

CHAPTER 5

Aggregates for Concrete

The importance of using the right type and quality of aggregates cannot be overemphasized. The fine and coarse aggregates generally occupy 60% to 75% of the concrete volume (70% to 85% by mass) and strongly influence the concrete's freshly mixed and hardened properties, mixture proportions, and economy. Fine aggregates (Fig. 5-1) generally consist of natural sand or crushed stone with most particles smaller than 5 mm (0.2 in.). Coarse aggregates (Fig. 5-2) consist of one or a com-



Fig. 5-1. Closeup of fine aggregate (sand). (69792)



Fig. 5-2. Coarse aggregate. Rounded gravel (left) and crushed stone (right). (69791)

ination of gravels or crushed stone with particles predominantly larger than 5 mm (0.2 in.) and generally between 9.5 mm and 37.5 mm ($\frac{3}{8}$ in. and 1½ in.). Some natural aggregate deposits, called pit-run gravel, consist of gravel and sand that can be readily used in concrete after minimal processing. Natural gravel and sand are usually dug or dredged from a pit, river, lake, or seabed. Crushed stone is produced by crushing quarry rock, boulders, cobbles, or large-size gravel. Crushed air-cooled blast-furnace slag is also used as fine or coarse aggregate.

The aggregates are usually washed and graded at the pit or plant. Some variation in the type, quality, cleanliness, grading, moisture content, and other properties is expected. Close to half of the coarse aggregates used in portland cement concrete in North America are gravels; most of the remainder are crushed stones.

Naturally occurring concrete aggregates are a mixture of rocks and minerals (see Table 5-1). A mineral is a naturally occurring solid substance with an orderly internal structure and a chemical composition that ranges within narrow limits. Rocks, which are classified as igneous, sedimentary, or metamorphic, depending on origin, are generally composed of several minerals. For example, granite contains quartz, feldspar, mica, and a few other minerals; most limestones consist of calcite, dolomite, and minor amounts of quartz, feldspar, and clay. Weathering and erosion of rocks produce particles of stone, gravel, sand, silt, and clay.

Recycled concrete, or crushed waste concrete, is a feasible source of aggregates and an economic reality, especially where good aggregates are scarce. Conventional stone crushing equipment can be used, and new equipment has been developed to reduce noise and dust.

Aggregates must conform to certain standards for optimum engineering use: they must be clean, hard, strong, durable particles free of absorbed chemicals, coatings of clay, and other fine materials in amounts that could affect hydration and bond of the cement paste. Aggregate particles that are friable or capable of being split are undesirable. Aggregates containing any appreciable amounts of shale or other shaly rocks, soft and porous materials,

Table 5-1. Rock and Mineral Constituents in Aggregates

Minerals	Igneous rocks	Metamorphic rocks
Silica	Granite	Marble
Quartz	Syenite	Metaquartzite
Opal	Diorite	Slate
Chalcedony	Gabbro	Phyllite
Tridymite	Peridotite	Schist
Cristobalite	Pegmatite	Amphibolite
Silicates	Volcanic glass	Hornfels
Feldspars	Obsidian	Gneiss
Ferromagnesian	Pumice	Serpentinite
Hornblende	Tuff	
Augite	Scoria	
Clay	Perlite	
Illites	Pitchstone	
Kaolins	Felsite	
Chlorites	Basalt	
Montmorillonites		
Mica	Sedimentary rocks	
Zeolite	Conglomerate	
Carbonate	Sandstone	
Calcite	Quartzite	
Dolomite	Graywacke	
Sulfate	Subgraywacke	
Gypsum	Arkose	
Anhydrite	Claystone, siltstone, argillite, and shale	
Iron sulfide	Carbonates	
Pyrite	Limestone	
Marcasite	Dolomite	
Pyrrhotite	Marl	
Iron oxide	Chalk	
Magnetite	Chert	
Hematite		
Goethite		
Imenite		
Limonite		

For brief descriptions, see “Standard Descriptive Nomenclature of Constituents of Natural Mineral Aggregates” (ASTM C 294).

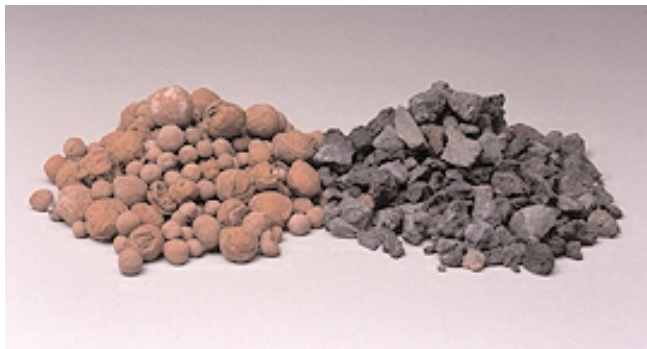


Fig. 5-3. Lightweight aggregate. Expanded clay (left) and expanded shale (right). (69793)

should be avoided; certain types of chert should be especially avoided since they have low resistance to weathering and can cause surface defects such as popouts.

Identification of the constituents of an aggregate cannot alone provide a basis for predicting the behavior of aggregates in service. Visual inspection will often disclose weaknesses in coarse aggregates. Service records are invaluable in evaluating aggregates. In the absence of a performance record, the aggregates should be tested before they are used in concrete. The most commonly used aggregates—sand, gravel, crushed stone, and air-cooled blast-furnace slag—produce freshly mixed normal-weight concrete with a density (unit weight) of 2200 to 2400 kg/m³ (140 to 150 lb/ft³). Aggregates of expanded shale, clay, slate, and slag (Fig. 5-3) are used to produce structural lightweight concrete with a freshly mixed density ranging from about 1350 to 1850 kg/m³ (90 to 120 lb/ft³). Other lightweight materials such as pumice, scoria, perlite, vermiculite, and diatomite are used to produce insulating lightweight concretes ranging in density from about 250 to 1450 kg/m³ (15 to 90 lb/ft³). Heavyweight materials such as barite, limonite, magnetite, ilmenite, hematite, iron, and steel punchings or shot are used to produce heavyweight concrete and radiation-shielding concrete (ASTM C 637 and C 638). Only normal-weight aggregates are discussed in this chapter. See Chapter 18 for special types of aggregates and concretes.

Normal-weight aggregates should meet the requirements of ASTM C 33 or AASHTO M 6/M 80. These specifications limit the permissible amounts of deleterious substances and provide requirements for aggregate characteristics. Compliance is determined by using one or more of the several standard tests cited in the following sections and tables. However, the fact that aggregates satisfy ASTM C 33 or AASHTO M 6/M 80 requirements does not necessarily assure defect-free concrete.

For adequate consolidation of concrete, the desirable amount of air, water, cement, and fine aggregate (that is, the mortar fraction) should be about 50% to 65% by absolute volume (45% to 60% by mass). Rounded aggregate, such as gravel, requires slightly lower values, while crushed aggregate requires slightly higher values. Fine aggregate content is usually 35% to 45% by mass or volume of the total aggregate content.

CHARACTERISTICS OF AGGREGATES

The important characteristics of aggregates for concrete are listed in Table 5-2 and most are discussed in the following section:

Grading

Grading is the particle-size distribution of an aggregate as determined by a sieve analysis (ASTM C 136 or AASHTO

T 27). The range of particle sizes in aggregate is illustrated in Fig. 5-4. The aggregate particle size is determined by using wire-mesh sieves with square openings. The seven standard ASTM C 33 (AASHTO M 6/M 80) sieves for fine aggregate have openings ranging from 150 μm to 9.5 mm (No. 100 sieve to $\frac{3}{8}$ in.). The 13 standard sieves for coarse aggregate have openings ranging from 1.18 mm to 100 mm

(0.046 in. to 4 in.). Tolerances for the dimensions of openings in sieves are listed in ASTM E 11 (AASHTO M 92).

Size numbers (grading sizes) for coarse aggregates apply to the amounts of aggregate (by mass) in percentages that pass through an assortment of sieves (Fig. 5-5). For highway construction, ASTM D 448 (AASHTO M 43) lists the same 13 size numbers as in ASTM C 33

Table 5.2. Characteristics and Tests of Aggregate

Characteristic	Significance	Test designation*	Requirement or item reported
Resistance to abrasion and degradation	Index of aggregate quality; wear resistance of floors and pavements	ASTM C 131 (AASHTO T 96) ASTM C 535 ASTM C 779	Maximum percentage of weight loss. Depth of wear and time
Resistance to freezing and thawing	Surface scaling, roughness, loss of section, and aesthetics	ASTM C 666 (AASHTO T 161) ASTM C 682 AASHTO T 103	Maximum number of cycles or period of frost immunity; durability factor
Resistance to disintegration by sulfates	Soundness against weathering action	ASTM C 88 (AASHTO T 104)	Weight loss, particles exhibiting distress
Particle shape and surface texture	Workability of fresh concrete	ASTM C 295 ASTM D 3398	Maximum percentage of flat and elongated particles
Grading	Workability of fresh concrete; economy	ASTM C 117 (AASHTO T 11) ASTM C 136 (AASHTO T 27)	Minimum and maximum percentage passing standard sieves
Fine aggregate degradation	Index of aggregate quality; Resistance to degradation during mixing	ASTM C 1137	Change in grading
Uncompacted void content of fine aggregate	Workability of fresh concrete	ASTM C 1252 (AASHTO T 304)	Uncompacted voids and specific gravity values
Bulk density (unit weight)	Mix design calculations; classification	ASTM C 29 (AASHTO T 19)	Compact weight and loose weight
Relative density (specific gravity)	Mix design calculations	ASTM C 127 (AASHTO T 85) fine aggregate ASTM C 128 (AASHTO T 84) coarse aggregate	—
Absorption and surface moisture	Control of concrete quality (water-cement ratio)	ASTM C 70 ASTM C 127 (AASHTO T 85) ASTM C 128 (AASHTO T 84) ASTM C 566 (AASHTO T 255)	—
Compressive and flexural strength	Acceptability of fine aggregate failing other tests	ASTM C 39 (AASHTO T 22) ASTM C 78 (AASHTO T 97)	Strength to exceed 95% of strength achieved with purified sand
Definitions of constituents	Clear understanding and communication	ASTM C 125 ASTM C 294	—
Aggregate constituents	Determine amount of deleterious and organic materials	ASTM C 40 (AASHTO T 21) ASTM C 87 (AASHTO T 71) ASTM C 117 (AASHTO T 11) ASTM C 123 (AASHTO T 113) ASTM C 142 (AASHTO T 112) ASTM C 295	Maximum percentage allowed of individual constituents
Resistance to alkali reactivity and volume change	Soundness against volume change	ASTM C 227 ASTM C 289 ASTM C 295 ASTM C 342 ASTM C 586 ASTM C 1260 (AASHTO T 303) ASTM C 1293	Maximum length change, constituents and amount of silica, and alkalinity

* The majority of the tests and characteristics listed are referenced in ASTM C 33 (AASHTO M 6/M 80). ACI 221R-96 presents additional test methods and properties of concrete influenced by aggregate characteristics.



Fig. 5-4. Range of particle sizes found in aggregate for use in concrete. (8985)

(AASHTO M 6/ M 80) plus an additional six more coarse aggregate size numbers. Fine aggregate or sand has only one range of particle sizes for general construction and highway work.

The grading and grading limits are usually expressed as the percentage of material passing each sieve. Fig. 5-6 shows these limits for fine aggregate and for one size of coarse aggregate.

