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Aggregates for Concrete

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Aggregates for Concrete

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AGGREGATES FOR CONCRETE

Developed by Committee E-701, Materials for Concrete Construction

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Note: Special credit is extended to Ward R. Malisch, who developed the first edition and made an editorial contribution to this edition.

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CHAPTER 1—INTRODUCTION

Hydraulic cement concrete is a cement and water paste in which aggregate particles are embedded. Aggregate is granular material such as sand, gravel, crushed stone, blast-furnace slag, and lightweight aggregates that usually occupies approximately 60 to 75% of the volume of concrete. Aggregate properties significantly affect the workability of plastic concrete and also the durability, strength, thermal properties, and density of hardened concrete.

This Bulletin describes types of aggregates normally used in concrete, aggregate properties affecting performance of the concrete, tests used to measure aggregate properties, and methods used to obtain test samples. Normalweight as well as lightweight aggregates are discussed.

The measurement system used in this Bulletin is the International System of Units, or SI Units. Accordingly, readers should make particular note that the term "weight" has been replaced with "mass," and "unit weight" has been replaced with "density" when used in reference to the absolute volume aggregates occupy in concrete, and with "bulk density" when used in reference to aggregates, such as the mass per unit volume of a collection of graded aggregate particles as compacted in a volumetric bucket or the relation of mass to volume of aggregates in a stockpile or bin. As a convenience, most of the examples provided in the Bulletin are in both SI and U.S. customary (in.-lb) units.

Frequent references are made to ASTM International (ASTM) standards. These include test methods, definitions, recommended practices, classifications, and specifications that have been formally adopted by ASTM. New editions of the *ASTM Book of Standards* are issued annually, and all references to these standards in this Bulletin refer to the most recent edition. Organizations such as ACI and others have similar or additional standards that may be applicable.

CHAPTER 2—CLASSIFICATION OF AGGREGATES

Aggregates may be broadly classified as natural or artificial, both with respect to source and to method of preparation. Natural sands and gravels are the product of weathering and the action of wind or water, while manufactured crushed fine aggregate and crushed stone coarse and fine aggregate are produced by crushing natural stone. Crushing, screening, and washing may be used to process aggregates from either sand and gravel deposits or stone quarries. Aggregates may be produced from igneous, sedimentary, or metamorphic rocks, but geological type does not by itself make an aggregate suitable or unsuitable for use in concrete. The acceptance of an aggregate for use in concrete on a particular job or in meeting a particular specification should be based upon specific information obtained from tests used to measure the aggregate's quality or, more importantly, its service record, or both. More performance tests are also used to test aggregates in concrete. A typical consensus specification for fine and coarse aggregate for concrete is ASTM C 33.

Synthetic aggregates may be either byproducts of an industrial process, in the case of blast-furnace slag, or products of processes developed to manufacture aggregates with special properties, as in the case of expanded clay, shale, or slate used for lightweight aggregates. Some lightweight aggregates such as pumice or scoria also occur naturally.

Other classifications of aggregates may be based on bulk density, (previously termed "unit weight") (ASTM C 33, C 330, and C 637), mineralogical composition (ASTM C 294), and particle shape, but these, as well as the ones previously discussed, serve mainly as aids in describing an aggregate. To understand the role played by aggregate in the performance of concrete, it is necessary to define specific aggregate properties and show their effect on concrete properties.

CHAPTER 3—AGGREGATE PROPERTIES AND TEST METHODS

3.1—Grading

3.1.1 *Definition and test method*—Grading refers to the distribution of particle sizes present in an aggregate. The grading is determined in accordance with ASTM C 136, "Sieve or Screen Analysis of Fine and Coarse Aggregates." A sample of the aggregate is shaken through a series of wire-cloth sieves with square openings, nested one above the other in order of size, with the sieve having the largest openings on top, the one having the smallest openings at the bottom, and a pan underneath to catch material passing the finest sieve (Fig. 1). Sieve sizes commonly used for concrete aggregates are detailed in Table 1, and various physical properties of normalweight aggregates, with typical range values, are shown in Table 2.

Coarse and fine aggregates are generally sieved separately. That portion of an aggregate passing the 4.75 mm (No. 4)

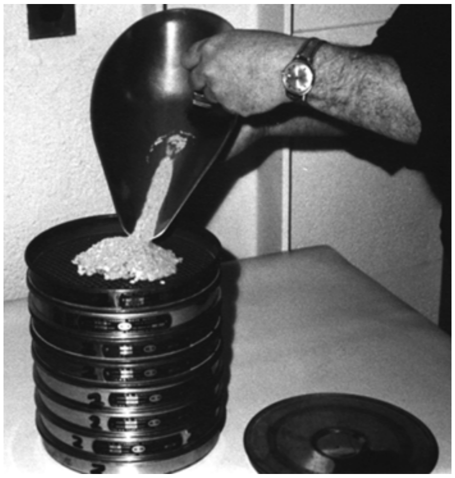

Fig. 1—Nest of sieves.

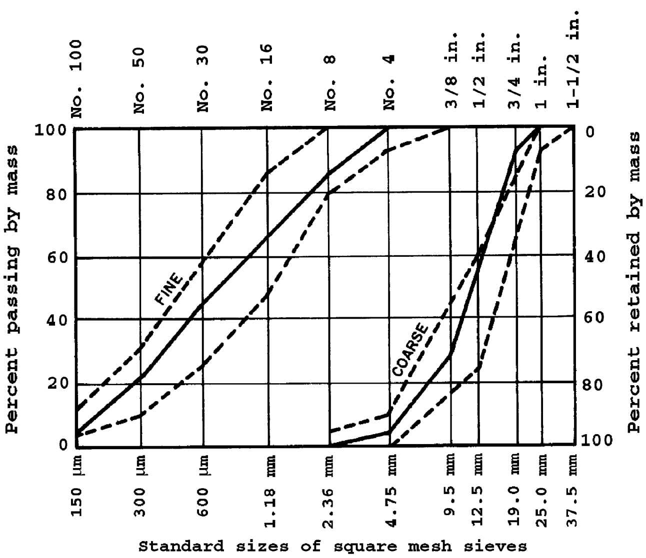

Fig. 2—Typical grading chart. Dashed lines indicate limits specified in ASTM C 33 for fine aggregates and for 25.0 mm (1 in.) coarse aggregate.

Table 1—Sieves commonly used for sieve analysis of concrete aggregates

Standard sieve designation (ASTM E 11)		Nominal sieve opening	
		mm	in.
Coarse sieves			
Standard	Alternate		
75.0 mm	3 in.	75.0	3
63.0 mm	2-1/2 in.	63.0	2.5
50.0 mm	2 in.	50.0	2
37.5 mm	1-1/2 in.	37.5	1.5
25.0 mm	1 in.	25.0	1
19.0 mm	3/4 in.	19.0	0.75
12.5 mm	1/2 in.	12.5	0.5
9.5 mm	3/8 in.	9.5	0.375
Fine sieves			
4.75 mm	No. 4	4.75	0.1870
2.36 mm	No. 8	2.36	0.0937
1.18 mm	No. 16	1.18	0.0469
600 µm*	No. 30	0.60	0.0234
300 µm	No. 50	0.30	0.0117
150 µm	No. 100	0.15	0.0059
Finest sieve normally used for aggregates			
75 µm	No. 200	0.075	0.0029

*1000 µm (micro-meters) = 1 mm.

Table 2—Ranges in physical properties for normal-weight aggregates used in concrete

Property		Typical ranges
Fineness modulus of fine aggregate (defined in the following)		2.0 to 3.3
Nominal maximum size of coarse aggregate		9.5 to 37.5 mm (3/8 to 1-1/2 in.)
Absorption		0.5 to 4%
Bulk specific gravity (relative density)		2.30 to 2.90
Dry-rodded bulk density* of coarse aggregate		1280 to 1920 kg/m^3 (80 to 120 lb/ft^3)
Surface moisture content	Coarse aggregate	0 to 2%
	Fine aggregate	0 to 10%

*Previously dry-rodded unit weight.

sieve and predominantly retained on the 75 µm (No. 200) sieve is called "fine aggregate" or "sand," and larger aggregate is called "coarse aggregate." Coarse aggregate may be available in several different size groups, such as 19 to 4.75 mm (3/4 in. to No. 4), or 37.5 to 19 mm (1-1/2 to 3/4 in.).

ASTM C 33 ("Standard Specifications for Concrete Aggregates") lists several such size groups using the simplified practice recommendation (SPR) number designation. The number and size of sieves selected for a sieve analysis depends on the particle sizes present in the sample and the grading requirements specified.

After sieving, the mass of material retained on each sieve and in the pan is obtained using a balance accurate to 0.1% of the test-sample mass. Results are recorded in tabular form with some or all of the following quantities retained on each sieve, individual percent retained on each sieve (and passing the sieve above), and total percent of the whole sample passing each sieve. For an accurate determination of the amount of material finer than the 75 µm (No. 200) sieve, a specimen is washed in accordance with ASTM C 117. This may be done on the sieve analysis sample before sieving (with the results included in the sieve analysis) or it can be done on a separate sample.

Grading charts are often used to show the results of a sieve analysis graphically. The percent passing is usually plotted on the vertical axis, while the sieve sizes are plotted on the horizontal axis. Upper and lower limits specified for the allowable percentage of material passing each sieve may also be included on the grading chart. Figure 2 shows a typical grading chart for coarse and fine aggregates having grading calculated in the following two examples. To evaluate consistency of the grading the individual size fractions of a coarse aggregate, fine aggregate (or the calculated proposed combined aggregate grading in concrete) is sometimes plotted separately to identify any gaps or excess amounts in particular sizes.

Example 1: *Calculations for sieve analysis of fine aggregate*

A sample of fine aggregate with a mass of 510.5 g is passed through the sieves shown in the following and the masses retained on each sieve are as shown.

Sieve size	Mass retained, g, individual on each sieve	Individual % retained	Total % retained cumulative	Total % passing
3/8	0.0	0.0	0	100
4.75 mm (No. 4)	9.2	2	2	98
2.36 mm (No. 8)	67.6	13	15	85
1.18 mm (No. 16)	101.2	20	35	65
600 µm (No. 30)	102.2	20	55	45
300 µm (No. 50)	120.5	24	79	21
150 µm (No. 100)	93.1	18	97	3
75 µm (No. 200)	10.2	2	99	1
Pan	4.5	1	100	0
Total	508.5	100	—	—

Note that the total of masses retained may differ slightly from the original sample mass due to loss or gain in the sieving process or due to round-off error. Because the mass of material on each sieve is determined to within 0.1% of the total sample mass, the maximum difference should not exceed 0.1% times the number of mass determinations. In this example, seven mass determinations were made, so the difference should not exceed 0.7%. The total of masses retained differs from the mass of the original sample by 2 g, or only 0.4%. If the difference had been too great, a check would have been made for possible errors in mass determination, calculation, accidental loss due to spillage, or material stuck in the sieve openings. Normally, the sieve analysis calculations are done to the nearest 0.1% and then reported to the nearest 1%, except for the percent passing the No. 200 sieve, which is reported to the nearest 0.1%

The total mass of the material after sieving should check closely with the original mass of the sample placed on the sieves. If the amounts differ by more than 0.3%, based on the original dry sample mass, the results should not be used for acceptance purposes.

Individual percent retained is the percentage of material contained between successive sieves, recorded to the nearest whole percent. It is calculated by dividing the mass retained on each sieve (and passing the sieve above) by the sum of the masses retained on each sieve and the pan and multiplying by 100.

The total percent passing is calculated by subtracting the total (cumulative) percent retained from 100.

Example 2: *Calculations for sieve analysis of coarse aggregate*

A sample of coarse aggregate with a mass of 8145 g is passed through the sieves and the masses retained on each sieve are as shown.

Sieve size	Mass retained, g	Individual % retained	Total % retained	Total % passing
25.0 mm (1 in.)	0	0	0	100
19.0 mm (3/4 in.)	405	5	5	95
12.5 mm (1/2 in.)	2850	35	40	60
9.5 mm (3/8 in.)	2435	30	70	30
4.75 mm (No. 4)	2030	25	95	5
2.36 mm (No. 8)	375	5	100	0
Pan	35	0	100	0
Total	8130	100	—	—

Note again that the total of masses retained differs from the original sample mass. Six mass determinations were made so the difference should not exceed 0.6% of the total sample mass. The total of masses retained differs from the original sample mass by 15 g or only 0.2%. See Example 1 for steps to be taken if the difference had been too great. All other calculations are carried out as in Example 1.

If the test sample was first tested by ASTM C 117, include the mass of material finer than the 75 µm (No. 200) size that was obtained by washing in the sieve analysis calculation. Use the total dry sample mass before washing as the basis for calculating all the percentages and include the mass of the passing No. 200 in the calculation.

3.1.2 *Fineness modulus*—Using the sieve analysis results, a numerical index called the fineness modulus (FM) is often computed. The FM is the sum of the total percentages coarser than each of a specified series of sieves, divided by 100. The specified sieves are 75.0, 37.5, 19.0, and 9.5 mm (3, 1.5, 3/4, and 3/8 in.) and 4.75 mm, 2.36 mm, 1.18 mm, 600 µm, 300 µm, and 150 µm (No. 4, 8, 16, 30, 50, and 100). Note that the lower limit of the specified series of sieves is the 150 µm (No. 100) sieve and that the actual size of the openings in each larger sieve is twice that of the sieve below. The coarser the aggregate, the higher the FM. For fine aggregate used in concrete, the FM generally ranges from 2.3 to 3.1 as called for in ASTM C 33, but in some cases, fine sands are used with an FM less than 2.0 (for example, some Florida deposits) and in other cases, a coarser fine aggregate with an FM higher that 3.1 (for example, some western coarse sands or manufactured fine aggregate that is used in concrete with a finer natural sand).

