of recycled concrete as coarse aggregate only, air entrainment of both the original and the new concrete, reduction of the water-cement ratio, and introduction of fly ash as a partial replacement of the portland cement [*69*].

Concrete affected by a harmful degree of alkali-aggregate reactivity should be rejected as a source of recycled concrete unless it can be shown that the expansive processes have terminated, the new concrete will serve under conditions in which the internal relative humidity will be maintained at very low levels, say 70% or less, or that no deleterious effects are found in appropriately extended tests of the proposed concrete mixtures. The possibility of introduction of additional alkalies into the particles of recycled concrete during the service exposure of the new concrete should be recognized, such as from the cementitious binder of the new concrete or by penetration of alkaline solutions from an external source, such as sea water, alkaline soils, deicing chemicals, or industrial media.

The utility of concrete damaged by fire or high-temperature service must be examined individually. Portions of the constructions may be suitable for such use. Of particular concern is recycled concrete that contains aggregates including disseminated pyrite (ferrous sulfide, FeS_2), such as certain dolomites and firm shales, where the concrete in service was maintained for long periods at temperatures in the range 150 to 300°C (370 to 575°F). As noted previously [*23*], pyritiferous dolomite or shales in aggregate can produce distress when the concrete is heated in that range due to expansion of the particles by oxidation and hydration of the pyrite and subsequent crystallization of iron and calcium sulfates. These observations are pertinent to evaluation of recycled concrete derived from concrete exposed to temperatures in this intermediate range, such as structural members adjacent to kilns and furnaces or constituting the frame of such facilities. They pertain also to use of such recycled aggregates in new concrete intended for these applications.

Chemical Contamination or Radioactivity

Concrete contaminated by noxious, toxic, or radioactive substances should be rejected for use as recycled aggregate. An otherwise desirable source may be salvaged by elimination of excessively contaminated portions of the concrete if they can be isolated and disposed of separately, such as portions of pavements or marine structures in which high concentrations of chloride or water-soluble sodium are found.

Contamination by Bituminous Materials

Recycled concrete containing asphaltic materials, such as bituminous concrete, may or may not affect air entrainment of the new concrete [*69*]. Enhanced entrainment of air may require use of an air-detraining admixture, but elimination of the contaminant is preferable. The proportions of such materials can be brought to acceptable levels by specifications on removal of overlayments, joint fillers, and the like during the course of demolition and processing of the recycled aggregate.

Metallic Contaminants

Metallic particles or fragments that survive the crushing and screening operations and magnetic separation usually will be in acceptable proportions in the finished recycled concrete. Ferrous particles may cause staining where they lie adjacent to exposed surfaces, especially in the presence of appreciable concentrations of water-soluble chloride salts. Small particles of aluminum metal or galvanized iron may produce blisters or shallow cracking on surfaces of fresh or "green" concrete as a result of the release of hydrogen formed by the interaction with the alkalies within the cementitious matrix.

Glass as a Contaminant

Fragments of plate glass, bottle glass, or glassware may be present in demolished concrete structures and difficult to avoid or to extract during production of recycled aggregate. As scattered particles lying adjacent to exposed surfaces, they can produce popouts and local cracking as a result of the alkali-silica reaction, and unsightly and annoying bulges may develop on floors where the eruptions are confined by flexible coverings. The effects of the alkali-silica reaction may develop in the presence of either low- or high-alkali cements.

Contamination by Brickwork

The report of RILEM Committee 37-RDC [*70*] concludes that up to 5% by mass of fragmented brick masonry usually can be tolerated in building rubble for production of recycled-concrete aggregate. On the other hand, highly porous, fired-clay brick may be susceptible to disruption when particles of such brick lie adjacent to surfaces that are exposed to freezing and thawing while wet. The report recommends that particles of brick rubble having a density less than 1.95 g/cm^3 be rejected as lightweight particles in accordance with ASTM C 33.