There are several reasons for specifying grading limits and nominal maximum aggregate size; they affect relative

Video



Fig. 5-5. Making a sieve analysis test of coarse aggregate in a laboratory. (30175-A)

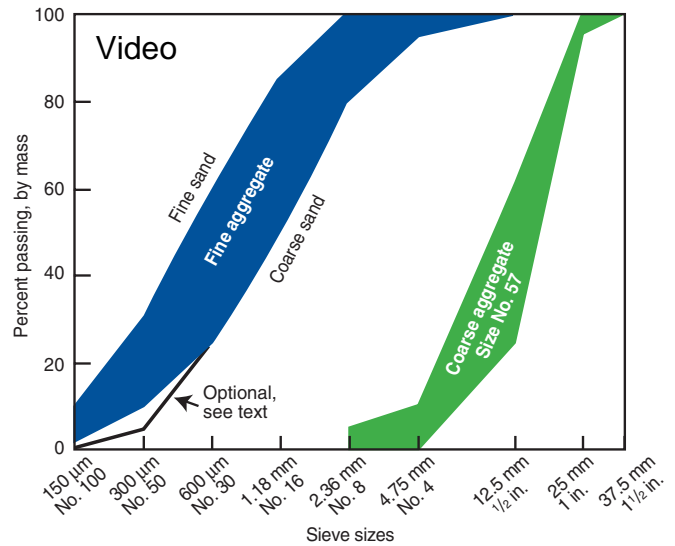


Fig. 5-6. Curves indicate the limits specified in ASTM C 33 for fine aggregate and for one commonly used size number (grading size) of coarse aggregate.

aggregate proportions as well as cement and water requirements, workability, pumpability, economy, porosity, shrinkage, and durability of concrete. Variations in grading can seriously affect the uniformity of concrete from batch to batch. Very fine sands are often uneconomical; very coarse sands and coarse aggregate can produce harsh, unworkable mixtures. In general, aggregates that do not have a large deficiency or excess of any size and give a smooth grading curve will produce the most satisfactory results.

The effect of a collection of various sizes in reducing the total volume of voids between aggregates is illustrated by the simple method shown in Fig. 5-7. The beaker on the left is filled with large aggregate particles of uniform size

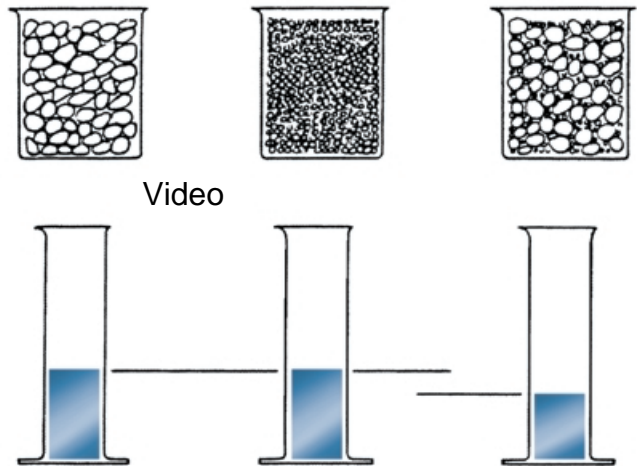


Fig. 5-7. The level of liquid in the graduates, representing voids, is constant for equal absolute volumes of aggregates of uniform but different size. When different sizes are combined, the void-content decreases. The illustration is not to scale.

and shape; the middle beaker is filled with an equal volume of small aggregate particles of uniform size and shape; and the beaker on the right is filled with particles of both sizes. Below each beaker is a graduate with the amount of water required to fill the voids in that beaker. Note that when the beakers are filled with one particle size of equal volume, the void content is constant, regardless of the particle size. When the two aggregate sizes are combined, the void content is decreased. If this operation were repeated with several additional sizes, a further reduction in voids would occur. The cement paste requirement for concrete is related to the void content of the combined aggregates.

During the early years of concrete technology it was sometimes assumed that the smallest percentage of voids (greatest density of aggregates) was the most suitable for concrete. At the same time, limits were placed on the amount and size of the smallest particles. It is now known that, even on this restricted basis, this is not the best target for the mix designer. However, production of satisfactory, economical concrete requires aggregates of low void content, but not the lowest. Voids in aggregates can be tested according to ASTM C 29 or AASHTO T 19.

In reality, the amount of cement paste required in concrete is greater than the volume of voids between the aggregates. This is illustrated in Fig. 5-8. Sketch A represents large aggregates alone, with all particles in contact. Sketch B represents the dispersal of aggregates in a matrix of paste. The amount of paste is necessarily greater than the void content of sketch A in order to provide workability to the concrete; the actual amount is influenced by the workability and cohesiveness of the paste.

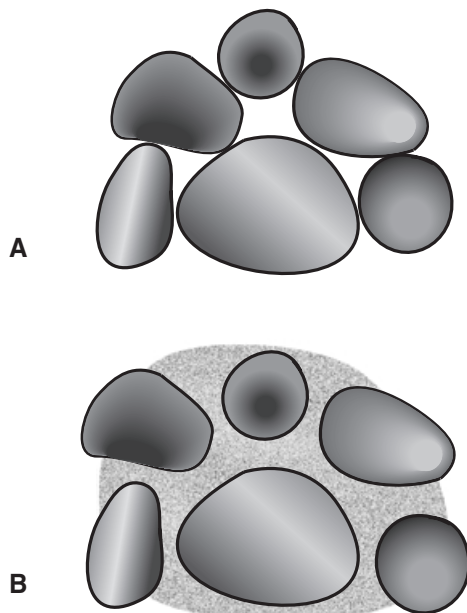


Fig. 5-8. Illustration of the dispersion of aggregates in cohesive concrete mixtures.

Fine-Aggregate Grading

Requirements of ASTM C 33 or AASHTO M 6/M 43 permit a relatively wide range in fine-aggregate gradation, but specifications by other organizations are sometimes more restrictive. The most desirable fine-aggregate grading depends on the type of work, the richness of the mixture, and the maximum size of coarse aggregate. In leaner mixtures, or when small-size coarse aggregates are used, a grading that approaches the maximum recommended percentage passing each sieve is desirable for workability. In general, if the water-cement ratio is kept constant and the ratio of fine-to-coarse aggregate is chosen correctly, a wide range in grading can be used without measurable effect on strength. However, the best economy will sometimes be achieved by adjusting the concrete mixture to suit the gradation of the local aggregates.

Fine-aggregate grading within the limits of ASTM C 33 (AASHTO M 6) is generally satisfactory for most concretes. The ASTM C 33 (AASHTO M 6) limits with respect to sieve size are shown in Table 5-3.

Table 5-3. Fine-Aggregate Grading Limits (ASTM C 33/AASHTO M 6)

Sieve size	Percent passing by mass
9.5 mm (% in.)	100
4.75 mm (No. 4)	95 to 100
2.36 mm (No. 8)	80 to 100
1.18 mm (No. 16)	50 to 85
600 μm (No. 30)	25 to 60
300 μm (No. 50)	5 to 30 (AASHTO 10 to 30)
150 μm (No. 100)	0 to 10 (AASHTO 2 to 10)

The AASHTO specifications permit the minimum percentages (by mass) of material passing the 300 μm (No. 50) and 150 μm (No. 100) sieves to be reduced to 5% and 0% respectively, provided:

1. The aggregate is used in air-entrained concrete containing more than 237 kilograms of cement per cubic meter (400 lb of cement per cubic yard) and having an air content of more than 3%.
2. The aggregate is used in concrete containing more than 297 kilograms of cement per cubic meter (500 lb of cement per cubic yard) when the concrete is not air-entrained.
3. An approved supplementary cementitious material is used to supply the deficiency in material passing these two sieves.

Other requirements of ASTM C 33 (AASHTO M 6) are:

1. The fine aggregate must not have more than 45% retained between any two consecutive standard sieves.
2. The fineness modulus must be not less than 2.3 nor more than 3.1, nor vary more than 0.2 from the typical value of the aggregate source. If this value is ex-

ceeded, the fine aggregate should be rejected unless suitable adjustments are made in proportions of fine and coarse aggregate.

The amounts of fine aggregate passing the 300 µm (No. 50) and 150, µm (No. 100) sieves affect workability, surface texture, air content, and bleeding of concrete. Most specifications allow 5% to 30% to pass the 300 µm (No. 50) sieve. The lower limit may be sufficient for easy placing conditions or where concrete is mechanically finished, such as in pavements. However, for hand-finished concrete floors, or where a smooth surface texture is desired, fine aggregate with at least 15% passing the 300 µm (No. 50) sieve and 3% or more passing the 150 µm (No. 100) sieve should be used.

Video

Fineness Modulus. The fineness modulus (FM) of either fine or coarse aggregate according to ASTM C 125 is calculated by adding the cumulative percentages by mass retained on each of a specified series of sieves and dividing the sum by 100. The specified sieves for determining FM are: 150 µm (No. 100), 300 µm (No. 50), 600 µm (No. 30), 1.18 mm (No. 16), 2.36 mm (No. 8), 4.75 mm (No. 4), 9.5 mm (¾ in.), 19.0 mm (¾ in.), 37.5 mm (1½ in.), 75 mm (3 in.) and, 150 mm (6 in.).

FM is an index of the fineness of an aggregate—the higher the FM, the coarser the aggregate. Different aggregate grading may have the same FM. FM of fine aggregate is useful in estimating proportions of fine and coarse aggregates in concrete mixtures. An example of how the FM of a fine aggregate is determined (with an assumed sieve analysis) is shown in Table 5-4.

Degradation of fine aggregate due to friction and abrasion will decrease the FM and increase the amount of materials finer than the 75 µm (No. 200) sieve.

Coarse-Aggregate Grading

The coarse aggregate grading requirements of ASTM C 33 (AASHTO M 80) permit a wide range in grading and a variety of grading sizes (see Table 5-5). The grading for a

Table 5-4. Determination of Fineness Modulus of Fine Aggregates

Sieve size	Percentage of individual fraction retained, by mass	Percentage passing, by mass	Cumulative percentage retained, by mass
9.5 mm (¾ in.)	0	100	0
4.75 mm (No. 4)	2	98	2
2.36 mm (No. 8)	13	85	15
1.18 mm (No. 16)	20	65	35
600 µm (No. 30)	20	45	55
300 µm (No. 50)	24	21	79
150 µm (No. 100)	18	3	97
Pan	3	0	—
Total	100		283

Fineness modulus
= 283 ÷ 100 = 2.83

given maximum-size coarse aggregate can be varied over a moderate range without appreciable effect on cement and water requirement of a mixture if the proportion of fine aggregate to total aggregate produces concrete of good workability. Mixture proportions should be changed to produce workable concrete if wide variations occur in the coarse-aggregate grading. Since variations are difficult to anticipate, it is often more economical to maintain uniformity in manufacturing and handling coarse aggregate than to reduce variations in gradation.