Example 3: *Calculation of fineness modulus for fine aggregate*

Given the following sieve analysis, determine the FM.

Sieve size	Total % retained
3/8	0
4.75 mm (No. 4)	2
2.36 mm (No. 8)	15
1.18 mm (No. 16)	35
600 µm (No. 30)	55
300 µm (No. 50)	79
150 µm (No. 100)	97
Sum	283
Fineness modulus = 283/100 = 2.83	

Note that all of the FM sieves below the maximum size (that has nothing retained, 3/8 in. in this case) must be included, and none of the non-FM sieves can be included. For example, if a No. 200 or a 1/2 in. sieve were included in the sieve analysis, the cumulative percent retained on those sieves would not be included in the FM calculation because they are not in the FM series.

Although the FM is most commonly computed for fine aggregates, the FM of coarse aggregate is needed for some proportioning methods. It is calculated in the same manner, while taking care to exclude sieves that are not specified in the definition (for example, 25.0 and 12.5 mm [l and 1/2 in.] sieves) and to include all of the specified finer sieves.

Example 4: *Calculation of fineness modulus for coarse aggregate*

Given the following sieve analysis, determine the FM.

Sieve size	Total % retained
25.0 mm (1 in.)	0
19.0 mm (3/4 in.)	5
12.5 mm (1/2 in.)	40
9.5 mm (3/8 in.)	70
4.75 mm (No. 4)	95
2.36 mm (No. 8)	100

Even though the 25 and 12.5 mm (l and 1/2 in.) sieves were used in the sieve analysis, they are not included in the calculation. Because the total percent retained on the 2.36 mm (No. 8) sieve is 100%; 100% will also be retained on the smaller sieves specified in the FM definition. Thus, the calculation is as follows.

Sieve size	Total % retained
19.0 mm (3/4 in.)	5
9.5 mm (3/8 in.)	70
4.75 mm (No. 4)	95
2.36 mm (No. 8)	100
1.18 mm (No. 16)	100
600 µm (No. 30)	100
300 µm (No. 50)	100
150 µm (No. 100)	100
Sum	670
Fineness modulus = 670/100 = 6.70	

Example 5: *Calculation of grading when two or more aggregates are combined*

Suppose that three aggregates are combined in the mass percentages indicated. For the given individual aggregate grading, determine the grading of the combined aggregate.

Sieve size	Percent passing		
	Aggregate 1	Aggregate 2	Aggregate 3
50 mm (2 in.)	100	100	100
37.5 mm (1-1/2 in.)	100	100	95
25.0 mm (1 in.)	100	100	51
19.0 mm (3/4 in.)	100	100	25
12.5 mm (1/2 in.)	100	99	8
9.5 mm (3/8 in.)	100	89	2
4.75 mm (No. 4)	99	24	0
2.36 mm (No. 8)	85	3	—
1.18 mm (No. 16)	65	0	—
600 µm (No. 30)	38	—	—
300 µm (No. 50)	15	—	—
150 µm (No. 100)	4	—	—
Sieve size	Percent passing		
	Aggregate 1	Aggregate 2	Aggregate 3
75 µm (No. 200)	1	—	—
Percentage by mass	35	25	40

The combined grading is shown in the table that follows. The percent passing is calculated for each of the sieve sizes as follows. Example: Calculate the percent passing the 9.5 mm (3/8 in.) sieve of the combined blended aggregates. One-hundred percent of Aggregate 1 passes the 9.5 mm (3/8 in.) sieve, but only 35% of this aggregate is used in the mixture. Similarly, only 25 and 40%, respectively, of Aggregate 2 and 3 are used. Therefore,

	% of combined	Individual % passing 9.5 mm (3/8 in.)	Combined % passing 9.5 mm (3/8 in.)
Aggregate 1	35	100	35% = (35% × 100%)
Aggregate 2	25	89	22% = (25% × 89%)
Aggregate 3	40	2	1% = (40% × 2%)

Sieve size	Aggre-gate 1,%	Aggre-gate 2, %	Aggre-gate 3, %	% passing combined	% retained = 100% – % passing	Individual % retained combined aggregate
50 mm (2 in.)	35	25	40	100	0	0
37.5 mm (1-1/2 in.)	35	25	38	98	2	2
25.0 mm (1 in.)	35	25	20	80	20	18
19.0 mm (3/4 in.)	35	25	10	70	30	10
12.5 mm (1/2 in.)	35	25	3	63	27	7
9.5 mm (3/8 in.)	35	22	1	58	42	12
4.75 mm (No. 4)	35	6	0	41	59	17
2.36 mm (No. 8)	30	1	—	31	69	10
1.18 mm (No. 16)	23	0	—	23	77	8
600 µm (No. 30)	13	—	—	13	87	9
300 µm (No. 50)	5	—	—	5	95	8
150 µm (No. 100)	1	—	—	1	99	4
75 µm (No. 200)	0	—	—	0	100	1
				Sum:	560	

The FM of the combined aggregate can be determined by adding the percentage retained on the specified series of sieves. In this case, the total percentage retained on the 50.0 mm (2 in.), 25.0 mm (1 in.), 12.5 mm (1/2 in.), and 75 µm (No. 200) sieves should not be included in the calculation. For this reason, they are shown struck out in the previous table. Therefore

Fineness modulus = 560/100 = 5.60

The individual percentage of material between successive sieves is sometimes of interest. This can be determined from the grading of the combined aggregate as follows.

% passing 25 mm (1 in.) sieve	80%
% passing 19.0 mm (3/4 in.) sieve	70%
% of material between 25.0 and 19 mm (1 and 3/4 in.) sieves	10% (80% to 70%)

3.1.3 *Maximum size and nominal maximum size (ASTM definitions)*—In specifications for aggregates, the smallest sieve opening through which the entire amount of aggregate is required to pass is called the maximum size. The smallest sieve opening through which the entire amount of aggregate is permitted to pass is called the nominal maximum size.

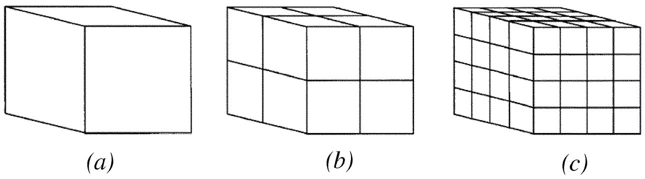

Fig. 3—Effect of particle size on aggregate surface area: (a) one 25.0 mm (1 in.) cube of aggregate (surface area = 6 x 25.0 x 25.0 = 3750 mm² [6 in.²]); (b) eight 12.5 mm (1/2 in.) cubes of aggregate (surface area = 6 x 12.5 x 12.5 x 8 = 7500 mm² [12 in.²]); and (c) sixty-four 6.25 mm (1/4 in.) cubes of aggregate (surface area = 6 x 6.25 x 6.25 x 64 = 15,000 mm² [24 in.²]).

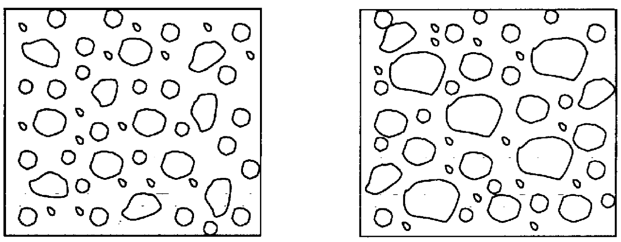

Fig. 4—As maximum size of well-graded aggregate increases, void content decreases.

Aggregate meeting the specification limits shown in the following would have a maximum size of 37.5 mm (1-1/2 in.) and a nominal maximum size of 25.0 mm (1 in.).

Specification limits

Sieve size	Percent passing
37.5 mm (1-1/2 in.)	100
25.0 mm (1 in.)	95 to 100
12.5 mm (1/2 in.)	25 to 60
4.75 mm (No. 4)	0 to 10
2.36 mm (No. 8)	0 to 5

3.1.4 *Significance of aggregate grading*—There are several reasons for specifying both grading limits and maximum aggregate size. Aggregates having a smooth grading curve and neither a deficiency nor excess of any one particle size generally produce mixtures with fewer voids between particles. Because cement costs more than aggregate and the cement paste requirement for concrete increases with increasing void content of the combined aggregates, it is desirable to keep the void content as low as possible. If there is not enough fine aggregate to fill the voids between coarse aggregate particles, the space must be filled with cement paste. Such under-sanded mixtures also tend to be harsh and difficult to finish. On the other hand, aggregate combinations with excessive amounts of fine aggregate or excessively fine sands may produce uneconomical concretes because of the larger surface area of finer particles, which requires additional cement.

To understand how surface area increases with increasing aggregate fineness, visualize a 25 mm (1 in.) cube of aggregate. As shown in Fig. 3, this cube has a surface area of 3750 mm² (6 in.²) and a volume of 15,625 mm³ (1 in.³). If it is cut into eight 12.5 mm (0.5 in.) cubes, the volume does not change, but the surface area increases to 7500 mm² (12 in.²). If a large coarse aggregate particle is replaced by an equal mass of aggregate particles whose diameter is one-half that of the original particle, the resulting surface area is twice as great as the original. If those particles were further reduced in size to fine sand, the same volume of 15,625 mm³ (1 in.³) of particles would have a surface area perhaps 100 times greater than that of the original cube.

When the surface area increases, more cement paste is needed to coat the additional surface; otherwise, the concrete would be too stiff. One might visualize the problem of excessive fineness of the aggregate as being similar to the problem faced by a painter who finds that he has forgotten to paint one side of a house and has only a liter of paint left. He has three choices: 1) he can put the paint on in a thinner coat; 2) he can extend the paint by adding cheap diluents; or 3) he can buy more paint. Each of these options has at least one disadvantage. It will take more effort to paint the side with a thinner layer; the cheap diluents will reduce the quality of the paint; and buying more paint will increase the cost. Similarly, when the aggregate surface area increases, if the cement paste content is left constant, the thinner layers of paste surrounding the aggregate particles result in a stiffer concrete that is harder to place and compact. If the paste is made more fluid by adding water, the concrete strength and durability will suffer, while if more cement and water are added, the cost of the concrete increases. Consequently, it is best to avoid adding too much fine aggregate to a concrete mixture, and to avoid using extremely fine sand unless an intermediate aggregate is used in the batch proportions to fill in some of the missing sizes.

The maximum size of coarse aggregate used in concrete also affects surface area and economy. Usually, as the maximum size of well-graded coarse aggregate increases, the amount of paste required to produce concrete of a given slump or consistency decreases. To see why this is true, refer to Fig. 4. Shown on the left is a container filled with well-graded aggregate with a maximum size of 12.5 mm (1/2 in.). If some of this material is replaced with 19.0 and 25.0 mm (3/4 and 1 in.) particles, the surface area and the void content decrease, because a number of smaller particles and the voids between them are replaced by a single larger particle. If too many larger particles were added, however, there would not be enough fines to fill the voids between them and voids would increase again due to the poor grading.

The maximum nominal size of aggregate that can be used is determined by the size and shape of the concrete member and by the clear spacing between reinforcing bars. In general, nominal maximum size should not be more than one-fifth of the narrowest dimension between sides of forms, one-third the depth of slabs, or three-fourths of the minimum clear spacing between reinforcing bars. Use of the largest possible maximum aggregate size consistent with placing requirements is sometimes recommended to minimize the amount of cement required and to minimize drying shrinkage of concrete.

Aggregates of different maximum sizes, however, may give different concrete strengths for the same water-cementitious material ratio (*w/cm*). In many instances, at the same *w/cm*, concrete with smaller maximum-size aggregate has higher compressive strength. This is especially true in strength ranges in excess of 35 MPa (5100 psi). An aggregate having a maximum size of 19.0 mm (3/4 in.) or smaller may be the most efficient in that its use will require the least amount of cement to produce the required strength.

One of the most important characteristics of the fine aggregate grading is the amount of material passing the 300 and 150 μm (No. 50 and 100) sieves. Inadequate amounts of materials in these size ranges can cause excessive bleeding, difficulties in pumping concrete, and difficulties in obtaining smooth troweled surfaces. Most specifications allow 10 to 30% to pass the 300 μm (No. 50) sieve, and 2 to 10% to pass the 150 μm (No. 100) sieve. ASTM C 33 permits the lower limits for percent passing the 300 and 150 μm (No. 50 and 100) sieves to be reduced to 5 and 0, respectively. A precautionary note in ASTM C 33 states that to alleviate potential problems with decreased fines, one can add entrained air, additional cement, or a supplemental cementitious material to supply the deficient fines.

The lower limits given previously may be adequate for easy placing conditions or for mechanically finished concrete. For hand-finished concrete floors or where a smooth texture is needed, however, fine aggregate with at least 15% passing the 300 μm (No. 50) sieve and 3% passing the 150 μm (No. 100) sieve is sometimes recommended. When concrete is to be pumped through lines less than 150 mm (6 in.) in diameter, 15 to 30% should pass the 300 μm (No. 50) sieve, and 5 to 10% should pass the 150 μm (No. 100) sieve. Remember, however, that with a fixed *w/cm*, use of greater-than-previously-stated amounts of these finer fractions increases the surface area and therefore increases the amount of paste needed to maintain a given workability for the concrete. This is particularly true for high-strength concrete with a high cement content, where a coarser fine aggregate with minimal material passing a No. 200 material may be preferred.

3.1.5 *Permissible variations in grading*—Many specifications permit a relatively wide range of grading for both fine and coarse aggregates. ASTM C 33, for example, states that fine aggregate failing to meet the sieve analysis requirements may be accepted if it is demonstrated that concrete made with the fine aggregate under consideration will have relevant properties at least equal to those of similar concrete containing a fine aggregate that conforms to the specification requirements and that is selected from a source having an acceptable performance record in similar concrete construction. Once a specific grading is selected, close control should be exercised to minimize variation. If wide variations in coarse aggregate grading occur on a given project, it may be necessary to adjust mixture proportions to produce workable concrete.