Refractory bricks having a high content of crystalline magnesia (MgO, periclase) present special problems, such as where recycled concrete is obtained from facilities that include furnaces or kilns lined by such masonry. Large-size fragments of such bricks included in conventional aggregates are known to create cracking, spalling, and popouts as deep as 50 mm (2 in.) in portland-cement structural concrete, pavements, and tunnel linings.

Miscellaneous Contaminants

A Japanese standard for use of recycled concrete limits various impurities as shown in Table 9 [*70*].

Stringent limits are required on the allowable concentration of water-soluble sulfates in recycled concrete, such as that derived from gypsum plaster or plasterboard. The RILEM Committee report [*70*] recommends that the sulfate content of the new concrete be limited to 4%, expressed as the SO_3 content by mass of the entire concrete, and that the same limit be applied to the recycled-concrete aggregate. The Committee recommended further that stringent limits be placed on allowable amounts of

TABLE 9—Recommended Limits on Contaminants for New Concrete to be Subjected to Wetting and Drying or Freezing and Thawing as Reported by Committee 37-RDC, International Union of Testing Laboratories for Materials and Structures.

Material	Maximum Allowable % by Volume of Recycled Concrete[a]
Lime plaster	7
Gypsum plaster	3
Soil	5
Wood	4
Asphalt	2
Vinyl acetate paint	0.2

[a] Amount that reduced compressive strength 15% compared to the control concrete containing recycled concrete.

the contaminants listed in Table 9 for new concrete to be subjected to wetting and drying or freezing and thawing. Noting that organic substances, such as paint, may entrain excessive amounts of air, they recommend a limit of 0.15% by mass of the recycled-concrete aggregate for organic particles.

Examination of Prospective Sources of Recycled Concrete in the Field

The petrographer can assist in evaluation of prospective sources of recycled concrete by examining the intact structures or pavements at the site of demolition prior to initiation of procedures for aggregate production. This evaluation might constructively designate those locations or portions of concrete placements that are unsuitable or of questionable quality for use as concrete aggregate, such as portions highly contaminated by sea water, industrial chemicals or wastes, or radioactivity, and where extensive fenestration, installations of gypsum plaster or wallboard, or applications of paints or other coatings or overlayments will make difficult the securing of aggregate containing acceptable levels of deleterious substances. Similar avoidance of difficulties may relate to installations of lightweight and porous brickwork or potentially deleterious refractory bricks.

Such inspection should reveal the existence of portions of the installations that are seriously affected by the alkali-silica or alkali-carbonate reactions or severe corrosion of steel embedments. In each instance, use of the concrete in production of recycled concrete aggregate would be brought into question.

Performance of Petrographic Examination of Recycled Concrete

ASTM C 295 does not contemplate petrographic examination of recycled-concrete aggregate. Nevertheless, the procedures for examination of ledge rock, crushed stone, lightweight aggregates, and manufactured sand may be employed as appropriate.

The petrographic examination should be carried out with recognition of the possibility that the aggregate was derived from rubble that comprises two or more classes of concrete of differing composition and condition, possibly from more than one source, and may include contaminants of divergent types.

Objectives of the examination may include evaluation of processing procedures and facilities as well as determination of composition, quality, and anticipated performance of the aggregate in one or more concretes to be subjected to differing levels of attrition, impact, and load and to various types of environmental exposure.

The following features should be observed, recorded, and reported relative to the effectiveness of operations that constitute the production of the recycled concrete:

Grading
Particle shape
Surface texture
Angularity
Coatings of dust of fracture
Variability among nominally similar production lots
Contamination by foreign materials

The following features should be observed, recorded, and reported relative to the composition and condition of the particles:

Hardness (hard, moderately hard, weak, soft)
Relative proportion of mortar and coarse aggregate
Bond of mortar to coarse aggregate
Characteristics of the cement-paste matrix (firmness, absorptivity, bond to fine aggregate, luster on fresh fracture, presence of a mineral admixture, estimated water-cement ratio or water-to-cementitious materials ratio, microcracking)
Air-void content and parameters of the air-void system
Alteration of the cementitious matrix (carbonation, leaching, sulfate attack, staining)
Secondary chemical deposits in included aggregate, air voids, cracks, and cement-aggregate interface
Nature of coarse and fine aggregates (natural, crushed natural, crushed stone, slag, calcined or sintered lightweight aggregate, other)
Lithologic composition of aggregate and foreign materials
Quality of aggregates (sound, unsound, alkali reactive, thermal stability, cement-aggregate reactivity other than alkali-aggregate reaction)
Damage to original concrete during service (freezing before setting, freeze-thaw, leaching, sulfate attack, in situ hydration of iron sulfides, fire damage, high-temperature exposure, other)

Techniques of the petrographic examination directed to these objectives are covered by ASTM C 295, C 457, and C 856. Where the examination, other information, or instructions by the purchaser or supervisor show the need for partial chemical analysis of the recycled concrete or portions thereof, the chemical analytical work and petrographic examination should be closely coordinated and the data mutually exchanged.

Because of its great effect on the properties and performance of concrete containing recycled concrete, Hansen and Narud [71] determined the volumetric ratio of coarse aggregate and mortar in the recycled concrete used in their tests by casting specimens of a mixture of the aggregate and a binder identified by them as "red cement." Presumably, satisfactory specimens could be prepared with the portland cement blended with a suitable red iron-oxide pigment so as to allow easy distinction between the particles of recycled concrete and the binder. After hardening of the specimen, the relative proportions of coarse aggregate and mortar in the recycled concrete were determined on sawed and lapped surfaces by the linear traverse method. No details were provided as to the explicit criteria applied to distinguish sections of coarse aggregate from those of larger particles of fine aggregate.

This writer has employed the point-count method of ASTM C 457 in analysis of ordinary portland-cement concrete, distinguishing coarse aggregate from fine aggregate by classifying as coarse aggregate all particles that include a dimension greater than 4.75 mm (3/16 in.) in the plane of the section (see the previous section on Petrographic Examination of Aggregates in Hardened Concrete).

In any event, the method of Hansen and Narud can be employed to determine the relative proportions of coarse aggregate and mortar and of coarse aggregate, fine aggregate, and cementitious matrix. The same type of specimen can be used to determine air-void content and other parameters of the air-void system of the recycled concrete in accordance with ASTM C 457, these being features important to the performance of new concrete subjected to moderate or severe conditions of weathering exposure.

As noted previously, detection of rock types or other particles susceptible to the alkali-silica reaction or the alkali-carbonate reaction in recycled concrete presents two general problems, namely: (1) if pre-existing manifestations of one or both of these reactions are found, will they proceed sufficiently to damage the new concrete; and (2) if no evidence of these reactions is seen, will the composition and environmental exposure of the new concrete be such as to initiate and propagate these reactions to a deleterious extent? These questions require careful analysis of all factors concerned, including the kind and amount of alkali-reactive aggregate, the concentration of available alkalies in the recycled concrete, the previous extent of development of distress, the availability of alkalies in the new concrete (including those derived from the cement, mineral admixtures, and other sources), and the availability of moisture to the new concrete during the service exposure.

CONCLUSION

Petrographic examination should be included in the investigation and testing of concrete aggregate for use in permanent construction and in the manufacture of concrete products and precast structural elements. Applied in the field, the method aids exploration and sampling and permits preliminary evaluation of materials from alternative sources. Detailed examination of aggregates in the laboratory supplements the standard acceptance tests, especially by (1) detecting adverse properties, (2) comparing the aggregate with aggregates for which service records or previous tests are available, (3) explaining results of tests and justifying special tests as required, (4) detecting contamination, and (5) determining the efficiency and relative merit of processing and manufacturing methods for aggregate production.

Validity of the results depends upon the training and experience of the petrographer. However, with proper training and the adoption of uniform techniques and nomenclature, subjective elements in the examination are not significant.

The method can be applied effectively to sand, gravel, crushed stone, slag, natural and synthetic lightweight aggregates, and aggregates produced from recycled concrete.

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