The maximum size of coarse aggregate used in concrete has a bearing on the economy of concrete. Usually more water and cement is required for small-size aggregates than for large sizes, due to an increase in total aggregate surface area. The water and cement required for a slump of approximately 75 mm (3 in.) is shown in Fig. 5-9 for a wide range of coarse-aggregate sizes. Fig. 5-9 shows that, for a given water-cement ratio, the amount of cement required decreases as the maximum size of coarse aggregate increases. The increased cost of obtaining and/or

Table 5-5. Grading Requirements for Coarse Aggregates (ASTM C 33 and AASHTO M 80)

Size number	Nominal size, sieves with square openings	Amounts finer than each laboratory sieve, mass percent passing				
		100 mm (4 in.)	90 mm (3½ in.)	75 mm (3 in.)	63 mm (2½ in.)	50 mm (2 in.)
1	90 to 37.5 mm (3½ to 1½ in.)	100	90 to 100	—	25 to 60	—
2	63 to 37.5 mm (2½ to 1½ in.)	—	—	100	90 to 100	35 to 70
3	50 to 25.0 mm (2 to 1 in.)	—	—	—	100	90 to 100
357	50 to 4.75 mm (2 in. to No. 4)	—	—	—	100	95 to 100
4	37.5 to 19.0 mm (1½ to ¾ in.)	—	—	—	—	100
467	37.5 to 4.75 mm (1½ in. to No. 4)	—	—	—	—	100
5	25.0 to 12.5 mm (1 to ½ in.)	—	—	—	—	—
56	25.0 to 9.5 mm (1 to ¾ in.)	—	—	—	—	—
57	25.0 to 4.75 mm (1 in. to No. 4)	—	—	—	—	—
6	19.0 to 9.5 mm (¾ to ¾ in.)	—	—	—	—	—
67	19.0 to 4.75 mm (¾ in. to No. 4)	—	—	—	—	—
7	12.5 to 4.75 mm (½ in. to No. 4)	—	—	—	—	—
8	9.5 to 2.36 mm (¾ in. to No. 8)	—	—	—	—	—

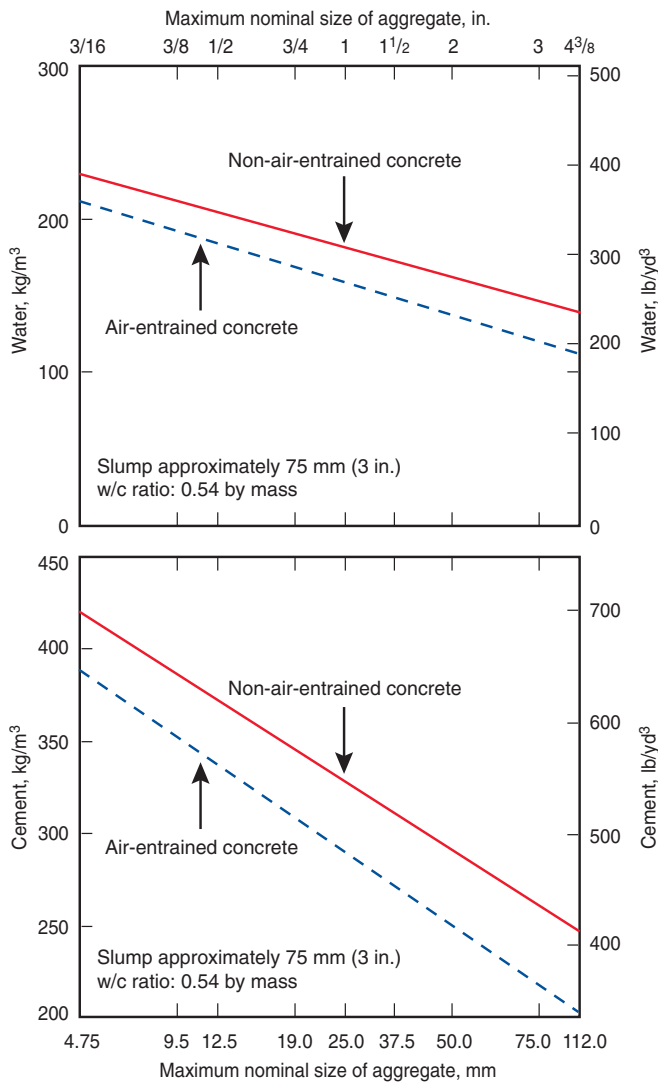


Fig. 5-9. Cement and water contents in relation to maximum size of aggregate for air-entrained and non-air-entrained concrete. Less cement and water are required in mixtures having large coarse aggregate (Bureau of Reclamation 1981).

handling aggregates much larger than 50 mm (2 in.) may offset the savings in using less cement. Furthermore, aggregates of different maximum sizes may give slightly different concrete strengths for the same water-cement ratio. In some instances, at the same water-cement ratio, concrete with a smaller maximum-size aggregate could have higher compressive strength. This is especially true for high-strength concrete. The optimum maximum size of coarse aggregate for higher strength depends on factors such as relative strength of the cement paste, cement-aggregate bond, and strength of the aggregate particles.

The terminology used to specify size of coarse aggregate must be chosen carefully. Particle size is determined by size of sieve and applies to the aggregate passing that sieve and not passing the next smaller sieve. When speaking of an assortment of particle sizes, the size number (or grading size) of the gradation is used. The size number applies to the collective amount of aggregate that passes through an assortment of sieves. As shown in Table 5-5, the amount of aggregate passing the respective sieves is given in percentages; it is called a sieve analysis.

Because of past usage, there is sometimes confusion about what is meant by the maximum size of aggregate. ASTM C 125 and ACI 116 define this term and distinguish it from nominal maximum size of aggregate. The maximum size of an aggregate is the smallest sieve that all of a particular aggregate must pass through. The nominal maximum size of an aggregate is the smallest sieve size through which the major portion of the aggregate must pass. The nominal maximum-size sieve may retain 5% to 15% of the aggregate depending on the size number. For example, aggregate size number 67 has a maximum size of 25 mm (1 in.) and a nominal maximum size of 19 mm (¾ in.). Ninety to one hundred percent of this aggregate must pass the 19-mm (¾-in.) sieve and all of the particles must pass the 25-mm (1-in.) sieve.

The maximum size of aggregate that can be used generally depends on the size and shape of the concrete member and the amount and distribution of reinforcing steel. The maximum size of aggregate particles generally should not exceed:

	37.5 mm (1½ in.)	25.0 mm (1 in.)	19.0 mm (¾ in.)	12.5 mm (½ in.)	9.5 mm (¾ in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)
0 to 15	—	—	0 to 5	—	—	—	—	—
0 to 15	—	—	0 to 5	—	—	—	—	—
35 to 70	0 to 15	—	—	0 to 5	—	—	—	—
—	35 to 70	—	—	10 to 30	—	0 to 5	—	—
90 to 100	20 to 55	—	0 to 15	—	0 to 5	—	—	—
95 to 100	—	—	35 to 70	—	10 to 30	0 to 5	—	—
100	90 to 100	—	20 to 55	0 to 10	0 to 5	—	—	—
100	90 to 100	—	40 to 85	10 to 40	0 to 15	0 to 5	—	—
100	95 to 100	—	—	25 to 60	—	0 to 10	0 to 5	—
—	100	—	90 to 100	20 to 55	0 to 15	0 to 5	—	—
—	100	—	90 to 100	—	25 to 55	0 to 10	0 to 5	—
—	—	—	100	90 to 100	40 to 70	0 to 15	0 to 5	—
—	—	—	—	100	85 to 100	10 to 30	0 to 10	0 to 5

1. One-fifth the narrowest dimension of a concrete member
2. Three-quarters the clear spacing between reinforcing bars and between the reinforcing bars and forms
3. One-third the depth of slabs

These requirements may be waived if, in the judgment of the engineer, the mixture possesses sufficient workability that the concrete can be properly placed without honeycomb or voids.

Combined Aggregate Grading

Aggregate is sometimes analyzed using the combined grading of fine and coarse aggregate together, as they exist in a concrete mixture. This provides a more thorough analysis of how the aggregates will perform in concrete. Sometimes mid-sized aggregate, around the 9.5 mm ($\frac{3}{8}$ in.) size, is lacking in an aggregate supply, resulting in a concrete with high shrinkage properties, high water demand, poor workability, poor pumpability, and poor placeability. Strength and durability may also be affected.

Fig. 5-10 illustrates an ideal gradation; however, a perfect gradation does not exist in the field—but we can try to approach it. If problems develop due to a poor gradation, alternative aggregates, blending, or special screening of existing aggregates, should be considered. Refer to Shilstone (1990) for options on obtaining optimal grading of aggregate.

The combined gradation can be used to better control workability, pumpability, shrinkage, and other properties of concrete. Abrams (1918) and Shilstone (1990) demonstrate the benefits of a combined aggregate analysis:

- With constant cement content and constant consistency, there is an optimum for every combination of aggregates that will produce the most effective water to cement ratio and highest strength.

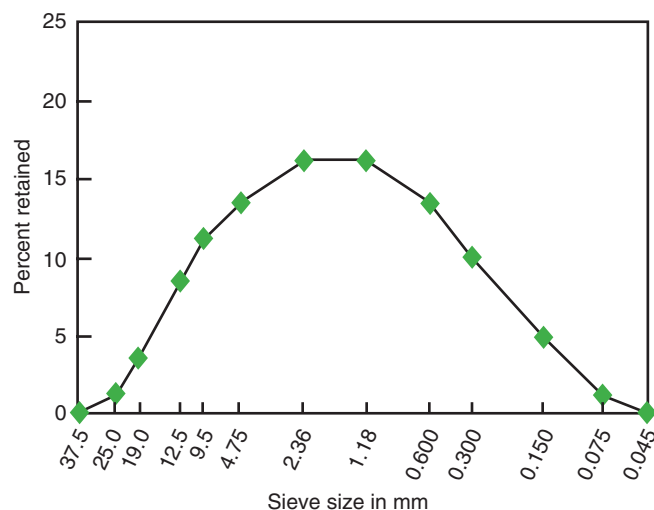


Fig. 5-10. Optimum combined aggregate grading for concrete.

- The optimum mixture has the least particle interference and responds best to a high frequency, high amplitude vibrator.

However, this optimum mixture cannot be used for all construction due to variations in placing and finishing needs and availability. Crouch (2000) found in his studies on air-entrained concrete that the water-cement ratio could be reduced by over 8% using combined aggregate gradation. Shilstone (1990) also analyzes aggregate gradation by coarseness and workability factors to improve aggregate gradation.

Gap-Graded Aggregates

Video

In gap-graded aggregates certain particle sizes are intentionally omitted. For cast-in-place concrete, typical gap-graded aggregates consist of only one size of coarse aggregate with all the particles of fine aggregate able to pass through the voids in the compacted coarse aggregate. Gap-graded mixes are used in architectural concrete to obtain uniform textures in exposed-aggregate finishes. They can also be used in normal structural concrete because of possible improvements in some concrete properties, and to permit the use of local aggregate gradations (Houston 1962 and Litvin and Pfeifer 1965).

For an aggregate of 19-mm ($\frac{3}{4}$ -in.) maximum size, the 4.75 mm to 9.5 mm (No. 4 to $\frac{3}{8}$ in.) particles can be omitted without making the concrete unduly harsh or subject to segregation. In the case of 37.5 mm (1½ in.) aggregate, usually the 4.75 mm to 19 mm (No. 4 to $\frac{3}{4}$ in.) sizes are omitted.

Care must be taken in choosing the percentage of fine aggregate in a gap-graded mixture. A wrong choice can result in concrete that is likely to segregate or honeycomb because of an excess of coarse aggregate. Also, concrete with an excess of fine aggregate could have a high water demand resulting in a low-density concrete. Fine aggregate is usually 25% to 35% by volume of the total aggregate. The lower percentage is used with rounded aggregates and the higher with crushed material. For a smooth off-the-form finish, a somewhat higher percentage of fine aggregate to total aggregate may be used than for an exposed-aggregate finish, but both use a lower fine aggregate content than continuously graded mixtures. Fine aggregate content also depends upon cement content, type of aggregate, and workability.

Air entrainment is usually required for workability since low-slump, gap-graded mixes use a low fine aggregate percentage and produce harsh mixes without entrained air.

Segregation of gap-graded mixes must be prevented by restricting the slump to the lowest value consistent with good consolidation. This may vary from zero to 75 mm (to 3 in.) depending on the thickness of the section, amount of reinforcement, and height of casting. Close control of grading and water content is also required because variations might cause segregation. If a stiff mixture is required, gap-

graded aggregates may produce higher strengths than normal aggregates used with comparable cement contents. Because of their low fine-aggregate volumes and low water-cement ratios, gap-graded mixtures might be considered unworkable for some cast-in-place construction. When properly proportioned, however, these concretes are readily consolidated with vibration.

Video Particle Shape and Surface Texture

The particle shape and surface texture of an aggregate influence the properties of freshly mixed concrete more than the properties of hardened concrete. Rough-textured, angular, elongated particles require more water to produce workable concrete than do smooth, rounded, compact aggregates. Hence, aggregate particles that are angular require more cement to maintain the same water-cement ratio. However, with satisfactory gradation, both crushed and noncrushed aggregates (of the same rock types) generally give essentially the same strength for the same cement factor. Angular or poorly graded aggregates can also be more difficult to pump.

The bond between cement paste and a given aggregate generally increases as particles change from smooth and rounded to rough and angular. This increase in bond is a consideration in selecting aggregates for concrete where flexural strength is important or where high compressive strength is needed.