Somewhat smaller variations in fine aggregate grading can affect the concrete workability due to the higher surface area. For this reason, ASTM C 33 states that, for continuing shipments from a given source, the fineness modulus of fine aggregate should not vary by more than 0.20 from the value that is typical of the source (base fineness modulus). If the base fineness modulus differs from that used in selecting proportions of the concrete, suitable adjustments must be made in the proportions of fine and coarse aggregate. As the fineness modulus of the fine aggregate decreases (aggregate becomes finer), a lower percentage of sand in the total aggregate will be required or the amount of coarse aggregate that may be used increases. It is often more economical to maintain uniformity in producing and handling aggregates than to adjust proportions for variations in grading.

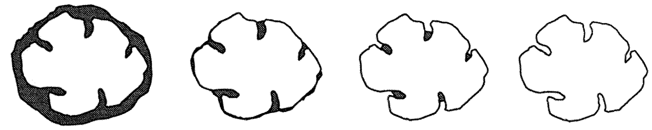

Fig. 5—Moisture condition of aggregates.

3.2—Specific gravity (relative density)

3.2.1 *Definition*—The specific gravity of an aggregate is the mass of the aggregate in air divided by the mass of an equal volume of water. An aggregate with a specific gravity of 2.50 would thus be two and one-half times as heavy as water.

Each aggregate particle is made up of solid matter and voids that may or may not contain water. Because the aggregate mass varies with its moisture content, specific gravity is determined at a fixed moisture content. Four moisture conditions are defined for aggregates depending on the amount of water held in the pores or on the surface of the particles. These conditions are shown in Fig. 5 and described as follows:

1. Damp or wet—Aggregate in which the pores connected to the surface are filled with water and with free water also on the surface.
2. Saturated surface-dry—Aggregate in which the pores connected to the surface are filled with water but with no free water on the surface.
3. Air-dry—Aggregate that has a dry surface but contains some water in the pores.
4. Oven-dry—Aggregate that contains no water in the pores or on the surface.

The volume of the aggregate particle is usually assumed to be the volume of solid matter and internal pores. Two different values of specific gravity may be calculated depending on whether the mass used is an oven-dry or a saturated surface-dry mass. Bulk specific gravity is the oven-dry mass divided by the mass of a volume of water equal to the SSD aggregate volume; while SSD bulk specific gravity is the saturated surface-dry mass divided by the mass of a volume of water equal to the SSD aggregate volume. Most normalweight aggregates have a bulk specific gravity SSD between 2.4 and 2.9.

3.2.2 *Determination of specific gravity*—Test methods for finding specific gravity of aggregates are described in ASTM C 127, "Specific Gravity and Absorption of Coarse Aggregate," and ASTM C 128, "Specific Gravity and Absorption of Fine Aggregate." Coarse aggregate is thoroughly washed, dried to

*Where the specific gravity values are to be used in proportioning concrete mixtures in which the aggregates will be in their naturally moist condition, the requirement for initial drying to constant mass may be eliminated, and, if the surfaces of the particles in the sample have been kept continuously wet until test, the 24-hour soaking may also be eliminated. Values for specific gravity in the saturated surface-dry condition may be significantly higher for aggregate not oven-dried before soaking and the variation in procedure should be noted in reporting the results.

constant mass at 100 to 110 °C (212 to 230 °F), cooled in air, and immersed in water for 24 hours.* It is then removed from the water and dried to a saturated surface-dry state with a large absorbent cloth. Care is taken to avoid evaporation of water from the aggregate pores during this operation.

After the mass of the sample in air is determined, the coarse aggregate is placed in a wire basket suspended in water for determination of its apparent mass in water. The apparent mass of the sample in water is less than that in air, and the loss in mass is equal to the mass of the water displaced. Therefore, the loss in mass is the mass of a volume of water equal to the aggregate volume. After the mass in water is determined, the sample is oven-dried and its oven-dry mass is determined. The bulk specific gravity and bulk specific gravity SSD are calculated as follows.

$$\text{Bulk specific gravity} = \frac{A}{B - C}$$

$$\text{Bulk specific gravity SSD} = \frac{B}{B - C}$$

where A = the mass of oven-dry sample in air; B = the mass of saturated surface-dry sample in air; and C = the apparent mass of saturated sample immersed in water.

Example 6: *Specific gravity calculation for coarse aggregate*

Oven-dry mass in air	=	3168.5 g
Saturated surface-dry mass in air	=	3190.0 g
Saturated mass in water	=	1972.0 g

$$\text{Bulk specific gravity} = \frac{3168.5\text{ g}}{3190.0\text{ g} - 1972.0\text{ g}} = 2.60$$

$$\text{Bulk specific gravity SSD} = \frac{3190.0\text{ g}}{3190.0\text{ g} - 1972.0\text{ g}} = 2.62$$

Fine aggregate is dried to a constant mass at 100 to 110 °C (212 to 230 °F), cooled in air, and either moistened to at least 6% total moisture and sealed for 24 hours or immersed in water for 24 hours. Immersion has the danger of allowing loss of fines and requires more drying time. Excess water is drained off and the sample is spread on a flat surface exposed to a gentle current of warm air. The sample is stirred frequently until it approaches a free-flowing condition, after which a portion is placed in a mold and tamped. If surface moisture is still present, the fine aggregate will retain its molded shape after the mold is lifted. Drying is continued with testing at frequent intervals until the tamped fine aggregate slumps slightly upon removal of the mold, indicating that it has reached a saturated surface-dry condition. Next, approximately 500 g of the surface-dried material is placed in a glass flask, and water is added to fill it to its calibrated capacity or mark. The total mass of the flask, specimen, and water is determined. The fine aggregate is then carefully washed from the flask into a pan, oven-dried, and its mass determined. Finally, the mass of the jar filled with water (and no aggregate) to its calibrated capacity is determined. The specific gravity values are then calculated as follows.

$$\text{Bulk specific gravity} = \frac{A}{S + B - C}$$

$$\text{Bulk specific gravity SSD} = \frac{S}{S + B - C}$$

where A = the mass of oven-dry sample in air; S = the mass of saturated surface-dry sample in air; B = the mass of flask filled with water; and C = the mass of flask with specimen and water to the calibration or filling mark.

Example 7: *Calculate specific gravity for fine aggregate*

Oven-dry mass in air	=	490.7 g
Saturated surface-dry mass in air	=	501.4 g
Mass of flask with specimen and water to fill mark	=	953.5 g
Mass of flask with water to fill mark	=	647.2 g

$$\text{Bulk specific gravity} = \frac{490.7\text{ g}}{501.4\text{ g} + 647.2\text{ g} - 953.5\text{ g}} = 2.51$$

$$\text{Bulk specific gravity SSD} = \frac{501.4\text{ g}}{501.4\text{ g} + 647.2\text{ g} - 953.5\text{ g}} = 2.57$$

3.2.3 *Significance of specific gravity*—The specific gravity of an aggregate is used in mixture proportioning calculations to find the absolute volume that a given mass of material will occupy in the mixture. Absolute volume of an aggregate refers to the space occupied by the aggregate particles alone; that is, the volume of solid matter and internal aggregate pores, excluding the voids between particles.

In a given concrete mixture, substituting one aggregate with another of a different specific gravity will cause the volume of concrete (yield) to change for the same batch mass. Because concrete is often sold by volume, this change means either that the purchaser is receiving less concrete than ordered or the producer is supplying more concrete than purchased. Changes in the aggregate specific gravity also cause the concrete density to change. This is undesirable if a minimum density is specified, for example, in heavyweight concrete for nuclear-radiation shielding.

While the specific gravity of an aggregate is not a measure of aggregate quality, a variation in the specific gravity may indicate a change in the aggregate characteristics.

3.2.4 *Absolute volume calculations*—To calculate the absolute volume an aggregate occupies in concrete, the mass of aggregate is divided by the absolute density (previously termed absolute or solid unit weight), which is the specific gravity multiplied by the density of water. If the mass is in kg, the specific gravity is multiplied by the density of water—1000 kg/m^3 (62.4 lb/ft^3 if the mass is in lb).

Example 8: *Calculation of absolute volume of an aggregate*

A sample of oven-dry aggregate has a mass of 47.7 kg (105.0 lb). The bulk specific gravity is 2.60. Calculate the absolute volume of the aggregate.

In SI units:

$$\text{Absolute volume} = \frac{47.7}{2.60 \times 1000} = \frac{47.7}{2600} = 0.018 \text{ m}^3$$

In in.-lb units:

$$\text{Absolute volume} = \frac{105.0}{2.60 \times 62.4} = \frac{105.0}{162.4} = 0.647 \text{ ft}^3$$

In a batch of concrete, the sum of the absolute volumes of cementitious materials, admixtures, aggregate, and water, plus the volume of air, gives the volume of concrete produced per batch.

Example 9: *Calculation of volume of a batch of concrete*

The following masses of materials are used to produce a batch of concrete. Calculate the volume of the concrete if the air content is 3%. (Air content is the volume of air expressed as a percentage of the concrete volume.)

In SI units:

Material	Mass, kg	Specific gravity
Cement	279	3.15
Water	166	1.00
SSD fine aggregate	780	2.60 (bulk SSD)
SSD coarse aggregate	1091	2.63 (bulk SSD)

It is convenient to calculate absolute volumes in a tabular manner, as follows.

Material	Mass, kg	Specific gravity	Absolute density, kg/m^3, = *SpG* × density of water	Absolute volume, m^3, = Mass/*SpG*/1000.kg/m^3
Cement	279	3.15	3150	0.089
Water	166	1.00	1000	0.166
SSD fine aggregate	780	2.60	2600	0.300
SSD coarse aggregate	1091	2.63	2630	0.415
		Total absolute volume = 0.970 m^3		

The volume of the concrete V_c is the summation of the absolute volume and the volume of the air V_a.

$$V_c = 0.970 + V_a$$

By definition, the volume of air content $V_a = 0.03V_c$, so $V_c = 0.970 + 0.03V_c$. Therefore $V_c = 0.970 \text{ m}^3 + 0.030 \text{ m}^3 = 1.000 \text{ m}^3$.

In in.-lb units:

Material	Mass, lb	Specific gravity
Cement	470	3.15
Water	280	1.00
SSD fine aggregate	1280	2.60 (bulk SSD)
SSD coarse aggregate	1760	2.63 (bulk SSD)

It is convenient to calculate absolute volumes in a tabular manner, as follows:

Material	Mass, lb	Specific gravity	Absolute density, lb/ft^3, = *SpG* × density of water	Absolute volume, ft^3, = Mass/*SpG*/1000.kg/ m^3
Cement	470	3.15	196.6	2.39
Water	280	1.00	62.4	4.49
SSD fine aggregate	1315	2.60	162.2	8.11
SSD coarse aggregate	1838	2.63	164.1	11.20
		Total absolute volume = 26.19 ft^3		

The volume of the concrete V_c is the summation of the absolute volume and the volume of the air V_a.

$$V_c = 26.19 + V_a$$

By definition of air content $V_a = 0.03V_c$, so $V_c = 26.19 \text{ ft}^3 + 0.03V_c$. Therefore, $V_c = 26.19 \text{ ft}^3 + 0.81 \text{ ft}^3 = 27.00 \text{ ft}^3$.

3.3—Absorption and surface moisture

3.3.1 *Mixing water and water-cementitious material ratio*—The various moisture states in which an aggregate may exist have been described previously. Two of these—oven-dry and saturated surface-dry—are used as the basis for calculations of specific gravity. Aggregates stockpiled on the job are seldom in either of these states. They usually carry some free or surface moisture that becomes part of the mixing water. Freshly washed coarse aggregates contain free water, but because they dry quickly, they are sometimes in an air-dry state when used, and they absorb some of the mixing water.

At this point, it is necessary to define the terms "mixing water" and "*w*/*cm*." The mixing water in a batch of concrete is all the water present in the concrete, with the exception of absorbed water within aggregate particles. Mixing water is the sum of the masses of free or surface moisture on the fine and coarse aggregate and the mass of water added separately, such as through a water meter or weigh batcher at the plant or through a truck mixer water system or added to the mixer in some other way. Mixing water is the water in freshly mixed sand-cement grout, mortar, or concrete exclusive of any previously absorbed by the aggregate.

The *w*/*cm* is the mass ratio of mixing water to cementitious material. In the paste, this ratio was frequently expressed in gallons of water per sack of cement (usually portland cement). Today, most specifying agencies express required quantities of cementitious material (portland cement or blended cement plus any separately batched supplementary cementitious materials) and water in kg or lb, and *w*/*cm* as a decimal fraction by mass, kg of water divided by kg of cementitious material, or lb of water divided by lb of cementitious material.

3.3.2 *Absorption and total moisture content*—To calculate the mixing water content of concrete, the absorption of the aggregates and their total moisture contents must be known. Absorption is computed as a percentage by subtracting the oven-dry mass from the saturated surface-dry mass, dividing by the oven-dry mass, and multiplying by 100. In concrete technology, aggregate moisture is expressed as a percent of the dry weight of the aggregate.

$$\text{Absorption, \%,} = \frac{W_{SSD} - W_{OD}}{W_{OD}} \times 100$$

Absorption is a measure of the total pore volume accessible to water, and is usually calculated using the results from a specific gravity determination (ASTM C 127 and C 128).

Example 10: *Calculation of aggregate absorption*

Mass of saturated surface-dry aggregate in air = 501.4 g

Mass of oven-dry aggregate in air = 490.7 g

$$\text{Absorption} = \frac{501.4\text{ g} - 490.7\text{ g}}{490.7\text{ g}} \times 100 = 2.2\%$$

Total moisture content is measured in accordance with ASTM C 566, "Total Moisture Content of Aggregate by Drying," by measuring the mass of a sample of the aggregate representative of the moisture content in the supply being tested, drying the sample, and obtaining the mass again.

$$\text{Total moisture content, \%,} = \frac{W - W_{OD}}{W_{OD}} \times 100$$

where W = the mass of the original sample and W_{OD} = the mass of the dried sample.