Void contents of compacted fine or coarse aggregate can be used as an index of differences in the shape and texture of aggregates of the same grading. The mixing water and cement requirement tend to increase as aggregate void content increases. Voids between aggregate particles increase with aggregate angularity.

Aggregate should be relatively free of flat and elongated particles. A particle is called flat and elongated when the ratio of length to thickness exceeds a specified value. See ASTM D 4791 for determination of flat, and/or elongated particles. ASTM D 3398 provides an indirect method of establishing a particle index as an overall measure of particle shape or texture, while ASTM C 295 provides procedures for the petrographic examination of aggregate.

Flat and elongated aggregate particles should be avoided or at least limited to about 15% by mass of the total aggregate. This requirement is equally important for coarse and for crushed fine aggregate, since fine aggregate made by crushing stone often contains flat and elongated particles. Such aggregate particles require an increase in mixing water and thus may affect the strength of concrete, particularly in flexure, if the water-cement ratio is not adjusted.

A number of automated test machines are available for rapid determination of the particle size distribution of aggregate. Designed to provide a faster alternative to the standard sieve analysis test, these machines capture and analyze digital images of the aggregate particles to determine gradation. Fig. 5-11 shows a videograder that measures size and shape of an aggregate by using line-scan

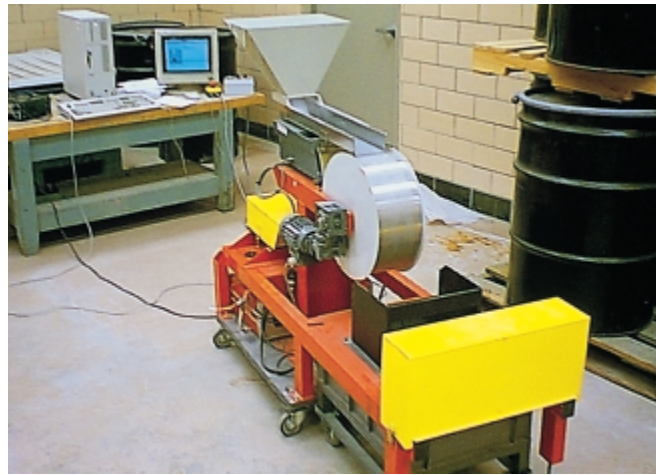


Fig. 5-11. Videograder for measuring size and shape of aggregate. (69545)

cameras wherein two-dimensional images are constructed from a series of line images. Other machines use matrix-scan cameras to capture two-dimensional snapshots of the falling aggregate. Maerz and Lusher (2001) developed a dynamic prototype imaging system that provides particle size and shape information by using a miniconveyor system to parade individual fragments past two orthogonally oriented, synchronized cameras.

Bulk Density (Unit Weight) and Voids

Video

The bulk density or unit weight of an aggregate is the mass or weight of the aggregate required to fill a container of a specified unit volume. The volume referred to here is that occupied by both aggregates and the voids between aggregate particles.

The approximate bulk density of aggregate commonly used in normal-weight concrete ranges from about 1200 to 1750 kg/m³ (75 to 110 lb/ft³). The void content between particles affects paste requirements in mix design (see preceding sections, “Particle Shape and Surface Texture” and “Grading”). Void contents range from about 30% to 45% for coarse aggregates to about 40% to 50% for fine aggregate. Angularity increases void content while larger sizes of well-graded aggregate and improved grading decreases void content (Fig. 5-7). Methods of determining the bulk density of aggregates and void content are given in ASTM C 29 (AASHTO T 19). In these standards, three methods are described for consolidating the aggregate in the container depending on the maximum size of the aggregate: rodding, jiggling, and shoveling. The measurement of loose uncompacted void content of fine aggregate is described in ASTM C 1252.

Relative Density (Specific Gravity)

Video

The relative density (specific gravity) of an aggregate is the ratio of its mass to the mass of an equal absolute volume of

water. It is used in certain computations for mixture proportioning and control, such as the volume occupied by the aggregate in the absolute volume method of mix design. It is not generally used as a measure of aggregate quality, though some porous aggregates that exhibit accelerated freeze-thaw deterioration do have low specific gravities. Most natural aggregates have relative densities between 2.4 and 2.9 with corresponding particle (mass) densities of 2400 and 2900 kg/m³ (150 and 181 lb/ft³).

Test methods for determining relative densities for coarse and fine aggregates are described in ASTM C 127 (AASHTO T 85) and ASTM C 128 (AASHTO T 84), respectively. The relative density of an aggregate may be determined on an ovdry basis or a saturated surface-dry (SSD) basis. Both the ovdry and saturated surface-dry relative densities may be used in concrete mixture proportioning calculations. Ovdry aggregates do not contain any absorbed or free water. They are dried in an oven to constant weight. Saturated surface-dry aggregates are those in which the pores in each aggregate particle are filled with water but there is no excess water on the particle surface.

Density

The density of aggregate particles used in mixture proportioning computations (not including voids between particles) is determined by multiplying the relative density (specific gravity) of the aggregate times the density of water. An approximate value of 1000 kg/m³ (62.4 lb/ft³) is often used for the density of water. The density of aggregate, along with more accurate values for water density, are provided in ASTM C 127 (AASHTO T 85) and ASTM C 128 (AASHTO T 84). Most natural aggregates have particle densities of between 2400 and 2900 kg/m³ (150 and 181 lb/ft³).

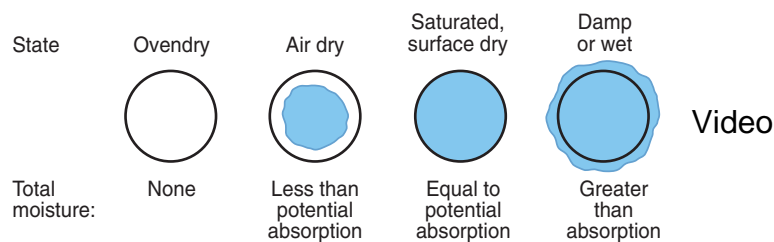
Absorption and Surface Moisture

The absorption and surface moisture of aggregates should be determined according to ASTM C 70, C 127, C 128, and C 566 (AASHTO T 255) so that the total water content of the concrete can be controlled and correct batch weights determined. The internal structure of an aggregate particle is made up of solid matter and voids that may or may not contain water.

The moisture conditions of aggregates are shown in Fig. 5-12. They are designated as:

1. **Ovdry**—fully absorbent
2. **Air dry**—dry at the particle surface but containing some interior moisture, thus still somewhat absorbent
3. **Saturated surface dry (SSD)**—neither absorbing water from nor contributing water to the concrete mixture
4. **Damp or wet**—containing an excess of moisture on the surface (free water)

The amount of water added at the concrete batch plant must be adjusted for the moisture conditions of the



Video

Fig. 5-12. Moisture conditions of aggregate.

aggregates in order to accurately meet the water requirement of the mix design. If the water content of the concrete mixture is not kept constant, the water-cement ratio will vary from batch to batch causing other properties, such as the compressive strength and workability to vary from batch to batch.

Coarse and fine aggregate will generally have absorption levels (moisture contents at SSD) in the range of 0.2% to 4% and 0.2% to 2%, respectively. Free-water contents will usually range from 0.5% to 2% for coarse aggregate and 2% to 6% for fine aggregate. The maximum water content of drained coarse aggregate is usually less than that of fine aggregate. Most fine aggregates can maintain a maximum drained moisture content of about 3% to 8% whereas coarse aggregates can maintain only about 1% to 6%.

Bulking. Bulking is the increase in total volume of moist fine aggregate over the same mass dry. Surface tension in the moisture holds the particles apart, causing an increase in volume. Bulking of a fine aggregate (such as sand) occurs when it is shoveled or otherwise moved in a damp condition, even though it may have been fully consoli-

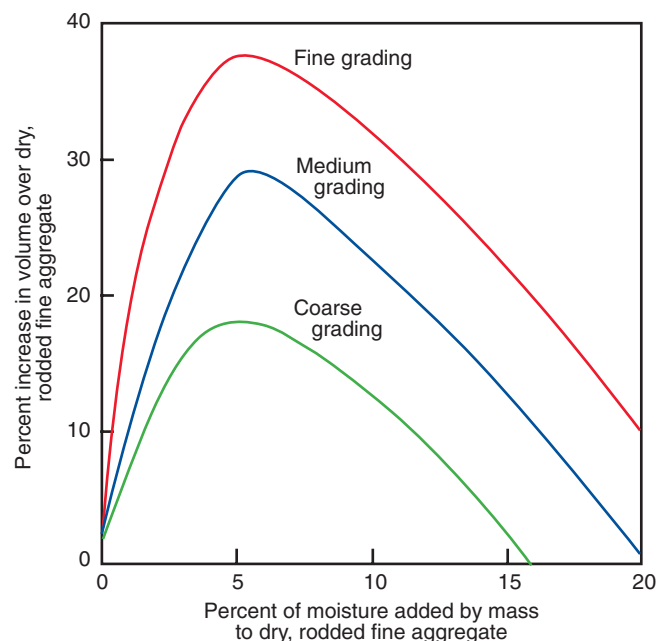


Fig. 5-13. Surface moisture on fine aggregate can cause considerable bulking; the amount varies with the amount of moisture and the aggregate grading (PCA Major Series 172 and PCA ST20).

dated beforehand. Fig. 5-13 illustrates how the amount of bulking of fine aggregate varies with moisture content and grading; fine gradings bulk more than coarse gradings for a given amount of moisture. Fig. 5-14 shows similar information in terms of weight for a particular fine aggregate. Since most fine aggregates are delivered in a damp condition, wide variations can occur in batch quantities if batching is done by volume. For this reason, good practice has long favored weighing the aggregate and adjusting for moisture content when proportioning concrete.

Resistance to Freezing and Thawing

The frost resistance of an aggregate, an important characteristic for exterior concrete, is related to its porosity, absorption, permeability, and pore structure. An aggregate particle may absorb so much water (to critical saturation) that it cannot accommodate the expansion and hydraulic pressure that occurs during the freezing of water. If enough of the offending particles are present, the result can be expansion of the aggregate and possible disintegration of the concrete. If a single problem particle is near the surface of the concrete, it can cause a popout. Popouts generally appear as conical fragments that break out of the concrete surface. The offending aggregate particle or a part of it is usually found at the bottom of the void. Generally it is coarse rather than fine aggregate particles

with higher porosity values and medium-sized pores (0.1 to 5 μm) that are easily saturated and cause concrete deterioration and popouts. Larger pores do not usually become saturated or cause concrete distress, and water in very fine pores may not freeze readily.

At any freezing rate, there may be a critical particle size above which a particle will fail if frozen when critically saturated. This critical size is dependent upon the rate of freezing and the porosity, permeability, and tensile strength of the particle. For fine-grained aggregates with low permeability (cherts for example), the critical particle size may be within the range of normal aggregate sizes. It is higher for coarse-grained materials or those with capillary systems interrupted by numerous macropores (voids too large to hold moisture by capillary action). For these aggregates the critical particle size may be sufficiently large to be of no consequence, even though the absorption may be high. If potentially vulnerable aggregates are used in concrete subjected to periodic drying while in service, they may never become sufficiently saturated to cause failure.

Cracking of concrete pavements caused by the freeze-thaw deterioration of the aggregate within concrete is called D-cracking. This type of cracking has been observed in some pavements after three or more years of service. D-cracked concrete resembles frost-damaged concrete caused by paste deterioration. D-cracks are closely spaced crack formations parallel to transverse and longitudinal joints that later multiply outward from the joints toward the center of the pavement panel (Fig. 5-15). D-cracking is a function of the pore properties of certain types of aggregate particles and the environment in which the pavement is placed. Due to the natural accumulation of water under pavements in the base and subbase layers, the aggregate may eventually become saturated. Then

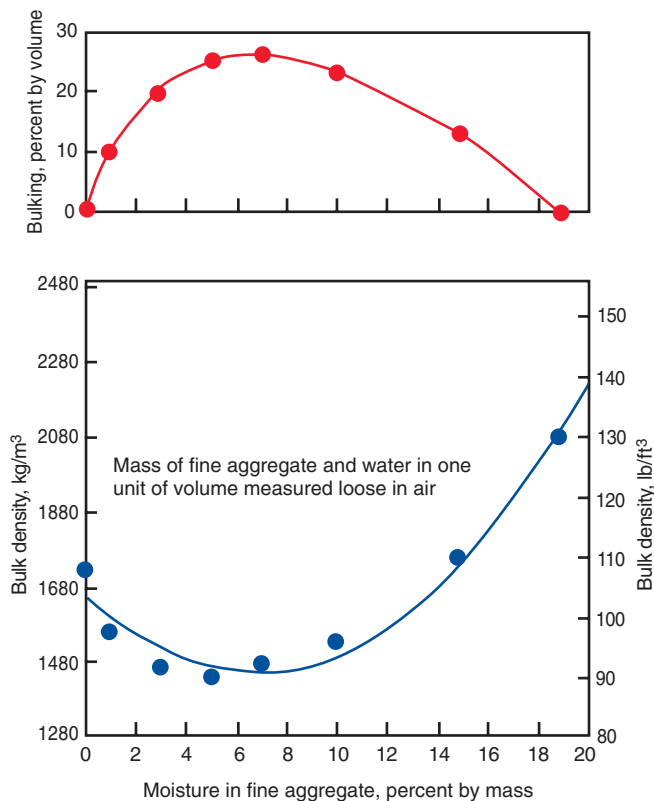


Fig. 5-14. Bulk density is compared with the moisture content for a particular sand (PCA Major Series 172).



Fig. 5-15. D-cracking along a transverse joint caused by failure of carbonate coarse aggregate (Stark 1976). (30639)

with freezing and thawing cycles, cracking of the concrete starts in the saturated aggregate (Fig. 5-16) at the bottom of the slab and progresses upward until it reaches the wearing surface. This problem can be reduced either by selecting aggregates that perform better in freeze-thaw cycles or, where marginal aggregates must be used, by reducing the maximum particle size. Also, installation of effective drainage systems for carrying free water out from under the pavement may be helpful.

The performance of aggregates under exposure to freezing and thawing can be evaluated in two ways: (1) past performance in the field, and (2) laboratory freeze-thaw tests of concrete specimens. If aggregates from the same source have previously given satisfactory service when used in concrete, they might be considered suitable. Aggregates not having a service record can be considered acceptable if they perform satisfactorily in air-entrained concretes subjected to freeze-thaw tests according to ASTM C 666 (AASHTO T 161). In these tests concrete specimens made with the aggregate in question are subjected to alternate cycles of freezing and thawing in water. Deterioration is measured by (1) the reduction in the dynamic modulus of elasticity, (2) linear expansion, and (3) weight loss of the specimens. An expansion failure criterion of 0.035% in 350 freeze-thaw cycles or less is used by a number of state highway departments to help indicate whether or not an aggregate is susceptible to D-cracking. Different aggregate types may influence the criteria levels and empirical correlations between laboratory freeze-thaw tests. Field service records should be made to select the proper criterion (Vogler and Grove 1989).

Specifications may require that resistance to weathering be demonstrated by a sodium sulfate or magnesium sulfate test (ASTM C 88 or AASHTO T 104). The test consists of a number of immersion cycles for a sample of the aggregate in a sulfate solution; this creates a pressure through salt-crystal growth in the aggregate pores similar to that produced by freezing water. The sample is then

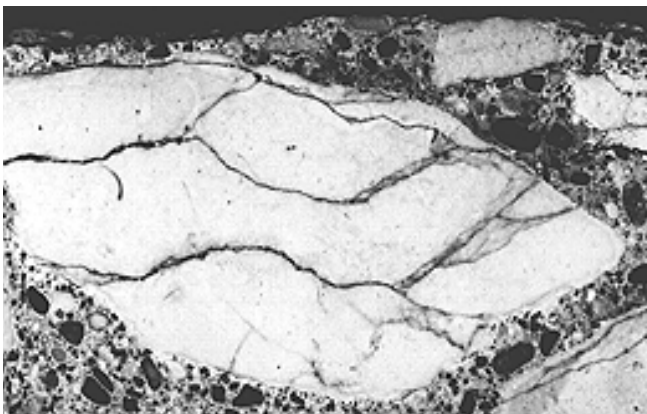


Fig. 5-16. Fractured carbonate aggregate particle as a source of distress in D-cracking (magnification 2.5X) (Stark 1976). (30639-A)

ovendried and the percentage of weight loss calculated. Unfortunately, this test is sometimes misleading. Aggregates behaving satisfactorily in the test might produce concrete with low freeze-thaw resistance; conversely, aggregates performing poorly might produce concrete with adequate resistance. This is attributed, at least in part, to the fact that the aggregates in the test are not confined by cement paste (as they would be in concrete) and the mechanisms of attack are not the same as in freezing and thawing. The test is most reliable for stratified rocks with porous layers or weak bedding planes.

An additional test that can be used to evaluate aggregates for potential D-cracking is the rapid pressure release method. An aggregate is placed in a pressurized chamber and the pressure is rapidly released causing the aggregate with a questionable pore system to fracture (Janssen and Snyder 1994). The amount of fracturing relates to the potential for D-cracking.

Wetting and Drying Properties

Weathering due to wetting and drying can also affect the durability of aggregates. The expansion and contraction coefficients of rocks vary with temperature and moisture content. If alternate wetting and drying occurs, severe strain can develop in some aggregates, and with certain types of rock this can cause a permanent increase in volume of the concrete and eventual breakdown. Clay lumps and other friable particles can degrade rapidly with repeated wetting and drying. Popouts can also develop due to the moisture-swelling characteristics of certain aggregates, especially clay balls and shales. While no specific tests are available to determine this tendency, an experienced petrographer can often be of assistance in determining this potential for distress.

Abrasion and Skid Resistance

The abrasion resistance of an aggregate is often used as a general index of its quality. Abrasion resistance is essential when the aggregate is to be used in concrete subject to abrasion, as in heavy-duty floors or pavements. Low abrasion resistance of an aggregate may increase the quantity of fines in the concrete during mixing; consequently, this may increase the water requirement and require an adjustment in the water-cement ratio.

The most common test for abrasion resistance is the Los Angeles abrasion test (rattler method) performed in accordance with ASTM C 131 (AASHTO T 96) or ASTM C 535. In this test a specified quantity of aggregate is placed in a steel drum containing steel balls, the drum is rotated, and the percentage of material worn away is measured. Specifications often set an upper limit on this mass loss. However, a comparison of the results of aggregate abrasion tests with the abrasion resistance of concrete made with the same aggregate do not generally show a clear

correlation. Mass loss due to impact in the rattler is often as much as that due to abrasion. The wear resistance of concrete is determined more accurately by abrasion tests of the concrete itself (see Chapter 1).

To provide good skid resistance on pavements, the siliceous particle content of the fine aggregate should be at least 25%. For specification purposes, the siliceous particle content is considered equal to the insoluble residue content after treatment in hydrochloric acid under standardized conditions (ASTM D 3042). Certain manufactured sands produce slippery pavement surfaces and should be investigated for acceptance before use.

Strength and Shrinkage

The strength of an aggregate is rarely tested and generally does not influence the strength of conventional concrete as much as the strength of the paste and the paste-aggregate bond. However, aggregate strength does become important in high-strength concrete. Aggregate stress levels in concrete are often much higher than the average stress over the entire cross section of the concrete. Aggregate tensile strengths range from 2 to 15 MPa (300 to 2300 psi) and compressive strengths from 65 to 270 MPa (10,000 to 40,000 psi).

Different aggregate types have different compressibility, modulus of elasticity, and moisture-related shrinkage characteristics that can influence the same properties in concrete. Aggregates with high absorption may have high shrinkage on drying. Quartz and feldspar aggregates, along with limestone, dolomite, and granite, are considered low shrinkage aggregates; while aggregates with sandstone, shale, slate, hornblende, and graywacke are often associated with high shrinkage in concrete (Fig. 5-17).

Resistance to Acid and Other Corrosive Substances

Portland cement concrete is durable in most natural environments; however, concrete in service is occasionally exposed to substances that will attack it.

Most acidic solutions will slowly or rapidly disintegrate portland cement concrete depending on the type and concentration of acid. Certain acids, such as oxalic acid, are harmless. Weak solutions of some acids have insignificant effects. Although acids generally attack and leach away the calcium compounds of the cement paste, they may not readily attack certain aggregates, such as siliceous aggregates. Calcareous aggregates often react readily with acids. However, the sacrificial effect of calcareous aggregates is often a benefit over siliceous aggregate in mild acid exposures or in areas where water is not flowing. With calcareous aggregate, the acid attacks the entire exposed concrete surface uniformly, reducing the rate of attack on the paste and preventing loss of aggregate particles at the surface. Calcareous aggregates also tend to neutralize the acid, especially in stagnant locations. Acids can also discolor

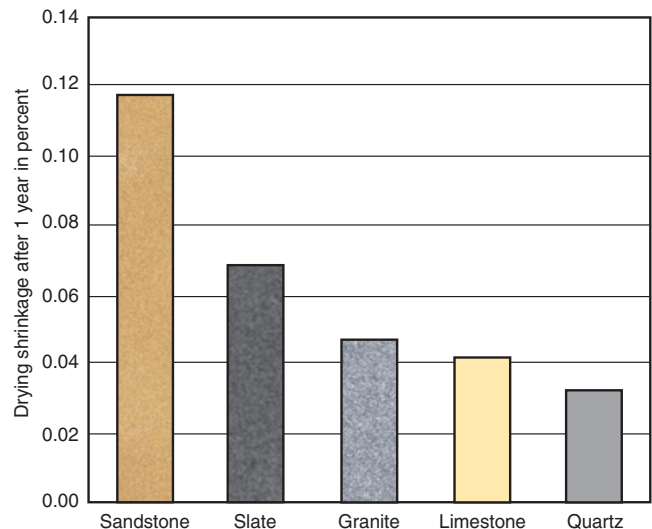


Fig. 5-17. Concretes containing sandstone or slate produce a high shrinkage concrete. Granite, limestone and quartz, are low shrinkage-producing aggregates (ACI 221R).

concrete. Siliceous aggregate should be avoided when strong solutions of sodium hydroxide are present, as these solutions attack this type of aggregate.

Acid rain (often with a pH of 4 to 4.5) can slightly etch concrete surfaces, usually without affecting the performance of exposed concrete structures. Extreme acid rain or strong acid water conditions may warrant special concrete designs or precautions, especially in submerged areas. Continuous replenishment in acid with a pH of less than 4 is considered highly aggressive to buried concrete, such as pipe (Scanlon 1987). Concrete continuously exposed to liquid with a pH of less than 3 should be protected in a manner similar to concrete exposed to dilute acid solutions (ACI 515.1R).

Natural waters usually have a pH of more than 7 and seldom less than 6. Waters with a pH greater than 6.5 may be aggressive if they contain bicarbonates. Carbonic acid solutions with concentrations between 0.9 and 3 parts per million are considered to be destructive to concrete (ACI 515.1R and Kerkhoff 2001).

A low water-cement ratio, low permeability, and low-to-moderate cement content can increase the acid or corrosion resistance of concrete. A low permeability resulting from a low water-cement ratio or the use of silica fume or other pozzolans, helps keep the corrosive agent from penetrating into the concrete. Low-to-moderate cement contents result in less available paste to attack. The use of sacrificial calcareous aggregates should be considered where indicated.

Certain acids, gases, salts, and other substances that are not mentioned here also can disintegrate concrete. Acids and other chemicals that severely attack portland cement concrete should be prevented from coming in contact with the concrete by using protective coatings (Kerkhoff 2001).