3.3.3 *Surface moisture content*—Surface or free moisture content of an aggregate can be determined by subtracting the absorption from the total moisture content.

Example 11: *Calculation of total and surface moisture*

An aggregate sample has an absorption of 1.2% and a mass of 847.3 g when wet. After oven drying, it has a mass of 792.7 g. Calculate the total moisture content and surface moisture content.

$$\text{Total moisture content} = \frac{847.3\text{ g} - 7927\text{ g}}{792.7\text{ g}} \times 100 = 6.9\%$$

$$\text{Surface moisture content} = 6.9\% - 1.2\% = 5.7\%$$

If an aggregate is air-dry (surface is dry but pores are partially filled with water), the total moisture content is less than the absorption and the surface moisture content has a negative value. This means that the aggregate will absorb water when mixed in concrete. This can cause unexpectedly rapid slump loss in the concrete if a significant amount of water is absorbed into the aggregate. For aggregates with unusually high absorption that are batched in an unusually dry state, water equal to the amount absorbed should be added to maintain the intended *w/cm* and consistency. It is difficult to determine precisely how much water will be absorbed while the concrete is still in a plastic state, however, because absorption is calculated after a 24-hour soaking period, although concrete typically sets sooner than this period.

For further information on techniques used in controlling the mixing water and *w/cm* for mixtures containing highly absorptive aggregates, the reader is referred to ACI 211.2-03, "Standard Practice for Selecting Proportions for Structural Lightweight Concrete."

3.3.4 *Computing mixing water and water-cementitious material ratio*—To compute the mixing water and *w/cm* for a batch of concrete, the batch masses of all ingredients and the absorption and total moisture contents of the aggregates used must be known.

Example 12: *Calculation of mixing water and water-cementitious material ratio*

In SI units:

What is the mixing water content and *w/cm* for the following 1 m^3 batch of concrete?

Material	Batch mass, kg
Cement	267
Fly ash	89
Wet sand (absorption 1.0%, total moisture content, 6.1%)	943
Wet gravel (absorption 0.7%, total moisture content 1.3%)	1092
Water (added through batching system)	146

Once the moisture content is determined, it is first necessary to determine the oven-dry masses of the sand and gravel. This can be done knowing the batch masses and total moisture content.

For sand:

Total moisture content =

$$\frac{943\text{ kg} - W_{OD}}{W_{OD}} \times 100 = 6.1\%$$

$$943\text{ kg} - W_{OD} = 0.061 W_{OD}$$

$$W_{OD} = \frac{943\text{ kg}}{1.061\text{ kg}} = 889\text{ kg}$$

For gravel:

Total moisture content =

$$\frac{1092\text{ kg} - W_{OD}}{W_{OD}} \times 100 = 1.3\%$$

$$1092\text{ kg} - W_{OD} = 0.013 W_{OD}$$

$$W_{OD} = \frac{1092\text{ kg}}{1.013\text{ kg}} = 1078\text{ kg}$$

Surface moisture content of sand	= 6.1%	– 1.0%	=	5.1%
Surface moisture content of gravel	= 1.3%	– 0.7%	=	0.6%
Free moisture on sand	= 0.051	× 889 kg	=	45.3 kg
Free moisture on gravel	= 0.006	× 1078 kg	=	6.5 kg
Total free moisture on aggregate	= 45.3 kg+ 6.5 kg		=	51.8 kg
Mixing water	= 146 kg + 51.8 kg		=	197.8 kg or 198 kg
w/cm	= 198 kg / (267 kg + 89 kg)=			0.55

These calculations are summarized in the following table.

Material	Dry mass, kg	Total moisture, %	Absorption, %	Surface moisture = total moisture – absorption, %	Mixing water, kg, = dry mass × surface water	Batch mass, kg, = dry mass × (1 + total moisture, %)
Cement	267	0	—	0	—	267
Fly ash	89	0	—	0	—	89
Sand	889	6.1	1.0%	5.1	45.3	943
Gravel	1078	1.3	0.7%	0.6	6.5	1092
Water	198	—		—	—	198
Total water					51.8	= 198 × 51.8 = 146.2

In in.-lb units:

What is the mixing water content and *w/cm* for the following 1 yd^3 batch of concrete?

Material	Batch mass, lb
Cement	450
Fly ash	150
Wet sand (absorption 1.0%, total moisture content 6.1%)	1590
Wet gravel (absorption 0.7%, total moisture content 1.3%)	1840
Water (added through batching system)	242

Once the moisture content has been determined, it is first necessary to determine the oven-dry masses of the sand and gravel. This can be done knowing the batch masses and total moisture content.

For sand:

Total moisture content =

$$\frac{1590\text{ lb} - W_{OD}}{W_{OD}} \times 100 = 6.1\%$$

$$1590\text{ lb} - W_{OD} = 0.061 W_{OD}$$

$$W_{OD} = \frac{1590\text{ lb}}{1.061\text{ lb}} = 1498\text{ lb}$$

For gravel:

Total moisture content =

$$\frac{1840\text{ lb} - W_{OD}}{W_{OD}} \times 100 = 1.3\%$$

$$1840\text{ lb} - W_{OD} = 0.013 W_{OD}$$

$$W_{OD} = \frac{1840\text{ lb}}{1.013\text{ lb}} = 1816\text{ lb}$$

Surface moisture content of sand	=	6.1% – 1.0%	= 5.1%
Surface moisture content of gravel	=	1.3% – 0.7%	= 0.6%
Free moisture on sand	=	0.051 × 1489 lb	= 76 lb
Free moisture on gravel	=	0.006 × 1816 lb	= 11 lb
Total free moisture on aggregate	=	76 lb + 11 lb	= 87 lb
Mixing water	=	242 lb + 87 lb	= 329 lb
w/cm	=	329 lb/(450 lb + 150 lb)	= 0.55

These calculations are summarized in the following table.

Material	Dry mass, lb	Total moisture, %	Absorption, %	Surface moisture = total moisture – absorption, %	Mixing water, lb, = dry mass × surface water	Batch mass, lb, = dry mass × (1 + total moisture, %)
Cement	450	0	—	0	—	450
Fly ash	150	0	—	0	—	150
Sand	1498	6.1	1.0%	5.1	76	1589
Gravel	1816	1.3	0.7%	0.6	11	1840
Water	329	—		—	—	—
Total water					87	= 329 – 87 = 242

3.3.5 *Adjusting batch masses for surface moisture*—When batch masses are set up for a specific class of concrete, the aggregate masses are usually expressed either as oven-dry or saturated surface-dry masses, and the amount of water indicated is the total mixing water (not including any water absorbed by the aggregate). Because aggregates as batched into the mixtures are very seldom oven-dry or saturated surface-dry, however, adjustments must be made in both the masses of aggregates and the quantity of water to be added.

Because total moisture content of the aggregate and absorption are given on the basis of oven-dry aggregate mass, saturated surface-dry masses must be converted to oven-dry masses before making adjustments. Two examples of that conversion are given in the following. In the first, batch quantities are given in terms of oven-dry aggregate masses and total mixing water. In the second, batch quantities are given in terms of saturated surface-dry masses and total mixing water.

Example 13: *Adjustment of batch masses for aggregate moisture*

In SI units:

Material design	Dry batch mass, kg
Cement	267
Fly ash	89
Oven-dry fine aggregate (absorption 1.0%)	770
Oven-dry coarse aggregate (absorption 2.0%)	1127
Total mixing water	190

At the batch plant, however, the stockpiled fine aggregate has a total moisture content of 6.0%, and the coarse aggregate has a total moisture content of 3.0%. Compute the adjusted batch masses.

The mass of the stockpiled fine aggregate required is calculated by multiplying the total moisture content, expressed as a decimal times the oven-dry mass, and adding this quantity to the oven-dry mass.

$$\text{Mass of fine aggregate} = (0.06 \times 770\text{ kg}) + 770\text{ kg} = 816\text{ kg}$$

To get 770 kg of oven-dry fine aggregate, 816 kg must be taken from the stockpile. The extra 46 kg is water. Coarse aggregate mass is calculated the same way.

$$\text{Mass of coarse aggregate} =$$

$$(0.03 \times 1127\text{ kg}) + 1127\text{ kg} = 1161\text{ kg}$$

To get 1127 kg of oven-dry coarse aggregate, 1161 kg must be taken from the stockpile. The extra 34 kg is water.

Both the fine and coarse aggregate batches will contain some free moisture on the particle surfaces, so the water batches will have to be adjusted separately to keep the total mixing water constant at 190 kg.

Free moisture content = total moisture content – absorption

Fine aggregate	=	6.0% – 1.0%	= 5.0% free moisture
Coarse aggregate	=	3.0% – 2.0%	= 1.0% free moisture
Fine aggregate free moisture content	=	0.05 × 770 kg = 38.5 kg	

Coarse aggregate
free moisture content = 0.01 × 1127 kg = 11.3 kg
Total aggregate
free moisture content = 38.5 kg + 11.3 kg = 49.8 kg
Water to be added
at the mixer = 190 kg – 49.8 kg = 140.2 or 140 kg

The final batch masses to be used are:

Material	Batch mass, kg
Cement	267
Fly ash	89
Wet fine aggregate	816
Wet coarse aggregate	1161
Water	140

The following table summarizes these calculations.

Material	Dry mass, kg	Total moisture, %	Absorp-tion, %	Surface moisture = total moisture – absorption, %	Mixing water, kg, = dry mass × surface moisture	Batch mass, kg, = dry mass × (1 + total moisture, %)
Cement	267	0	—	0	—	267
Fly ash	89	0	—	0	—	89
Sand	770	6.0%	1.0%	5.0%	38.5	816
Gravel	1127	3.0%	2.0%	1.0%	11.3	1161
Water	190	—	—	—	—	—
Total water					49.8	190 – 49.8 = 140.2

In in.-lb units:

The following masses of materials are required for 1 yd^3 of concrete.

Material	Batch mass, lb
Cement	450
Fly ash	150
Oven-dry fine aggregate (absorption 1.0%)	1300
Oven-dry coarse aggregate (absorption 2.0%)	1900
Total mixing water	320

At the batch plant, however, the stockpiled fine aggregate has a total moisture content of 6.0%, and the coarse aggregate has a total moisture content of 3.0%. Compute the adjusted batch masses.

The mass of stockpiled fine aggregate required is calculated by multiplying the total moisture content, expressed as a decimal times the oven-dry mass, and adding this quantity to the oven-dry mass.

$$\text{Mass of fine aggregate} = (0.06 \times 1300) + 1300 = 1378 \text{ lb}$$

To get 1300 lb of oven-dry fine aggregate, 1378 kg must be taken from the stockpile. The extra 78 lb is water.

$$\text{Mass of coarse aggregate} = (0.03 \times 1900) + 1900 = 1957 \text{ lb}$$

To get 1900 lb of oven-dry coarse aggregate, 1957 lb must be taken from the stockpile. The extra 57 lb is water.

Both the fine and coarse aggregate batches will contain some free moisture on the particle surfaces, so the water batches will have to be adjusted separately to keep the total mixing water constant at 320 lb.

Free moisture content	Total moisture content – absorption	Free moisture
Sand	6.0% × 1.0% =	5.0% free moisture
Stone	3.0% – 2.0% =	1.0% free moisture
Free moisture content of sand	0.05 × 1300 lb =	65 lb
Free moisture content of stone	0.01 × 1900 lb =	19 lb
Total aggregate free moisture content	65 lb × 19 lb =	84 lb
Water to be added at mixer	320 lb × 84 lb =	236 lb
Mass of wet fine aggregate	1313 lb (SSD) + 65 lb =	1378 lb
Mass of wet coarse aggregate	1938 lb (SSD) + 19 lb =	1957lb

The final batch masses to be used are:

Material	Batch mass, lb
Cement	450
Fly ash	150
Wet fine aggregate	1378
Wet coarse aggregate	1957
Water	236

The following table summarizes these calculations.

Material	Dry mass, lb	Total moisture, %	Absorp-tion, %	Surface moisture = total moisture – absorption, %	Mixing water, lb, = dry mass × surface water	Batch mass, lb, = dry mass × (1 + total moisture, %)
Cement	450	0	—	0	—	450
Fly ash	150	0		0	—	150
Sand	1300	6.0	1.0	5.0	65	1378
Gravel	1900	3.0	2.0	1.0	19	1957
Water	320	—	—	—	—	—
Total water					84	= 320 – 84 = 236

Example 14: *Adjustment of batch masses for aggregate moisture*

In SI units:

The following masses of material are required for 1 m^3 of concrete. The stockpiled sand has a total moisture content of 6.0% and the stone has a total moisture content of 3.0%. Compute adjusted batch masses.

Material	Batch mass, kg
Cement	267
Fly ash	89
SSD sand (absorption 1.0%)	779
SSD stone (absorption 2.0%)	1150
Total mixing water	190

It is necessary to convert SSD masses to oven-dry masses because moisture contents and absorption are percentages of oven-dry masses.

$$\text{From the definition of absorption, } W_{OD} = \frac{W_{SSD}}{(1 + Abs/100)}$$

$$\text{Oven-dry mass of sand} = \frac{779 \text{ kg}}{1 + 0.01} = 771 \text{ kg}$$

$$\text{Oven-dry mass of stone} = \frac{1150 \text{ kg}}{1 + 0.02} = 1127 \text{ kg}$$

Free moisture content	Total moisture content – absorption	Free moisture
Sand	6.0% – 1.0% =	5.0% free moisture
Stone	3.0% – 2.0% =	1.0% free moisture
Free moisture content of sand	0.05 × 771 kg =	38.5 kg
Free moisture content of rock	0.01 × 1127 kg =	11.3 kg
Total aggregate free moisture content	38.5 kg × 11.3 kg =	49.8 kg
Water to be added at mixer	190 kg × 49.8 kg =	140.2 kg
Mass of wet fine aggregate	779 kg (SSD) + 38.5 kg =	817 kg
Mass of wet coarse aggregate	1150 kg (SSD) + 11.3 kg =	1161 kg

The final batch masses to be used are:

Material	Batch mass, kg
Cement	267
Fly ash	89
Wet sand	817
Wet stone	1161
Water	140

The following table summarizes these calculations.