Fire Resistance and Thermal Properties

The fire resistance and thermal properties of concrete—conductivity, diffusivity, and coefficient of thermal expansion—depend to some extent on the mineral constituents of the aggregates used. Manufactured and some naturally occurring lightweight aggregates are more fire resistant than normal-weight aggregates due to their insulating properties and high-temperature stability. Concrete containing a calcareous coarse aggregate performs better under fire exposure than a concrete containing quartz or siliceous aggregate such as granite or quartzite. At about 590°C (1060°F), quartz expands 0.85% causing disruptive expansion (ACI 216 and ACI 221). The coefficient of thermal expansion of aggregates ranges from 0.55×10^{-6} per °C to 5×10^{-6} per °C (1×10^{-6} per °F to 9×10^{-6} per °F). For more information refer to Chapter 15 for temperature-induced volume changes and to Chapter 18 for thermal conductivity and mass concrete considerations.

POTENTIALLY HARMFUL MATERIALS

Harmful substances that may be present in aggregates include organic impurities, silt, clay, shale, iron oxide, coal, lignite, and certain lightweight and soft particles (Table 5-6). In addition, rocks and minerals such as some cherts, strained quartz (Buck and Mather 1984), and certain dolomitic limestones are alkali reactive (see Table 5-7). Gypsum and anhydrite may cause sulfate attack. Certain aggregates, such as some shales, will cause popouts by swelling (simply by absorbing water) or by freezing of absorbed water (Fig. 5-18). Most specifications limit the permissible amounts of these substances. The performance history of an aggregate should be a determining factor in setting the limits for harmful substances. Test methods for detecting harmful substances qualitatively or quantitatively are listed in Table 5-6.

Aggregates are potentially harmful if they contain compounds known to react chemically with portland cement concrete and produce any of the following: (1) significant volume changes of the paste, aggregates, or both; (2) interference with the normal hydration of cement; and (3) otherwise harmful byproducts.

Organic impurities may delay setting and hardening of concrete, may reduce strength gain, and in unusual cases may cause deterioration. Organic impurities such as peat, humus, and organic loam may not be as detrimental but should be avoided.

Materials finer than the 75-µm (No. 200) sieve, especially silt and clay, may be present as loose dust and may form a coating on the aggregate particles. Even thin coatings of silt or clay on gravel particles can be harmful because they may weaken the bond between the cement paste and aggregate. If certain types of silt or clay are present in excessive amounts, water requirements may increase significantly.

Table 5-6. Harmful Materials in Aggregates

Substances	Effect on concrete	Test designation
Organic impurities	Affects setting and hardening, may cause deterioration	ASTM C 40 (AASHTO T 21) ASTM C 87 (AASHTO T 71)
Materials finer than the 75-µm (No. 200) sieve	Affects bond, increases water requirement	ASTM C 117 (AASHTO T 11)
Coal, lignite, or other lightweight materials	Affects durability, may cause stains and popouts	ASTM C 123 (AASHTO T 113)
Soft particles	Affects durability	ASTM C 235
Clay lumps and friable particles	Affects workability and durability, may cause popouts	ASTM C 142 (AASHTO T 112)
Chert of less than 2.40 relative density	Affects durability, may cause popouts	ASTM C 123 (AASHTO T 113) ASTM C 295
Alkali-reactive aggregates	Causes abnormal expansion, map cracking, and popouts	ASTM C 227 ASTM C 289 ASTM C 295 ASTM C 342 ASTM C 586 ASTM C 1260 (AASHTO T 303) ASTM C 1293

Table 5-7. Some Potentially Harmful Reactive Minerals, Rock, and Synthetic Materials

Alkali-silica reactive substances*		Alkali-carbonate reactive substances**
Andesites	Opal	Calcitic dolomites
Argillites	Opaline shales	Dolomitic limestones
Certain siliceous limestones and dolomites	Phyllites	Fine-grained dolomites
Chalcedonic cherts	Quartzites	
Chalcedony	Quartzoses	
Cristobalite	Cherts	
Dacites	Rhyolites	
Glassy or cryptocrystalline volcanics	Schists	
Granite gneiss	Siliceous shales	
Graywackes	Strained quartz	
Metagraywackes	and certain other forms of quartz	
	Synthetic and natural silicious glass	
	Tridymite	

* Several of the rocks listed (granite gneiss and certain quartz formations for example) react very slowly and may not show evidence of any harmful degree of reactivity until the concrete is over 20 years old.

** Only certain sources of these materials have shown reactivity.

Video

Video



Fig. 5-18. A popout is the breaking away of a small fragment of concrete surface due to internal pressure that leaves a shallow, typically conical depression. (113)

There is a tendency for some fine aggregates to degrade from the grinding action in a concrete mixer; this effect, which is measured using ASTM C 1137, may alter mixing water, entrained air and slump requirements.

Video

Coal or lignite, or other low-density materials such as wood or fibrous materials, in excessive amounts will affect the durability of concrete. If these impurities occur at or near the surface, they might disintegrate, pop out, or cause stains. Potentially harmful chert in coarse aggregate can be identified by using ASTM C 123 (AASHTO T 113).

Video

Soft particles in coarse aggregate are especially objectionable because they cause popouts and can affect durability and wear resistance of concrete. If friable, they could break up during mixing and thereby increase the amount of water required. Where abrasion resistance is critical, such as in heavy-duty industrial floors, testing may indicate that further investigation or another aggregate source is warranted.

Clay lumps present in concrete may absorb some of the mixing water, cause popouts in hardened concrete, and affect durability and wear resistance. They can also break up during mixing and thereby increase the mixing-water demand.

Aggregates can occasionally contain particles of iron oxide and iron sulfide that result in unsightly stains on exposed concrete surfaces (Fig. 5-19). The aggregate should meet the staining requirements of ASTM C 330 (AASHTO M 195) when tested according to ASTM C 641; the quarry face and aggregate stockpiles should not show evidence of staining.

As an additional aid in identifying staining particles, the aggregate can be immersed in a lime slurry. If staining particles are present, a blue-green gelatinous precipitate will form within 5 to 10 minutes; this will rapidly change to a brown color on exposure to air and light. The reaction should be complete within 30 minutes. If no brown gelatinous precipitate is formed when a suspect aggregate is

placed in the lime slurry, there is little likelihood of any reaction taking place in concrete. These tests should be required when aggregates with no record of successful prior use are used in architectural concrete.



Fig. 5-19. Iron oxide stain caused by impurities in the coarse aggregate. (70024)

ALKALI-AGGREGATE REACTIVITY

Aggregates containing certain constituents can react with alkali hydroxides in concrete. The reactivity is potentially harmful only when it produces significant expansion (Mather 1975). This alkali-aggregate reactivity (AAR) has two forms—alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). ASR is of more concern than ACR because the occurrence of aggregates containing reactive silica minerals is more common. Alkali-reactive carbonate aggregates have a specific composition that is not very common.

Alkali-silica reactivity has been recognized as a potential source of distress in concrete since the late 1930s (Stanton 1940 and PCA 1940). Even though potentially reactive aggregates exist throughout North America, ASR distress in structural concrete is not common. There are a number of reasons for this:

- Most aggregates are chemically stable in hydraulic-cement concrete.
- Aggregates with good service records are abundant in many areas.
- Most concrete in service is dry enough to inhibit ASR.
- Use of certain pozzolans or slags can control ASR.
- In many concrete mixtures, the alkali content of the concrete is low enough to control harmful ASR.
- Some forms of ASR do not produce significant deleterious expansion.

To reduce ASR potential requires understanding the ASR mechanism; properly using tests to identify potentially reactive aggregates; and, if needed, taking steps to minimize the potential for expansion and related cracking.

Alkali-Silica Reaction

Visual Symptoms of Expansive ASR. Typical indicators of ASR might be any of the following: a network of cracks (Fig. 5-20); closed or spalled joints; relative displacements of different parts of a structure; or fragments breaking out of the surface of the concrete (popouts) (Fig. 5-21). Because ASR deterioration is slow, the risk of catastrophic failure is low. However, ASR can cause serviceability problems and can exacerbate other deterioration mechanisms such as those that occur in frost, deicer, or sulfate exposures.



Fig. 5-20 (top and bottom). Cracking of concrete from alkali-silica reactivity. (69549, 58352)

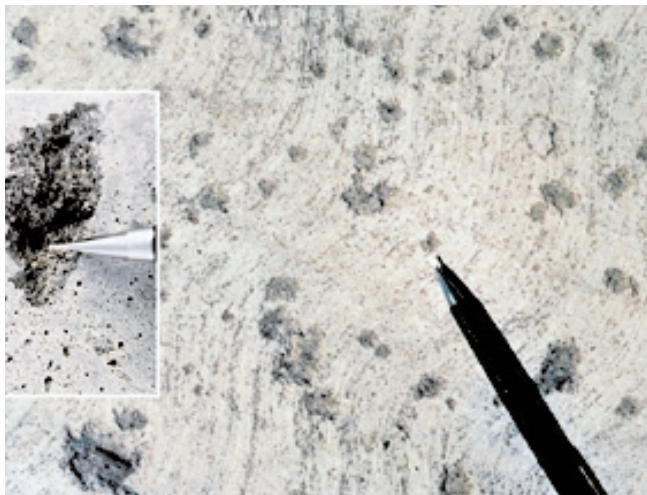


Fig. 5-21. Popouts caused by ASR of sand-sized particles. Inset shows closeup of a popout. (51117, 51118)

Mechanism of ASR. The alkali-silica reaction forms a gel that swells as it draws water from the surrounding cement paste. Reaction products from ASR have a great affinity for moisture. In absorbing water, these gels can induce pressure, expansion, and cracking of the aggregate and surrounding paste. The reaction can be visualized as a two-step process:

1. Alkali hydroxide + reactive silica gel → reaction product (alkali-silica gel)
2. Gel reaction product + moisture → expansion

The amount of gel formed in the concrete depends on the amount and type of silica and alkali hydroxide concentration. The presence of gel does not always coincide with distress, and thus, gel presence does not necessarily indicate destructive ASR.

Factors Affecting ASR. For alkali-silica reaction to occur, the following three conditions must be present:

1. reactive forms of silica in the aggregate,
2. high-alkali (pH) pore solution, and
3. sufficient moisture.

If one of these conditions is absent, ASR cannot occur.

Test Methods for Identifying ASR Distress. It is important to distinguish between the reaction and damage resulting from the reaction. In the diagnosis of concrete deterioration, it is most likely that a gel product will be identified. But, in some cases significant amounts of gel are formed without causing damage to concrete. To pinpoint ASR as the cause of damage, the presence of deleterious ASR gel must be verified. A site of expansive reaction can be defined as an aggregate particle that is recognizably reactive or potentially reactive and is at least partially replaced by gel. Gel can be present in cracks and voids and may also be present in a ring surrounding an aggregate particle at its edges. A network of internal cracks connecting reacted aggregate particles is an almost certain indication that ASR is responsible for cracking. A petrographic examination (ASTM C 856) is the most positive method for identifying ASR gel in concrete (Powers 1999). Petrography, when used to study a known reacted concrete, can confirm the presence of reaction products and verify ASR as an underlying cause of deterioration (Fig. 5-22).

Control of ASR in New Concrete. The best way to avoid ASR is to take appropriate precautions before concrete is placed. Standard concrete specifications may require modifications to address ASR. These modifications should be carefully tailored to avoid limiting the concrete producer's options. This permits careful analysis of cementitious materials and aggregates and choosing a control strategy that optimizes effectiveness and the economic selection of materials. If the aggregate is not reactive by historical identification or testing, no special requirements are needed.

Identification of Potentially Reactive Aggregates. Field performance history is the best method of evaluating the susceptibility of an aggregate to ASR. For the most definitive evaluation, the existing concrete should have been in service for at least 15 years. Comparisons should be made between the existing and proposed concrete's mix proportions, ingredients, and service environments. This process should tell whether special requirements are needed, are not needed, or whether testing of the aggregate or job concrete is required. The use of newer, faster test methods can be utilized for initial screening. Where uncertainties arise, lengthier tests can be used to confirm results. Table 5-8 describes different test methods used to evaluate potential alkali-silica reactivity. These tests should not be used to disqualify use of potentially reactive aggregates, as reactive aggregates can be safely used with the careful selection of cementitious materials as discussed below.

Materials and Methods to Control ASR. The most effective way of controlling expansion due to ASR is to design mixtures specifically to control ASR, preferably using locally available materials. The following options are not listed in priority order and, although usually not necessary, they can be used in combination with one another.

In North America, current practices include the use of a supplementary cementitious material or blended cement proven by testing to control ASR or limiting the alkali content of the concrete. Supplementary cementitious materials include fly ash, ground granulated blast-furnace slag, silica fume, and natural pozzolans. Blended cements use slag, fly ash, silica fume, and natural pozzolans to control ASR. Low-alkali portland cement (ASTM C 150) with an alkali content of not more than 0.60% (equivalent sodium oxide) can be used to control ASR. Its use has been successful with slightly reactive to moderately reactive aggregates. However, low-alkali cements are not available in all areas. Thus, the use of locally available cements in combination with pozzolans, slags, or blended cements is preferable for controlling ASR. When pozzolans, slags, or blended cements are used to control ASR, their effective-

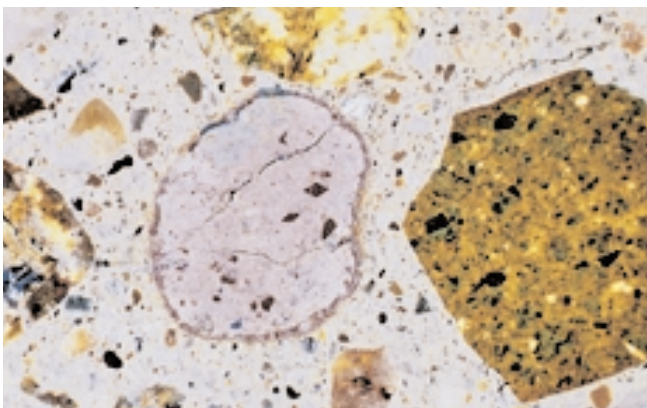


Fig. 5-22. Polished section view of an alkali reactive aggregate in concrete. Observe the alkali-silica reaction rim around the reactive aggregate and the crack formation. (43090)

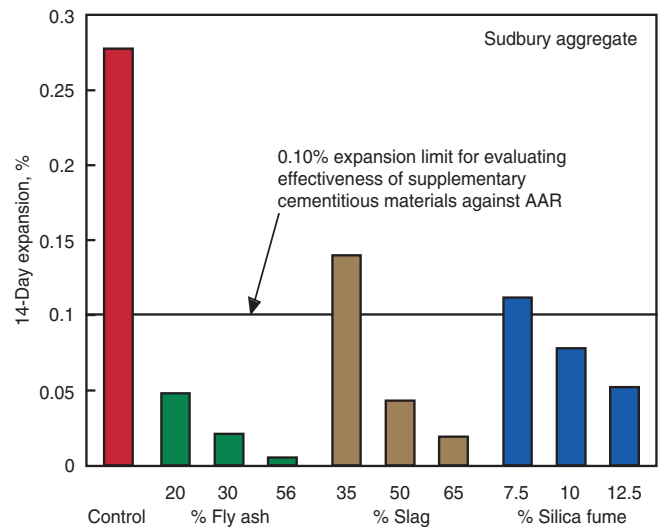


Fig. 5-23. Influence of different amounts of fly ash, slag, and silica fume by mass of cementing material on mortar bar expansion (ASTM C 1260) after 14 days when using reactive aggregate (Fournier 1997).

ness must be determined by tests such as ASTM C 1260 (modified) or C 1293. Where applicable, different amounts of pozzolan or slag should be tested to determine the optimum dosage. Expansion usually decreases as the dosage of the pozzolan or slag increases (see Fig. 5-23). Lithium-based admixtures are also available to control ASR. Limestone sweetening (the popular term for replacing approximately 30% of the reactive sand-gravel aggregate with crushed limestone) is effective in controlling deterioration in some sand-gravel aggregate concretes. See AASHTO (2001), Farny and Kosmatka (1997), and PCA (1998) for more information on tests to demonstrate the effectiveness of the above control measures.

Alkali-Carbonate Reaction

Mechanism of ACR. Reactions observed with certain dolomitic rocks are associated with alkali-carbonate reaction (ACR). Reactive rocks usually contain large crystals of dolomite scattered in and surrounded by a fine-grained matrix of calcite and clay. Calcite is one of the mineral forms of calcium carbonate; dolomite is the common name for calcium-magnesium carbonate. ACR is relatively rare because aggregates susceptible to this reaction are usually unsuitable for use in concrete for other reasons, such as strength potential. Argillaceous dolomitic limestone contains calcite and dolomite with appreciable amounts of clay and can contain small amounts of reactive silica. Alkali reactivity of carbonate rocks is not usually dependent upon its clay mineral composition (Hadley 1961). Aggregates have potential for expansive ACR if the following lithological characteristics exist (Ozol 1994 and Swenson 1967):

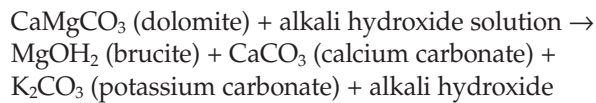
Table 5-8. Test Methods for Alkali-Silica Reactivity (Farny and Kosmatka 1997)

Test name	Purpose	Type of test	Type of sample
ASTM C 227, Potential alkali-reactivity of cement-aggregate combinations (mortar-bar method)	To test the susceptibility of cement-aggregate com- binations to expansive reactions involving alkalies	Mortar bars stored over water at 37.8°C (100°F) and high relative humidity	At least 4 mortar bars of standard dimensions: 25 x 25 x 285 mm (1 x 1 x 11¼ in.)
ASTM C 289, Potential alkali-silica reactivity of aggregates (chemical method)	To determine potential reactivity of siliceous aggregates	Sample reacted with alkaline solution at 80°C (176°F)	Three 25-gram samples of crushed and sieved aggregate
ASTM C 294, Constituents of natural mineral aggregates	To give descriptive nomenclature for the more common or impor- tant natural minerals—an aid in determining their performance	Visual identification	Varies, but should be representative of entire source
ASTM C 295, Petrographic examination of aggregates for concrete	To outline petrographic examination procedures for aggregates—an aid in determining their per- formance	Visual and microscopic examination of prepared samples—sieve analysis, microscopy, scratch or acid tests	Varies with knowledge of quarry: cores 53 to 100 mm in diameter (2½ to 4 in.) 45 kg (100 lb) or 300 pieces, or 2 kg (4 lb)
ASTM C 342, Potential volume change of cement- aggregate combinations	To determine the poten- tial ASR expansion of cement-aggregate combinations	Mortar bars stored in water at 23°C (73.4°F)	Three mortar bars per cement-aggregate combination of standard dimensions: 25 x 25 x 285 mm (1 x 1 x 11¼ in.)
ASTM C 441, Effectiveness of mineral admixtures or GBFS in preventing excessive expansion of concrete due to alkali-silica reaction	To determine effectiveness of supplementary cementing materials in controlling expansion from ASR high relative humidity	Mortar bars—using Pyrex glass as aggregate— stored over water at 37.8°C (100°F) and	At least 3 mortar bars and also 3 mortar bars of control mixture
ASTM C 856, Petrographic examination of hardened concrete	To outline petrographic examination procedures for hardened concrete— useful in determining condition or performance	Visual (unmagnified) and microscopic exam- ination of prepared samples	At least one 150-mm diameter by 300-mm long core (6-in. diameter by 12-in. long)
ASTM C 856 (AASHTO T 299), Annex uranyl-acetate treatment procedure	To identify products of ASR in hardened concrete	Staining of a freshly- exposed concrete surface and viewing under UV light	Varies: core with lapped surface, core with broken surface
Los Alamos staining method (Powers 1999)	To identify products of ASR in hardened concrete	Staining of a freshly-exposed concrete surface with two different reagents	Varies: core with lapped surface, core with broken surface
ASTM C 1260 (AASHTO T 303), Potential alkali-reactivity of aggregates (mortar- bar method)	To test the potential for deleterious alkali-silica reaction of aggregate in mortar bars	Immersion of mortar bars in alkaline solution at 80°C (176°F)	At least 3 mortar bars
ASTM C 1293, Determination of length change of concrete due to alkali-silica reaction (concrete prism test)	To determine the potential ASR expansion of cement-aggregate combinations	Concrete prisms stored over water at 38°C (100.4°F)	Three prisms per cement- aggregate combination of standard dimensions: 75 x 75 x 285 mm (3 x 3 x 11¼ in.)
Accelerated concrete prism test (modified ASTM C 1293)	To determine the potential ASR expansion of cement-aggregate combinations	Concrete prisms stored over water at 60°C (140°F)	Three prisms per cement- aggregate combination of standard dimensions: 75 x 75 x 285 mm (3 x 3 x 11¼ in.)

	Duration of test	Measurement	Criteria	Comments
	Varies: first measurement at 14 days, then 1,2, 3,4,6,9, and 12 months; every 6 months after that as necessary	Length change	Per ASTM C 33, maximum 0.10% expansion at 6 months, or if not available for a 6-month period, maximum of 0.05% at 3 months	Test may not produce significant expansion, especially for carbonate aggregate. Long test duration. Expansions may not be from AAR.
	24 hours	Drop in alkalinity and amount of silica solubilized	Point plotted on graph falls in deleterious or potentially deleterious area	Quick results. Some aggregates give low expansions even though they have high silica content. Not reliable.
	Short duration—as long as it takes to visually examine the sample	Description of type and proportion of minerals in aggregate	Not applicable	These descriptions are used to characterize naturally-occurring minerals that make up common aggregate sources.
	Short duration—visual examination does not involve long test periods	Particle characteristics, such as shape, size, texture, color, mineral composition, and physical condition	Not applicable	Usually includes optical microscopy. Also may include XRD analysis, differential thermal analysis, or infrared spectroscopy—see ASTM C 294 for descriptive nomenclature.
	52 weeks	Length change	Per ASTM C 33, unsatisfactory aggregate if expansion equals or exceeds 0.200% at 1 year	Primarily used for aggregates from Oklahoma, Kansas, Nebraska, and Iowa.
	Varies: first measurement at 14 days, then 1,2, 3,4,5,9, and 12 months; every 6 months after that as necessary	Length change	Per ASTM C 989, minimum 75% reduction in expansion or 0.020% maximum expansion or per ASTM C 618, comparison against low-alkali control	Highly reactive artificial aggregate may not represent real aggregate conditions. Pyrex contains alkalis.
	Short duration—includes preparation of samples and visual and microscope examination	Is the aggregate known to be reactive? Orientation and geometry of cracks. Is there any gel present?	See measurement—this examination determines if ASR reactions have taken place and their effects upon the concrete. Used in conjunction with other tests.	Specimens can be examined with stereomicroscopes, polarizing microscopes, metallographic microscopes, and scanning electron microscope.
	Immediate results	Intensity of fluorescence	Lack of fluorescence	Identifies small amounts of ASR gel whether they cause expansion or not. Opal, a natural aggregate, and carbonated paste can glow—interpret results accordingly. Tests must be supplemented by petrographic examination and physical tests for determining concrete expansion.
	Immediate results	Color of stain	Dark pink stain corresponds to ASR gel and indicates an advanced state of degradation	
	16 days	Length change	If greater than 0.10%, go to supplementary test procedures; if greater than 0.20%, indicative of potential deleterious expansion	Very fast alternative to C 227. Useful for slowly reacting aggregates or those that produce expansion late in the reaction.
	Varies: first measurement at 7 days, then 28 and 56 days, then 3,6,9, and 12 months; every 6 months as after that as necessary	Length change	Per Appendix X1, potentially deleteriously reactive if expansion equals or exceeds 0.04% at one year	Requires long test duration for meaningful results. Use as a supplement to C 227, C 295, C 289, and C 1260. Similar to CSA A23.2-14A.
	3 month (91 days)	Length change	Potentially deleteriously reactive if expansion equals or exceeds 0.04% at 91 days	Fast alternative to C 227. Good correlation to ASTM C 227 for carbonate and sedimentary rocks.