Material	SSD mass, kg	Absorption, %	Total moisture, %	Dry mass, kg, = SSD mass 1 + absorption	Surface moisture, %	Mixing water, kg, = dry mass × surface moisture	Batch mass, kg, = dry mass × (1 + total moisture)
Cement	267	—	—	267	—	—	267
Fly ash	89	—	—	89	—	—	89
Sand	779	1.0	6.0	771	5.0	38.5	817
Stone	1150	2.0	3.0	1127	1.0	11.3	1161
Water	190	—	—	—	—	—	—
Total water						49.8	190.0 – 49.8 = 140.2

In in.-lb units:

The following masses of material are required for 1 yd^3 of concrete. The stockpiled sand has a total moisture content of 6.0% and the stone has a total moisture content of 3.0%. Compute adjusted batch masses.

Material	Batch mass, lb
Cement	450
Fly ash	150
SSD sand (absorption 1.0%)	1313
SSD stone (absorption 2.0%)	1938
Total mixing water	320

It is necessary to convert SSD masses to oven-dry masses because moisture contents and absorption are percentages of oven-dry masses.

From the definition of absorption in Section 3.3.2

$$W_{OD} = \frac{W_{SSD}}{(1 + Abs/100)}$$

$$\text{Oven-dry mass of sand} = \frac{1313 \text{ lb}}{1 + 0.01} = 1300 \text{ lb}$$

$$\text{Oven-dry mass of stone} = \frac{1938 \text{ lb}}{1 + 0.02} = 1900 \text{ lb}$$

Free moisture content	Total moisture content – absorption	Free moisture
Sand	6.0% – 1.0% =	5.0% free moisture
Stone	3.0% – 2.0% =	1.0% free moisture
Free moisture content of sand	0.05 × 1300 lb =	65 lb
Free moisture content of stone	0.01 × 1900 lb =	19 lb
Total aggregate free moisture content	65 lb × 19 lb =	84 lb
Water to be added at mixer	320 lb × 84 lb =	236 lb
Mass of wet fine aggregate	1313 lb (SSD) + 65 lb =	1378 lb
Mass of wet coarse aggregate	1938 lb (SSD) + 19 lb =	1957lb

The final batch masses to be used are:

Material	Batch mass, lb
Cement	450
Fly ash	150
Wet sand	1378
Wet stone	1957
Water	236

The following table summarizes these calculations.

Material	SSD mass, lb	Absorption, %	Total moisture, %	Dry mass, lb, = SSD mass/1 + absorption	Surface moisture, %	Mixing water, lb, = dry mass × surface moisture	Batch mass, lb, = dry mass × (1 + total moisture)
Cement	450		—	450	—	—	450
Fly ash	150		—	150	—	—	150
Sand	1313	1.0	6.0	1300	5.0	65	1378
Stone	1938	2.0	3.0	1900	1.0	19	1957
Water	320		—	—	—		
Total water						84	320 – 84 = 236

3.3.6 *Alternate definition of surface moisture*—Some specifying agencies require proportions in terms of saturated surface-dry aggregate masses prefer to define surface moisture as a percentage of the saturated surface-dry mass. If surface moisture is given in terms of the saturated surface-dry mass, there is no need to convert saturated surface-dry aggregate masses to oven-dry masses before calculating batch masses.

$$\text{Surface moisture, \%,} = \frac{W_S - W_{SSD}}{W_{SSD}} \times 100$$

where W_S = the original mass of the sample (usually a wet or damp mass) and W_{SSD} = the saturated surface-dry mass of the sample.

A method for determining the surface moisture in fine aggregate is described in ASTM C 70. To use this method, the bulk specific gravity SSD of the aggregate must be known. The mass of a sample to be tested for surface moisture is obtained and the amount of water displaced by the sample is determined using a pycnometer, a volumetric flask, a graduated volumetric flask, or other suitable measuring device. The mass and volume of the wet sample is then used to determine the mass of surface water as a percentage of the saturated surface-dry mass. The formula is as follows.

$$P = \frac{W_d - V_d}{W_s - W_d} \times 100$$

where P = the surface moisture in terms of saturated surface-dry fine aggregate, percent; W_d = the mass of water displaced (determined either by a mass determination or by a volumetric method); V_d = the mass of the sample divided by the bulk specific gravity SSD; and W_S = the mass of the sample.

The development of this formula is explained in the appendix to ASTM C 70.

Example 15: *Calculation of surface moisture content (SSD basis)*

The Chapman flask is a commonly used graduated volumetric flask for calculating the surface moisture content of aggregate. It is filled to the 200 mL mark with water and a sample of previously weighed wet or damp aggregate is added to the flask. After agitating to free any entrapped air bubbles, the combined volume of water and aggregate is read off a scale on the upper neck of the flask.

Mass of wet aggregate	500.0 g
Original flask reading	200 mL
Final flask reading	403 mL
Bulk specific gravity SSD of aggregate	2.60

The bulk specific gravity SSD indicates that 1 g of water is displaced by each 2.6 g of SSD aggregate. The portion of the sample that is surface moisture displaces 1 g of water for each 1 g of surface moisture. Therefore, the wet sample displaces a greater volume of water than would an SSD sample of equal mass, and the increased displacement is used to calculate the surface moisture.

Volume of water displaced = 403 mL – 200 mL = 203 mL

Mass of water displaced = 203 mL ×1 g/mL = 203 g

Surface moisture content, %, =

$$\frac{203\text{ g} - \frac{500}{2.60}\text{ g}}{500\text{ g} - 203\text{ g}} \times 100 = \frac{203\text{ g} - 192\text{ g}}{500\text{ g} - 203\text{ g}} \times 100 = 3.7\%$$

The mass of water displaced can also be determined by using a volumetric flask and a mass determination method similar to that used to obtain the specific gravity of fine aggregate.

Example 16: *Calculate adjustment of batch masses to take aggregate moisture into account given saturated surface-dry masses*

In SI units:

The following masses of material are required for 1 m^3 of concrete.

Material	Mass, kg
Cement	320
SSD sand	765
SSD gravel	902
Total mixing water	193

At the batch plant, the stockpiled fine aggregate has a surface moisture content (SSD basis) of 3.5% and the coarse aggregate surface moisture content (SSD basis) is 0.8%.

Compute the adjusted batch masses.

Fine aggregate free moisture = 0.035 × 765 kg = 26.8 kg
Coarse aggregate free moisture = 0.008 × 902 kg = 7.2 kg
Total aggregate free moisture = 26.8 kg + 7.2 kg = 34 kg
Water to be added at mixer = 193 kg × 34 kg = 159 kg
Wet fine aggregate mass = 765 kg + 26.8 kg = 791.8 kg (792 kg)
Wet coarse aggregate mass = 902 kg + 7.2 kg = 909.2 kg (909 kg)

The final batch masses to be used are:

Material	Mass, kg
Cement	320
Wet fine aggregate	792
Wet coarse aggregate	909
Water	159

The following table summarizes these calculations.

Material	SSD mass, kg	Surface moisture SSD basis, %	Mixing water, kg, = SSD mass × surface moisture	Wet batch mass, kg, = SSD mass + mixing water
Cement	320	—	—	320
Fine aggregate	765	3.5	26.8	792
Coarse aggregate	902	0.8	7.2	909
Water	193	—	159.0	159
		Total:	193.0	

In in.-lb units:

The following masses of material are required for 1 yd^3 of concrete.

Material	Mass, lb
Cement	540
SSD sand	290
SSD gravel	1520
Total mixing water	325

At the batch plant, the stockpiled fine aggregate has a surface moisture content (SSD basis) of 3.5% and the coarse aggregate surface moisture content (SSD basis) is 0.8%.

Compute the adjusted batch masses.

Fine aggregate free moisture = 0.035 × 1290 lb = 45 lb
Coarse aggregate free moisture = 0.008 × 1520 lb = 12 lb
Total aggregate free moisture = 45 lb + 12 lb = 57 lb
Water to be added at mixer = 325 lb × 57 lb = 268 lb
Wet fine aggregate mass = 1290 lb + 45 lb = 1335 lb
Wet coarse aggregate mass = 1520 lb + 12 lb = 1532 lb

The final batch masses to be used are:

Material	Mass, lb
Cement	540
Wet fine aggregate	1335
Wet coarse aggregate	1532
Water	268

The following table summarizes these calculations.

Material	SSD mass, lb	Surface moisture SSD basis, %	Mixing water, lb = SSD mass × surface moisture	Wet batch mass, lb = SSD mass + mixing water
Cement	540	—	—	540
Fine aggregate	1290	3.5	45	1335
Coarse aggregate	1520	0.8	12	1532
Water	325	—	268	268
		Total:	325	

3.4—Bulk density (replaces de-emphasized term "unit weight")

3.4.1 *Definition and test method*—The bulk density (previously "unit weight" or sometimes "dry-rodded unit weight") of an aggregate is the mass of the aggregate divided by the volume of particles and the voids between particles. Methods for determining bulk density are given in ASTM C 29/C 29M. The method most commonly used requires placing three layers of oven-dry aggregate in a container of known volume, rodding each layer 25 times with a tamping rod, leveling off the surface, and determining the mass of the container and its contents. The mass of the container is subtracted to give the mass of the aggregate, and the bulk density is the aggregate mass divided by the volume of the container. For aggregates having a maximum size greater than 37.5 mm (1-1/2 in.), jigging is used for compacting instead of rodding and, if a loose bulk density is desired, the container is simply filled to overflowing with a shovel before leveling it and determining its mass.

Example 17: *Calculation of the bulk density of an aggregate.*

In SI units:

Mass of aggregate and container	=	36.8 kg
Mass of container	=	13.1 kg
Volume of container	=	0.0141 m^3
Bulk density =		
(36.8 – 31.1)/0.0141 = 23.7/0.0141	=	1681 kg/m^3

In in.-lb units:

Mass of aggregate and container	=	81.1 lb
Mass of container	=	28.8 lb
Volume of container	=	0.498 ft^3
Bulk density =		
(81.1 – 28.8)/0.498 = 52.3/0.498	=	105 lb/ft^3

3.4.2 *Factors affecting bulk density*—Bulk density depends on the moisture content of the aggregate. For coarse aggregate, increasing moisture content increases the bulk density; for fine aggregate, however, increasing moisture content beyond the saturated surface-dry condition can decrease the bulk density. This is because thin films of water on the sand particles cause them to stick together so that they are not as easily compacted. The resulting increase in volume decreases the bulk density. This phenomenon, called "bulking," is of little importance if the aggregates for a concrete mixture are batched by mass, but must be taken into account if volumetric batching is used and moisture content varies.

Other properties that affect the bulk density of an aggregate include grading, specific gravity, surface texture, shape, and angularity of particles. Aggregates having neither a deficiency nor an excess of any one size usually have a higher bulk density than those with a preponderance of one particle size. Higher specific gravity of the particles results in higher bulk density for a particular grading, and smooth rounded aggregates generally have a higher bulk density than rough angular particles of the same mineralogical composition and grading. The rodded bulk density of aggregates used for normalweight concrete generally ranges from 1200 to 1760 kg/m^3 (75 to 110 lb/ft^3).

3.5—Particle shape, angularity, and surface texture

3.5.1 *Definition*—Particle shape is defined in terms of "compactness," which is a measure of whether the particle is compact in shape, that is, if it is close to being spherical or cubical as opposed to being flat (disk-like) or elongated (needle-like). Angularity refers to the relative sharpness or angularity of the particle edges and corners. The higher a particle's compactness (the closer it is to a sphere or cube), the lower its surface area per unit weight and therefore the lower its demand for mixing water in concrete and the lower the amount of sand needed in the mixture to provide workability. More angular and less spherical coarse aggregates require higher mixing water and fine aggregate content to provide a given workability.

Surface texture refers to the degree of roughness or irregularity of the aggregate particle surface. Surface texture is usually described qualitatively using terms such as rough, granular, crystalline, smooth, or glassy rather than being described quantitatively. Smooth particles require less mixing water and therefore less cementitious material at a fixed *w/cm* to produce concrete with a given workability, but also have less surface area than rougher particles to bond with the cement paste.

3.5.2 *Test methods*—A number of test methods to determine compactness or surface texture have been evaluated separately and in combination. While no one method has gained universal acceptance, the procedures summarized in the following (or variations thereof) have been used reasonably widely. Three methods have been adopted as ASTM standard procedures: ASTM C 1252, ASTM D 3398, and ASTM D 4791. In ASTM D 4791, the percentage of flat or elongated particles in an aggregate is determined by measuring the length, width, and thickness of each particle in a sample using a special caliper and determining whether the width-to-thickness ratio exceeds 3 (flat particles), or the length-to-width ratio exceeds 3 (elongated particles). Other specifying agencies have also used this procedure, sometimes also determining if the ratio of length to thickness exceeds 5 (flat and elongated particles). This method is feasible only for coarse aggregate sizes. It is tedious, involving the handling of each individual particle in the sample. Also, it provides no measure of the angularity or roundness of the corners and edges, nor of surface texture.