- clay content, or insoluble residue content, in the range of 5% to 25%;
- calcite-to-dolomite ratio of approximately 1:1;
- increase in the dolomite volume up to a point at which interlocking texture becomes a restraining factor; and
- small size of the discrete dolomite crystals (rhombs) suspended in a clay matrix.

Dedolomitization. Dedolomitization, or the breaking down of dolomite, is normally associated with expansive ACR (Hadley 1961). Concrete that contains dolomite and has expanded also contains brucite (magnesium hydroxide, $Mg(OH)_2$), which is formed by dedolomitization. Dedolomitization proceeds according to the following equation (Ozol 1994):



The dedolomitization reaction and subsequent crystallization of brucite may cause considerable expansion. Whether dedolomitization causes expansion directly or indirectly, it's usually a prerequisite to other expansive processes (Tang, Deng, Lon, and Han 1994).

Test Methods for Identifying ACR Distress. The three test methods commonly used to identify potentially alkali-carbonate reactive aggregate are:

- petrographic examination (ASTM C 295);
- rock cylinder method (ASTM C 586); and
- concrete prism test (ASTM C 1105).

See Farny and Kosmatka (1997) for detailed information.

Materials and Methods to Control ACR. ACR-susceptible aggregate has a specific composition that is readily identified by petrographic testing. If a rock indicates ACR-susceptibility, one of the following preventive measures should be taken:

- selective quarrying to completely avoid reactive aggregate;
- blend aggregate according to Appendix in ASTM C 1105; or
- limit aggregate size to smallest practical.

Low-alkali cement and pozzolans are generally not very effective in controlling expansive ACR.

Video AGGREGATE BENEFICIATION

Aggregate processing consists of: (1) basic processing—crushing, screening, and washing—to obtain proper gradation and cleanliness; and (2) beneficiation—upgrading quality by processing methods such as heavy media separation, jigging, rising-current classification, and crushing.

In heavy media separation, aggregates are passed through a heavy liquid comprised of finely ground heavy

minerals and water proportioned to have a relative density (specific gravity) less than that of the desirable aggregate particles but greater than that of the deleterious particles. The heavier particles sink to the bottom while the lighter particles float to the surface. This process can be used when acceptable and harmful particles have distinguishable relative densities.

Jigging separates particles with small differences in density by pulsating water current. Upward pulsations of water through a jig (a box with a perforated bottom) move the lighter material into a layer on top of the heavier material; the top layer is then removed.

Rising-current classification separates particles with large differences in density. Light materials, such as wood and lignite, are floated away in a rapidly upward moving stream of water.

Crushing is also used to remove soft and friable particles from coarse aggregates. This process is sometimes the only means of making material suitable for use. Unfortunately, with any process some acceptable material is always lost and removal of all harmful particles may be difficult or expensive.

HANDLING AND STORING AGGREGATES

Aggregates should be handled and stored in a way that minimizes segregation and degradation and prevents contamination by deleterious substances (Fig. 5-24). Stockpiles should be built up in thin layers of uniform thickness to minimize segregation. The most economical and acceptable method of forming aggregate stockpiles is the truck-dump method, which discharges the loads in a way that keeps them tightly joined. The aggregate is then reclaimed with a front-end loader. The loader should remove slices from the edges of the pile from bottom to top so that every slice will contain a portion of each horizontal layer.



Fig. 5-24. Stockpile of aggregate at a ready mix plant. (69552)

When aggregates are not delivered by truck, acceptable and inexpensive results can be obtained by forming the stockpile in layers with a clamshell bucket (cast-and-spread method); in the case of aggregates not subject to degradation, spreading the aggregates with a rubber-tire dozer and reclaiming with a front-end loader can be used. By spreading the material in thin layers, segregation is minimized. Whether aggregates are handled by truck, bucket loader, clamshell, or conveyor belt, stockpiles should not be built up in high, cone-shaped piles since this results in segregation. However, if circumstances necessitate construction of a conical pile, or if a stockpile has segregated, gradation variations can be minimized when the pile is reclaimed; in such cases aggregates should be loaded by continually moving around the circumference of the pile to blend sizes rather than by starting on one side and working straight through the pile.

Crushed aggregates segregate less than rounded (gravel) aggregates and larger-size aggregates segregate more than smaller sizes. To avoid segregation of coarse aggregates, size fractions can be stockpiled and batched separately. Proper stockpiling procedures, however, should eliminate the need for this. Specifications provide a range in the amount of material permitted in any size fraction partly because of segregation in stockpiling and batching operations.

Washed aggregates should be stockpiled in sufficient time before use so that they can drain to a uniform moisture content. Damp fine material has less tendency to segregate than dry material. When dry fine aggregate is dropped from buckets or conveyors, wind can blow away the fines; this should be avoided if possible.

Bulkheads or dividers should be used to avoid contamination of aggregate stockpiles. Partitions between stockpiles should be high enough to prevent intermingling of materials. Storage bins should be circular or nearly square. Their bottoms should slope not less than 50 degrees from the horizontal on all sides to a center outlet. When loading the bin, the material should fall vertically over the outlet into the bin. Chuting the material into a bin at an angle and against the bin sides will cause segregation. Baffle plates or dividers will help minimize segregation. Bins should be kept as full as possible since this reduces breakage of aggregate particles and the tendency to segregate. Recommended methods of handling and storing aggregates are discussed at length in Matthews (1965 to 1967), NCHRP (1967), and Bureau of Reclamation (1981).

MARINE-DREDGED AGGREGATE

Marine-dredged aggregate from tidal estuaries and sand and gravel from the seashore can be used with caution in some concrete applications when other aggregate sources are not available. Aggregates obtained from seabeds have two problems: (1) seashells and (2) salt.

Seashells may be present in the aggregate source. These shells are a hard material that can produce good quality concrete, however, a higher cement content may be required. Also, due to the angularity of the shells, additional cement paste is required to obtain the desired workability. Aggregate containing complete shells (uncrushed) should be avoided as their presence may result in voids in the concrete and lower the compressive strength.

Marine-dredged aggregates often contain salt from the seawater. The primary salts are sodium chloride and magnesium sulfate and the amount of salt on the aggregate is often not more than about 1% of the mass of the mixing water. The highest salt content occurs in sands located just above the high-tide level. Use of these aggregates with drinkable mix water often contributes less salt to the mixture than the use of seawater (as mix water) with salt-free aggregates.

Marine aggregates can be an appreciable source of chlorides. The presence of these chlorides may affect the concrete by (1) altering the time of set, (2) increasing drying shrinkage, (3) significantly increasing the risk of corrosion of steel reinforcement, and (4) causing efflorescence. Generally, marine aggregates containing large amounts of chloride should not be used in reinforced concrete.

Marine-dredged aggregates can be washed with fresh water to reduce the salt content. There is no maximum limit on the salt content of coarse or fine aggregate; however, the chloride limits presented in Chapter 9 should be followed.

RECYCLED-CONCRETE AGGREGATE

In recent years, the concept of using old concrete pavements, buildings, and other structures as a source of aggregate has been demonstrated on several projects, resulting in both material and energy savings (ECCO 1999). The procedure involves (1) breaking up and removing the old concrete, (2) crushing in primary and secondary crushers (Fig. 5-25), (3) removing reinforcing steel and other embed-



Fig. 5-25. Heavily reinforced concrete is crushed with a beamcrusher. (69779)

ded items, (4) grading and washing, and (5) finally stockpiling the resulting coarse and fine aggregate (Fig. 5-26). Dirt, gypsum board, wood, and other foreign materials should be prevented from contaminating the final product.

Recycled concrete is simply old concrete that has been crushed to produce aggregate. Recycled-concrete aggregate is primarily used in pavement reconstruction. It has been satisfactorily used as an aggregate in granular subbases, lean-concrete subbases, soil-cement, and in new concrete as the only source of aggregate or as a partial replacement of new aggregate.

Recycled-concrete aggregate generally has a higher absorption and a lower specific gravity than conventional aggregate. This results from the high absorption of porous mortar and hardened cement paste within the recycled concrete aggregate. Absorption values typically range from 3% to 10%, depending on the concrete being recycled; this absorption lies between those values for natural and lightweight aggregate. The values increase as coarse particle size decreases (Fig. 5-27). The high absorption of the recycled aggregate makes it necessary to add more water to achieve the same workability and slump than for concrete with conventional aggregates. Dry recycled aggregate absorbs water during and after mixing. To avoid this, recycled aggregate should be prewetted or stockpiles should be kept moist.

The particle shape of recycled-concrete aggregate is similar to crushed rock as shown in Fig. 5-28. The relative density decreases progressively as particle size decreases. The sulfate content of recycled-concrete aggregate should be determined to assess the possibility of deleterious sulfate reactivity. The chloride content should also be determined where applicable.

New concrete made from recycled-concrete aggregate generally has good durability. Carbonation, permeability, and resistance to freeze-thaw action have been found to be the same or even better than concrete with conventional aggregates. Concrete made with recycled coarse aggregates and conventional fine aggregate can obtain an

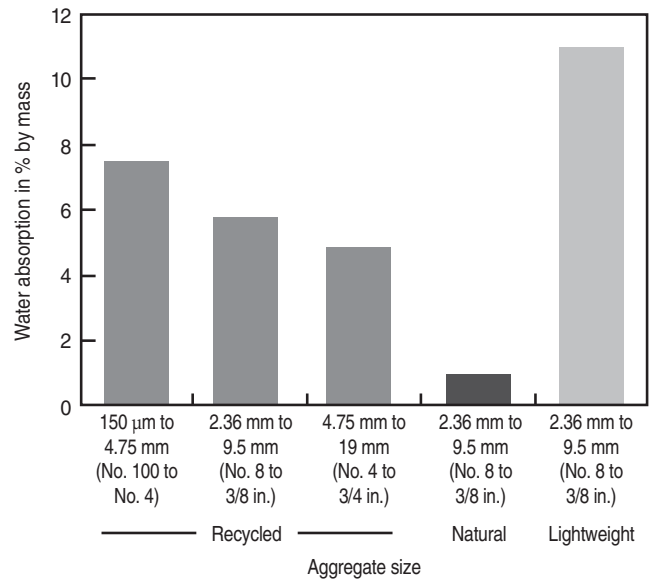


Fig. 5-27. Comparison of water absorption of three different recycled aggregate particle sizes and one size of natural and lightweight coarse aggregate. (Kerkhoff and Siebel 2001)

adequate compressive strength. The use of recycled fine aggregate can result in minor compressive strength reductions. However, drying shrinkage and creep of concrete made with recycled aggregates is up to 100% higher than concrete with a corresponding conventional aggregate. This is due to the large amount of old cement paste and mortar especially in the fine aggregate. Therefore, considerably lower values of drying shrinkage can be achieved using recycled coarse aggregate with natural sand (Kerkhoff and Siebel 2001). As with any new aggregate source, recycled-concrete aggregate should be tested for durability, gradation, and other properties.

Recycled concrete used as coarse aggregate in new concrete possesses some potential for alkali-silica-reaction if the old concrete contained alkali-reactive aggregate. The



Fig. 5-26. Stockpile of recycled-concrete aggregate. (69813)



Fig. 5-28. Recycled-concrete aggregate. (69812)

alkali content of the cement used in the old concrete has little effect on expansion due to alkali-silica-reaction. For highly reactive aggregates made from recycled concrete, special measures discussed under “Alkali-Silica Reaction” should be used to control ASR. Also, even if expansive ASR did not develop in the original concrete, it can not be assumed that it will not develop in the new concrete if special control measures are not taken. Petrographic examination and expansion tests are recommended to make this judgment (Stark 1996).

Concrete trial mixtures should be made to check the new concrete’s quality and to determine the proper mixture proportions. One potential problem with using recycled concrete is the variability in the properties of the old concrete that may in turn affect the properties of the new concrete. This can partially be avoided by frequent monitoring of the properties of the old concrete that is being recycled. Adjustments in the mixture proportions may then be needed.

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