Another test, the flakiness index, was developed in Britain and involves determining what percentage of a closely sized sieve fraction, such as 19 to 12.5 mm (3/4 to 1/2 in.) particles, will pass through a slotted opening that is only 60% of the average size of the size fraction. For example, suppose that the average size of the 19 to 12.5 mm (3/4 to 1/2 in.) fraction is 16 mm (5/8 in.), and 60% of that is 9.5 mm (3/8 in.). A particle in this size fraction is thus considered to be flaky if its least dimension is less than 9.5 mm (3/8 in.). The percentage of flaky particles in each of several size fractions is determined, and low percentages indicate aggregates with a high degree of compactness. This procedure as well is time consuming, because each particle is handled to see if it can be fitted through the appropriate slot; again, only coarse aggregate is considered.

Fine and coarse aggregate characteristics relating to shape, angularity, and surface texture can also be measured in an integrated fashion by measuring the percentage of voids in an aggregate compacted in a standard manner in a container of known volume. ASTM C 1252 provides a method for the determination of percent voids in fine aggregate. The absolute volume of the solid mass of a sample in a container is determined by dividing the mass of the aggregate by the product of its bulk specific gravity and the density of water. The void percentage (percent voids) is the volume of the container minus the volume of the solid mass of the sample, expressed as a percentage of the container volume. The more angular and rough an aggregate, the greater the percentage of voids. In addition, because the grading of the sample affects the percentage of voids, the test must be run either using a standardized grading or measuring the percentage of voids in each size fraction.

ASTM C 1252 includes a procedure for fine aggregate involving the measurement of voids in three separate size fractions, and also a procedure using a fixed grading for both fine and coarse aggregates to obtain companion void percentages related to shape and texture. The mixing water required to produce concrete with a given level of workability can be related to shape and texture, as indirectly measured by voids in the fine aggregate. The flow rate of aggregate through a funnel-like orifice has also been used as a measure of shape and texture, and has been found to be closely related to percent voids.

The particle index (ASTM D 3398) is determined by measuring the percentage of voids of each aggregate size fraction at two levels of compaction, and then extrapolating the straight line through the two data points back to the loose-voids condition with no compactive effort. In essence, this gives a property related to voids at loose compaction without the problems of trying to reproduce a loose-voids condition that is more difficult to standardize. The particle index is determined by the following formula for each size, and a weighted index is then calculated for the overall grading.

$$I = 1.25V_{10} - 0.25V_{50} - 32.0$$

where I = the particle index, V_{10} = the percent voids at 10 drops compaction, and V_{50} = the percent voids at 50 drops compaction.

Another somewhat tedious procedure involving the handling of each particle is to count the particles with more than one (or sometimes more than two) crushed faces. This method is usually applicable only to coarse aggregate, and is subject to a wide variation in results, sometimes due to the opinion of the operator as to what constitutes a face produced by crushing. It has been standardized as ASTM D 5821.

3.5.3 *Significance of particle shape, angularity, and surface texture*—The shape, angularity, and surface texture of the individual particles of sand, crushed stone, gravel, blast furnace slag, or lightweight aggregate making up an aggregate have an important influence on the workability of freshly mixed concrete and the strength of hardened concrete. Fine-aggregate particle shape and texture affect concrete mainly through their influence on the workability of fresh concrete. Other factors being equal, more mixing water is required to obtain a particular level of slump or workability in fresh concrete using fine aggregates that are angular and rough, rather than using fine aggregates that are rounded and smooth. This in turn affects the required *w/cm* for a particular cementitious content, or the required cementitious content for a particular *w/cm*.

The influence of fine aggregate shape and texture on the strength of hardened concrete is almost entirely related to the resulting *w/cm* of the concrete, provided that the fine aggregate has a grading within normally accepted limits and that grading is taken into account in selecting concrete proportions.

Coarse aggregate shape and texture also affect requirements for mixing water and for the *w/cm* in a manner similar to that of fine aggregate. Coarse aggregate particles, however, due to their much smaller ratio of surface area to volume, affect strength through a more complex relationship between the bond between aggregate and cement paste and the concrete *w/cm*. Therefore, the effects of aggregate shape and texture on the strength of hardened concrete should not be over-generalized.

Failure of a concrete strength specimen most often starts as microcracks between the paste or mortar and the surfaces of the largest coarse aggregate particles. This is a bond failure mode. Angular, rough-textured aggregates, for example, have an increased surface area for bond to the cement paste when compared with rounded, smooth particles of similar size.

Considering all of the factors that have an effect on concrete strength, the following appear to be most important:

1. The surface area available for bond to the cement paste. Here, the shape and texture of the largest particles is most important.

2. The surface texture of the largest pieces, which affects the bond strength per unit of surface area. The mineralogy and crystal structure of these largest pieces affects bond strength per unit area as well.

3. The relative rigidity of the aggregate particles compared with the surrounding paste or mortar. The closer the deformation characteristics of the aggregate are to that of the surrounding media, the lower are the stresses developed at particle surfaces.

4. Maximum size of the aggregate. For a given *w/cm*, as the size of the larger particles is increased, the likelihood of bond failure between paste and aggregate increases because stresses at the interface are higher than those for smaller particles.

Factors that give higher intrinsic bond strength are relatively unimportant in fine aggregates because of the large total surface area available for bond and the lower stresses around small particles. Likewise, the larger surfaces of angular sands compared with rounded sands are of no particular benefit to bond strength. This leads to the conclusion that the shape and surface texture of fine aggregate affect the amount of mixing water required for a given workability and that the effects of different fine aggregates on concrete strength can be predicted from a knowledge of their effects on mixing water and *w/cm*.

For coarse aggregate, however, the situation is quite different and the final effects on strength are more difficult to predict due to the importance of bond-strength characteristics in the larger particles. This is the fundamental reason why different maximum sizes of coarse aggregates, different grading, and different sources of coarse aggregate produce different curves of compressive strength versus *w/cm*. For example, in very high-strength concrete mixtures where coarse aggregate bond is critical, angular cubical-shaped coarse aggregates generally give higher strengths than either rounded smooth aggregates or those with a large proportion of flat or elongated pieces; also, smaller maximum size aggregates, such as the 12.5 or 19 mm (1/2 or 3/4 in.) fractions, give higher compressive strengths than do larger sizes, such as the 37.5 and 50 mm (1-1/2 and 2 in.) maximum sizes. Where extremely high strengths are not required, acceptable concrete can be made with many different types of aggregates, with some variation in the *w/cm* required to provide the needed strength.

3.6—Abrasion and impact resistance

3.6.1 *Definition and significance*—The abrasion and impact resistance of an aggregate is its ability to resist being worn away by rubbing and friction or shattering upon impact. It is a general measure of aggregate quality and resistance to degradation due to handling, stockpiling, or mixing.

3.6.2 *Test method*—The most common test method for abrasion and impact resistance of coarse aggregate is the Los Angeles machine method (ASTM C 131 for aggregate between 2.36 and 37.5 mm [No. 8 sieve opening and 1-1/2 in.], and ASTM C 535 for aggregate between 19 and 75 mm [3/4 and 3 in.]). This test method combines the effects of impact and abrasion by tumbling aggregate particles together with steel balls in a slowly revolving steel drum. A specified quantity of aggregate is placed in the steel drum with an abrasive charge of steel balls of a specified diameter. The drum is rotated for 500 or 1000 revolutions, during which a shelf inside the drum tumbles and drops the aggregate and balls. The percentage of the aggregate worn away is determined by sieving the aggregate using the 1.70 mm (No. 12) sieve and mass measurement. Specifications often set an allowable upper limit on the percentage loss of mass. ASTM C 33, "Concrete Aggregates," specifies a maximum mass loss of 50% for gravel, crushed gravel, or crushed stone. Comparisons of results of aggregate abrasion tests with those of abrasion resistance of concrete do not generally show a direct correlation, however. The abrasion resistance of concrete is generally related to its compressive strength.

3.7—Soundness

3.7.1 *Definition and mechanism of deterioration*—Soundness of an aggregate refers to its ability in concrete to withstand aggressive exposure, particularly due to weather. In areas with severe or moderate winters, a major cause of aggregate deterioration in exposed concrete is freezing and thawing. If an aggregate particle absorbs so much water that its pores are nearly completely filled, it may not accommodate the expansion that occurs when water turns to ice. As ice forms, the resulting expansion pushes unfrozen water through the aggregate pores and the resistance to this flow results in pressures that may be high enough to crack the particle. These pressures may crack the aggregate particle, and, in concrete, the surrounding concrete as well. This is known as "D-cracking." The developed pressure depends on the rate of freezing and the particle size above which the particle will fail if completely saturated. This critical size depends on the porosity, pore size, and total pore volume of the aggregate; the permeability or rate of discharge of water flowing through the aggregate; and the tensile strength of the particle.

For fine-grained aggregates with low permeability (such as some cherts), the critical particle size may be in the range of normal aggregate sizes. It is higher for coarse-grained materials or those with pore systems interrupted by numerous pores too large to hold water by capillary action. For these materials, the critical size may be too large to be of consequence, even though absorption may be high. Also, if potentially vulnerable aggregates are dry when used or are used in concrete subjected to periodic drying while in service, they may never become sufficiently saturated to cause failure under freezing-and-thawing cycling.

3.7.2 *Test methods*—Several methods have been used to predict the performance of aggregates under exposure to freezing and thawing. One of these is evaluation of past performance. If aggregates from the same source have previously given satisfactory service when used in concrete, the aggregate may be considered acceptable. Aggregates not having a service record may be considered acceptable if they perform satisfactorily in concrete specimens subjected to freezing-and-thawing tests. In these tests (ASTM C 666), concrete specimens are subjected to alternate cycles of freezing, either in air or water, and thawing in water. Deterioration is measured by the reduction in the frequency of an energy wave passed through the specimens, which is related to the dynamic modulus of elasticity of the specimens.

Some specifications may require that resistance to weathering be demonstrated by the sodium sulfate or magnesium sulfate soundness test (ASTM C 88). This test consists of immersing a sample of the aggregate specimen in a sulfate solution for a prescribed number of cycles, oven-drying the sample, and determining the percentage loss of mass. This test sometimes produces inconsistent results, in that aggregates behaving satisfactorily in the test may produce concrete having low freezing-and-thawing resistance; conversely, aggregates performing poorly may produce concrete with adequate resistance. This may be attributed in part to the fact that the aggregates in the test are not surrounded by cement paste as they would be when used in concrete.

3.7.3 *Pop-outs*—A pop-out is the breaking away of a small portion of a concrete surface due to internal pressure that leaves a shallow, usually conical, depression, as shown in Fig. 6.

Fig. 6—Pop-out due to unsound aggregate particle.

Fig. 7—Cracking caused by abnormal expansion due to alkali-aggregate reaction.

Pop-outs result from freezing and thawing of porous aggregate that is critically saturated or from alkali-silica reaction (refer to the following). Due to the critical size effect mentioned previously, pop-outs caused by freezing can sometimes be minimized by reducing the maximum aggregate size. In other instances, however, it is necessary to remove harmful substances such as chert, opaline shale, coal, or lignite that also cause pop-outs.

3.8—Chemical stability

3.8.1 *Definition and reaction mechanisms*—Aggregates that are chemically stable will neither react chemically with cement in a harmful manner nor be affected chemically by normal external influences. In some areas, reactions can occur between aggregates made up of certain minerals and alkalis present in concrete, from internal or external sources. One such reaction, alkali-silica reaction (ASR), involves certain silica minerals found in some aggregates. The process starts when alkalis (sodium and potassium oxide) from concrete ingredients enter into solution and combine with reactive siliceous minerals to form an alkali-silica gel that has a tendency to absorb water and swell. This swelling may cause abnormal expansion and cracking of concrete in a characteristic random or map pattern (Fig. 7). The most common constituents causing ASR are siliceous minerals such as tripolitic chert, strained quartz, microcrystalline quartz, chalcedony and opal, natural volcanic glass, and andesite or tridymite. These reactive materials can occur in quartzose, chalcedonic or opaline cherts, opaline or siliceous limestone, opaline shale, and acid to intermediate glassy volcanic rocks. Some phyllites, argillites, quartzites, granite gneisses, and quartz gravels are also reactive because of the reactivity of strained or microcrystalline quartz. Refer to ASTM C 294 for a description of aggregate mineralogy. Another kind of harmful reaction is alkali-carbonate reaction (ACR), which normally results from dedolomitization (the conversion of magnesium-rich limestone to calcium-rich limestone) and occurs between alkalis and argillaceous dolomitic limestone with appreciable amounts of clay. These rocks have a characteristic microstructure that can be recognized by an experienced petrographer. ACR is less common than ASR.

3.8.2 *Test methods*—Field service records, when available, generally provide the best information for selection of aggregates based on chemical stability. The service record should consider the severity of the exposure and the characteristics of the cementitious materials used with the aggregate. If an aggregate has no field service record, a petrographic examination (ASTM C 295) is useful. A petrographic examination involves looking at the aggregate particles under a microscope, and includes additional procedures for determining the mineral constituents present. Such an examination by a qualified petrographer is often helpful in identifying potentially reactive aggregates. In addition, several ASTM tests are available for identifying reactive aggregates, as described in the following.

Tests for ASR potential:

ASTM C 227, the mortar bar test, is used to determine the potentially expansive alkali-silica reactivity of cement-aggregate combinations. In this test, the expansion developed in mortar bars during storage under prescribed temperature and moisture conditions is measured. While the mortar bar test can be used for either fine or coarse aggregates, it takes at least 3 to 6 months.

ASTM C 289, known as the quick chemical test, is used for identifying potentially reactive siliceous aggregates. It can be completed in 24 hours. Results are based on the degree of reaction (change in alkalinity and amount of dissolved silica) when a crushed specimen of the aggregate in question is placed in a concentrated alkaline solution of sodium hydroxide at a high temperature.

ASTM C 1260 is a rapid mortar bar test developed to supplement slower test methods. In this test, mortar bars are immersed in a strong alkaline solution (sodium hydroxide) at an elevated temperature. The potential for reactivity is assessed based on the length change of the mortar bars after two weeks of this immersion.

ASTM C 1567 is similar to ASTM C 1260 but test combinations of cementitious materials such as cement, fly ash, and ground granulated blast furnace slag with the aggregates that are being evaluated. The sample preparation and storage conditions are similar to those of ASTM C 1260.

ASTM C 1293, a 1-year concrete prism test, involves making concrete with the test aggregate. The alkali content of the concrete is increased by adding sodium hydroxide to the mixture ingredients. The concrete prisms, typically measuring 75 x 75 x 250 mm (3 x 3 x 10 in.), are placed in containers at a prescribed temperature and humidity, similar to those used in ASTM C 227. Expansion is measured over 1 year, although longer test periods have sometimes been used.

Considerable controversy exists regarding how to assess the potential reactivity of an aggregate based on these test methods. While ASTM C 227 seems to correlate well with field performances for rapidly reacting siliceous aggregates, it can fail to identify slowly reactive aggregates that show distress in the field. ASTM C 289 does not work well with carbonate and siliceous aggregates, and is recommended for use only as a screening test. ASTM C 1260 is a severe test and is also recommended as a screening test. Although it has been shown to identify slowly reacting aggregates that are not identified by ASTM C 227, it also incorrectly identifies aggregates with a good service record. In Canada, ASTM C 1293 is considered to provide the best correlation with field performance. For the best indication of potential for aggregate reactivity, ASR tests should be performed in conjunction with a petrographic examination of the aggregate.

Tests for ACR potential:

ASTM C 586, known as the rock-cylinder test, is used to determine potentially expansive dolomitic aggregates. Length changes are determined for a cylindrical sample of the rock immersed in a sodium hydroxide solution. Expansive tendencies are usually observable after 28 days of immersion. Different expansion criteria at different ages are used by various organizations.

ASTM C 1105 is a concrete prism test for ACR similar to ASTM C 1293 for ASR. The test is typically run for approximately 6 months, but a 1-year exposure is preferred.

Dolomitic aggregates with the potential for causing concrete expansions due to ACR can be identified with relative assurance by an experienced petrographer.

3.8.3 *Corrective measures*—Several options are available for dealing with aggregates found to be potentially reactive with alkalis. Laboratory tests and field performance show that expansion due to ASR can be reduced or eliminated by adding a pozzolan or ground slag as cementitious materials to the concrete mixture in sufficient quantities, using a blended cement, or by using a lithium-based admixture. Some pozzolans, however, are less effective in reducing expansion. It is necessary to test the ability of a given pozzolanic material or ground granulated blast-furnace slag to control ASR, and an accelerated mortar test (ASTM C 441 or ASTM C 1567) is usually used for this purpose. Long-term tests on concrete (such as ASTM C 1293) can also be used. Another way of controlling expansion due to ASR is to use a low-alkali cement. A potentially reactive aggregate should be rejected only after all other available options are exhausted. In very rare instances, the best course of action may be to choose a different aggregate.

Expansions due to ACR, in contrast, cannot be easily controlled by modifying the concrete mixture. Pozzolans and slag are not effective in reducing expansions. Cement with an alkali content less than 0.4% (sodium oxide equivalent) has been recommended in some cases. Potential expansion due to ACR is best controlled by the choice of aggregate. Recommended methods are selective quarrying to eliminate potentially reactive layers in a quarry, blending the aggregate, or reducing the maximum size of the aggregate.

3.9—Harmful substances in aggregates

3.9.1 *Types of harmful substances*—Harmful substances that may be present in aggregates include organic impurities, silt, clay, lignite, and certain lightweight and soft particles. These may occur naturally in the aggregate, or may be introduced when the aggregates are transported in gondola cars, barges, or trucks previously used to haul those contaminating substances. Aggregate can be contaminated by oil during handling.

3.9.2 *Effects of harmful substances*—Organic impurities such as peat, humus, organic loam, and sugar delay setting and hardening of concrete, and sometimes lead to deterioration.

Silt, clay, or other materials passing the 75 μm (No. 200) sieve may be present as dust or may form a coating on aggregate particles. Excessive amounts of this material may unduly increase the water required to produce a given slump for the concrete, or, if the amount of fine material varies from batch to batch, may cause undesirable fluctuations in the slump, air content, and strength. Thin coatings of dust on the coarse particles may weaken the bond between cement paste and coarse aggregate.

Coal, lignite, lightweight cherts, and other lightweight or soft materials such as wood, may affect the durability of concrete if present in excessive amounts. If these impurities occur at or near the concrete surface, they may result in popouts or staining.

3.9.3 *Test methods*—The test for organic impurities in sands for concrete (ASTM C 40) detects the presence of some injurious organic impurities. In this test, sodium hydroxide solution is poured over a sample of the sand in a bottle that is then sealed with a stopper, shaken vigorously, and allowed to stand for 24 hours. The color of the liquid above the sample is then compared with a color standard. If the liquid's color is darker than the standard, the sand is considered to contain injurious organic compounds and it should be tested further before being approved for use in concrete. Because all organic materials resulting in a positive reaction (dark color) are not necessarily harmful, another test (ASTM C 87) is usually conducted to determine the effect of the impurities on strength. Mortar cubes are made using the sand in question and a sample of the same sand, previously washed in sodium hydroxide to remove the organic materials. After 7 days of curing, the cubes are tested in compression. The strength of cubes containing the sand in question is then divided by the strength of cubes containing washed sand, and if this strength ratio is at least 0.95, the sand in question is considered to be acceptable.

The amount of material passing the 75 μm (No. 200) sieve is determined by washing a sample of the aggregate over a 75 μm (No. 200) sieve (ASTM C 117) and determining the resulting loss in mass as a percentage of the original sample weight. ASTM C 33, "Concrete Aggregates," limits the percentage of material finer than a 75 μm (No. 200) sieve to

3% for fine aggregates used in concrete subject to abrasion, and to 5% for fine aggregate used in all other concrete. For manufactured fine aggregates where the minus No. 200 fines can be shown to be free of clay or shale, the limits are increased to 5 and 7%, respectively. Similarly, for coarse aggregate, material passing the 75 µm (No. 200) sieve is limited to 1%, or to 1.5% for crushed aggregates if the dust is essentially free of clay and shale.

The percentage of lightweight particles can be determined by the test for lightweight pieces in aggregate (ASTM C 123). A sample of the aggregate to be tested is placed in a heavy liquid and floating pieces are skimmed off and weighed. The percentage of lightweight pieces is then calculated. Where surface appearance of the concrete is important, the amount of coal or lignite is limited to 0.5% for both fine and coarse aggregates by ASTM C 33, while for all other concretes, the maximum is 1%. Requirements for soft particles are given in Table 3 of the most recent ASTM specifications for concrete aggregates, ASTM C 33.

CHAPTER 4—SAMPLING AGGREGATES

4.1—Variability in aggregates

In the previous section, methods for measuring aggregate properties are discussed. Aggregates vary from unit to unit and within each unit, however, and it is not economically feasible to test all of a unit, whether that unit is an entire stockpile or a smaller batch. Thus, a sampling procedure must be used. That is the subject of this section.

4.2—Sampling

4.2.1 *Definition*—A sample is a small portion of a larger volume or group of materials such as a stockpile, batch, carload, or truckload about which information is wanted. Sampling is the process of obtaining samples. The properties of the sample are considered to represent the properties of the larger unit from which it is taken.

4.2.2 *Significance of variability*—A series of samples can be used to provide information about average properties and the variability of those properties. This is important for many reasons. For example, given two lots of sand, suppose that the FM of each needs to be known. A single sample could be taken from each lot, a sieve analysis conducted, and the FM calculated. Further, suppose that in both cases, the FM is 2.70. Both samples can be said to have the same FM, but what about the lots? Is it reasonable to say that the sand in each lot has a FM of 2.70? Perhaps not. There would be more confidence in a conclusion if the results of sieve analysis from several samples, all from the same lot, were available. The following results might be obtained if five samples were taken from each lot.

Fineness modules of five samples:

Lot A	Lot B
2.70	2.70
2.75	2.95
2.63	2.47
2.68	2.88
2.74	2.50
Average = 2.70	Average = 2.70

The average of each five-sample set is still 2.70, so there would be more confidence in concluding that the sand in each lot has an FM of 2.70. Something else about the lots must be determined, however. Assuming that the correct sampling and testing procedures were used, it is obvious that Lot B is more variable than Lot A. For Lot B, the FM ranges from 2.47 to 2.95, while for Lot A, it ranges only from 2.63 to 2.75. Concrete made with sand from Lot B is likely to be more variable in quality than concrete made with sand from Lot A, because aggregate fineness affects slump if water content is held constant. Thus, the sand from Lot A would be preferable.

Therefore, test results on samples reveal the average properties of an aggregate and may also indicate the variability in these properties. Acceptance or rejection of an aggregate must be made based on results of tests on samples, and reasonable decisions can be made only if samples are taken correctly and in accordance with a sampling plan.

4.2.3 *Sampling plans*—Detailed discussion of how to formulate a sampling plan for aggregates is beyond the scope of this Bulletin. Each plan depends on the sampling situation and on the information to be extracted from the measurements on the sample. For instance, one might be interested in finding only the average gradation, or one might want the average gradation and the variation in gradation within a lot of aggregate. Formulation of an appropriate plan requires understanding of the fundamentals of probability sampling and a knowledge of the product being sampled. Models for probability sampling, significance, and interpretation are given in ASTM E 141, "Recommended Practice for Acceptance of Evidence on the Results of Probability Sampling." Other pertinent references are listed in the Reference section of this Bulletin.

4.2.4 *Sampling methods*—Methods of sampling aggregates are described in ASTM D 75, "Standard Methods of Sampling Aggregates." Samples should preferably be taken from conveyor belts or flowing aggregate streams, but may also be taken from stockpiles. In sampling from a conveyor belt, three approximately equal increments (explained in the following) are selected at random from the unit being sampled and are combined to form a field sample of a size equal to or exceeding the minimum recommended in the following section dealing with sample size. The conveyor belt is stopped while the sample increments are obtained. To obtain the increment, two templates are spaced and inserted so that the material contained between them provides an increment of the required weight. All material between the templates is carefully scooped into a suitable container, including the fines on the belt, which are collected with a brush and dust pan and added to the container.

Three approximately equal increments are also selected at random when sampling from a flowing aggregate stream (bin or belt discharge). Each increment is taken from the entire cross section of the material as it is being discharged. This usually requires the construction of a specially built pan large enough to intercept the entire cross section and hold the required amount of material without overflowing.

Sampling from stockpiles should be used only as a last resort, particularly when the sampling is done for the purpose of determining aggregate properties that may depend on the grading of the sample. When samples must be obtained from a stockpile, it is necessary to design a sampling plan for the specific case under consideration.

4.2.5 *Number and size of field samples*—The required number of field samples depends on the importance and variability of the properties to be measured. Guidance for determining the number of samples required to obtain the desired level of confidence in test results is given in the previously mentioned ASTM E 105, E 122, and E 141. The unit of material represented by a single sample may vary widely, but is usually approximately 45 to 50 tons.

The required size of field samples must be based on the type and number of tests to which the material is to be subjected. Minimum sample size varies with nominal maximum size of the aggregate, and recommendations are as follows.

Size of samples	
Nominal maximum size of aggregates	Approximate minimum mass of field samples, kg (lb)
Fine aggregate	
2.36 mm (No. 8)	10 (25)
4.75 mm (No. 4)	10 (25)
Coarse aggregate	
9.5 mm (3/8 in.)	10 (25)
12.5 mm (1/2 in.)	15 (35)
19.0 mm (3/4 in.)	25 (55)
25.0 mm (1 in.)	50 (110)
37.5 mm (1-1/2 in.)	75 (165)
50 mm (2 in.)	100 (220)
63 mm (2-1/2 in.)	125 (275)
75 mm (3 in.)	150 (330)
90 mm (3-1/2 in.)	175 (385)

Test portions are extracted from the field sample using a sample splitter or other appropriate methods as described in ASTM C 702, "Reducing Field Samples of Aggregate to Testing Size."

4.2.6 *Sample containers*—If samples are to be shipped to a laboratory for testing, the container should be clean, as even small amounts of some materials (such as those that adhere to sugar or fertilizer sacks) may represent serious contamination. Also, the container should be tightly sealed to prevent loss of fines and external contamination. The sample should be identified clearly, inside and outside the container, along with information giving the date of sampling, the kind of aggregate sampled, the quantity represented by the sample, the location and other conditions of sampling, the specifying authority or reason for test, and the kind of test desired.

CHAPTER 5—BLAST-FURNACE SLAG AGGREGATES

5.1—Blast-furnace slag

5.1.1 *Definition*—Blast-furnace slag is a nonmetallic combination of crystalline silica and other materials that form in a molten condition on the surface of molten iron being produced in a blast furnace. When the molten slag is poured into pits or banks and permitted to cool and solidify slowly under atmospheric conditions, the result is air-cooled slag. When molten blast-furnace slag is rapidly agited with a controlled amount of water, or when it is injected with a controlled amount of water, steam, or water-bearing compressed air, the result is expanded blast-furnace slag. When the molten slag is suddenly quenched in water, the result is granulated slag. However it is cooled, slag can be crushed and screened into a variety of sizes. Only air-cooled and expanded blast furnace slags are used as concrete aggregates. Ground granulated slag is ground to a fine powder and used as a cementitious material. Air-cooled slag is discussed in the rest of this section. Expanded slag is discussed in the section on lightweight aggregates.

5.1.2 *Properties*—Slag has many noninterconnected internal voids, resulting in a structurally strong aggregate with relatively low bulk specific gravity and bulk density. Because the pores are coarse and not interconnected, slag aggregate has good freezing-and-thawing durability. Slag aggregate is not harmed by alkalis, and it contains no clay, shale, chert, organic compounds, or other harmful substances usually restricted in specifications for natural aggregates.

Crushed blast furnace slag is roughly cubical in shape and has a rough surface texture. ASTM C 33, "Standard Specifications for Concrete Aggregates," does not specify a Los Angeles abrasion loss requirement for air-cooled blast-furnace slag because it has been determined that the test is not meaningful with respect to slag. It does, however, specify a minimum compacted bulk density of 1120 kg/m^3 (70 lb/ft^3).

Air-entraining agents are recommended to entrain air in concrete with slag aggregates to aid workability even in nonfreezing and thawing applications. Entrained air should of course be used in all concrete exposed to freezing and thawing. Entrained air is especially desirable when slag-aggregate concrete is to be pumped. It is also desirable to have the slag in a saturated condition before batching and mixing to ensure that mixing water is not absorbed by the coarse aggregate.

5.1.3 *Availability*—Air-cooled blast-furnace slag is available primarily in regional areas around steel-producing centers where blast furnaces are used to extract iron from iron ore

CHAPTER 6—LIGHTWEIGHT AGGREGATES

6.1—Introduction to lightweight aggregates

Lightweight aggregates are defined as aggregates of low density, such as: (a) expanded or sintered clay, shale slate, diatomaceous shale, perlite, vermiculite or slag; (b) natural pumice, scoria, volcanic cinders, tuff, and diatomite; or (c) sintered fly ash or industrial cinders used in lightweight concrete.

6.2—Definition of lightweight-aggregate concrete

Lightweight-aggregate concrete has a substantially lower bulk density than that of concrete made with gravel or crushed stone. This lower bulk density results from using lightweight aggregates, either natural or manufactured. Many types of aggregates are classified as lightweight, and are used to produce concretes with a wide range of densities and strengths. These include low-density concretes, structural lightweight concretes, and moderate-strength lightweight concretes, each of which is discussed in more detail in the following, along with the types of aggregates normally used in its production.

6.3—Low-density concretes and associated aggregates

Low-density concretes, whose density seldom exceeds 800 kg/m^3 (50 lb/ft^3), are used chiefly as insulation. While their thermal insulation values are high, their compressive strengths are low, ranging from approximately 0.7 to 7.0 MPa (100 to 1000 psi). Vermiculite and perlite are the most common aggregates used in this type of concrete. Vermiculite is a micaeous mineral. When heated, layers of combined water in the mica's laminar structure are converted to steam, and the material disintegrates by peeling off in successive layers, each of which swells and opens up. Perlite is a volcanic glass containing enough combined water so that when it is heated quickly, the internally generated steam expands violently and breaks the material into small expanded particles. The bulk density of vermiculite and perlite ranges from 96 to 192 kg/m^3 (6 to 12 lb/ft^3).

6.3.1 *Structural lightweight concrete and associated aggregates*—Structural lightweight concretes have densities ranging from 1360 to 1920 kg/m^3 (85 to 120 lb/ft^3) and minimum compressive strengths of 17.0 MPa (2500 psi). Their insulating efficiency is lower than that of low-density concretes, but substantially higher than that of normalweight concretes. The most common aggregates used in this type of concrete are expanded slags; sintering-grate expanded shale, clay, or fly ash; and rotary-kiln expanded shale, clay, or slate.

Sintering can produce either crushed or pelletized aggregates. Crushed aggregates are produced using raw materials that either contain organic matter that can serve as fuel, or have been mixed with fuel such as finely ground coal or coke. The raw materials are premoistened and burned so that gases are formed causing expansion. The resulting clinker is then cooled, crushed, and screened to the required gradation. The finished product tends to be generally sharp and angular with a porous surface texture. Pelletized aggregates are produced by mixing clay, pulverized shale, or fly ash with water and fuel; pelletizing or extruding that mixture; and then burning it. The resultant aggregate particles are generally spherical or cylindrical.

In the rotary kiln process, raw material such as shale, clay, or slate is introduced in a continuous stream at the upper end of a rotary kiln. As the material slowly moves toward the burner at the lower end, the heat, slope, and slow rotation of the kiln cause the material to soften and to trap internally forming gases into an internal cellular structure. In one variation of this process, the expanded (bloated) material is discharged, cooled, and then crushed and screened to the required aggregate gradations. The resultant particles tend to be cubical or angular in shape and have a porous surface texture. Alternatively, before being introduced into the kiln, the raw material is presized by crushing and screening, or by pelletizing. The individual particles then bloat without sticking together. They tend to have a smooth shell over a cellular interior. These two variants can be combined to produce coarse aggregate consisting mostly of uncrushed particles, obtained by screening, and fine particles obtained by crushing the fired product.

6.3.2 *Moderate-strength lightweight concrete and associated aggregates*—Moderate-strength lightweight concretes have a density and strength approximately midway between those of low-density and structural concretes, and are sometimes designated as fill concrete. They are usually made with pumice or scoria aggregate. Pumice is a spongy lava from which steam or gas escaped while it was still hot, and has tube-like, interconnected void pores. Scoria is a volcanic cinder whose pore structure consists mostly of isolated voids.

6.3.3 *Properties*—Due to their cellular structure, the bulk specific gravity of lightweight aggregates is lower than that of normalweight aggregates. The bulk specific gravity of lightweight aggregates also varies with particle size, being highest for fine particles and lowest for coarse particles. This is because crushing destroys larger voids, producing finer aggregates with lower porosity. With present ASTM methods, it is difficult to accurately determine bulk specific gravity and absorption for lightweight aggregates, due to problems in consistently achieving a saturated surface-dry state. Thus, in designing concretes using lightweight aggregates, a specific gravity factor is used instead of the bulk specific gravity. This factor is found in the same way as the bulk specific gravity SSD previously described except that Mass S is the mass of the aggregate at the stockpile moisture, and the mass of the sample in water is measured at a specified number of minutes after immersion. Additional information of specific gravity factors for lightweight aggregates is given in the Appendix of ACI 211.2.

The bulk density of structural lightweight coarse aggregate is normally from 480 to 1040 kg/m^3 (30 to 65 lb/ft^3), significantly lower than that of normalweight aggregates. The bulk density of structural lightweight fine aggregate is normally from 720 to 1120 kg/m^3 (45 to 70 lb/ft^3). For aggregates with the same gradation and particle shape, bulk density is essentially proportional to specific gravity. Although aggregates are usually batched by mass, the volume proportion of the aggregate determines the final yield (volume of the resulting concrete). For this reason, the bulk density of lightweight aggregate is generally checked daily. Variations in bulk density are usually due to changes in grading or particle shape, and can cause variations in concrete yield.

Particle shape and surface texture can vary considerably for lightweight aggregates produced by different methods. Particles are usually roughly spherical, but can be quite angular. Surface texture may range from relatively smooth with small exposed pores, to irregular with small to large exposed pores. These characteristics in both fine and coarse aggregates affect the workability, water requirement, and cement content of lightweight-aggregate concrete, just as they affect concrete made with normalweight aggregates.

In general, grading requirements for lightweight aggregates are similar to those for normalweight aggregates. Lightweight aggregates, however, require a larger percentage by mass of material retained on finer sieve sizes because the specific gravity increases with the decreasing particle size.

Thus, to get an adequate volume of smaller particles, the percent by mass of these particles must be increased. Grading requirements for lightweight aggregates are given in ASTM C 330. Maximum size grading designations generally available are 19, 12.5, and 9.5 mm (3/4, 1/2, and 3/8 in.). Sieve analysis is conducted as for normal aggregates, except that the test sample of fine aggregate has a smaller mass, and the mechanical sieving time is only 5 minutes. These modifications are intended to prevent clogging of smaller sieves and to prevent breakage of the more friable particles during sieving. For coarse aggregate, the test sample must be at least 3 L (0.10 ft^3) in volume.

Lightweight aggregates, due to their cellular structure, can absorb more water than normalweight aggregates. In a 24-hour absorption test, they generally absorb from 5 to 20% by mass of dry aggregate, depending on the pore structure of the aggregate. Normally, under conditions of outdoor storage in stockpiles, total moisture content does not exceed two-thirds of that value. This means that lightweight aggregates usually absorb water when placed in a concrete mixture, and the resulting rate of absorption is important in proportioning lightweight concrete. For further information on proportioning lightweight concrete, the reader is referred to ACI 211.2, "Recommended Practice for Selecting Proportions for Structural Lightweight Concrete."

The maximum compressive strength attainable in concrete made with a given lightweight aggregate may depend on the aggregate itself. The concept of "strength ceiling" may be useful in this regard. A mixture is near its strength ceiling when similar mixtures containing the same aggregates and with higher cement contents have only slightly higher strengths. The strength ceiling represents a point of diminishing returns, beyond which an increase in cement content does not produce a commensurate increase in strength. This ceiling is influenced predominantly by the coarse aggregate. The strength ceiling can be increased appreciably by reducing the maximum size of the coarse aggregate for most lightweight aggregates, especially weaker and more friable ones. As the maximum size of the aggregate is decreased, however, the density of the resulting concrete increases.

CHAPTER 7—RECYCLED AGGREGATES

7.1—Introduction to recycled aggregates

When concrete pavements, structures, sidewalks, curbs, and gutters are removed, they become waste or can be processed for reuse. The resulting concrete must either be disposed of in landfills, or crushed for subsequent use as aggregate base material or as aggregate in new concrete. Crushing the material and using it as coarse aggregate in new concrete makes sense because it reduces waste and reduces the need for virgin aggregate. Recycled aggregate may be of better quality than some virgin aggregate. While recycled aggregate is handled similarly to new aggregate, some differences between new and recycled aggregate must be addressed.

7.1.1 *Definition*—Recycling aggregate involves breaking old concrete (typically pavement), removing the reinforcement, and crushing the resulting material to a specified size and gradation. While any type of pavement or other concrete may be recycled, certain aggregates or certain types of mixtures may require testing of the material to be recycled. Examples include aggregates prone to D-cracking or concretes with ASR potential.

It is desirable to maximize the amount of coarse aggregate produced when concrete is recycled. Recycled fine aggregate normally accounts for approximately 25% of the finished recycled material. New concrete mixtures can contain both fine and coarse recycled aggregate. While up to 100% of the coarse aggregate can be recycled material, the percentage of fine aggregate is usually limited to 10 to 20%, with the remainder being virgin material. This is because of the high absorption of recycled fine aggregates, explained further in the following.

7.1.2 *Properties*—

Gradation and surface condition of recycled aggregate—Almost any gradation can be achieved with recycled aggregate. Crushing may leave some residual dust on the aggregate surfaces. While this does not normally pose a problem, the aggregate must sometimes be washed before use.

Specific gravity of recycled aggregate—The specific gravity of crushed recycled aggregate is lower than that of otherwise identical virgin aggregate, usually approximately 2.2 to 2.5 in the saturated surface-dry (SSD) condition. As particle size decreases, so does specific gravity. Recycled sand has a specific gravity of approximately 2.0 to 2.3 (SSD).

Absorption of recycled aggregates—Due to the cement mortar attached to the particles, the absorption of recycled aggregates is much higher than that of otherwise identical virgin aggregates, typically 2 to 6% for coarse aggregate and higher for fine aggregate. This high absorption can make the resulting fresh concrete less workable. To offset this, recycled aggregate should be sprinkled with water before the concrete is mixed, or extra water should be added to the mixture. Because fine aggregate made by crushing concrete is very angular and has a high absorption, it is generally necessary to limit it to approximately 10 to 20% of the total amount of fine aggregate in the mixture.

Durability of recycled aggregates—Abrasion loss and sulfate soundness are usually not of concern for recycled aggregate. Residual chlorides in a mixture, as from application of deicing salts to a pavement, are usually below threshold values for both fine and coarse aggregates and are not a concern either. Recycled aggregates made from concrete exposed to salt water, however, should receive further chemical and physical testing for their suitability for use in concrete.

Concretes with D-cracking aggregates should be tested before being used as recycled aggregates in concrete that will be subjected to freezing and thawing exposures.

While recycled concrete can be used as coarse aggregate in new concrete pavements, its ASR potential should be determined before such use. Several characteristics are helpful in determining the ability of this aggregate to perform without deleterious ASR during the pavement life. The alkali levels of both the recycled concrete and the new concrete can affect the expansion of the final concrete. To assess ASR potential, the following characteristics of the recycled aggregate should be investigated: the original alkali level of the old concrete, the expansion of the old concrete, the remaining potential for expansion, and the alkali content of the new concrete.

Alkali-silica reactivity in concrete containing recycled aggregates that have shown to be ASR reactive can be mitigated in many of the same ways as concrete made with virgin aggregates. Refer to Section 3.8.3.

CHAPTER 8—SELECTED REFERENCES ON AGGREGATES

American Association of State Highway and Transportation Officials, "Standard Specifications for Transportation Materials and Methods of Sampling and Testing," AASHTO, Washington, D.C.

AASHTO T 210, "Aggregate Durability Index for Fine and Coarse Aggregate."

AASHTO T 210, "Aggregate Durability Index for Fine and Coarse Aggregate."

AASHTO TP 58, "Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro Deval Apparatus."

ACI 213R-03, "Guide for Structural Lightweight Aggregate Concrete," American Concrete Institute, Farmington Hills, Mich., 2003.

ACI 221R-96, "Guide for Use of Normalweight and Heavyweight Aggregates in Concrete," American Concrete Institute, Farmington Hills, Mich., 1996.

ACI 221.1R-98, "Report on Alkali-Aggregate Reactivity," American Concrete Institute, Farmington Hills, Mich., 1998.

ACI Manual of Concrete Inspection, SP-2, 9th Edition, American Concrete Institute, Farmington Hills, Mich., 1999.

For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website. The following ASTM standards are published by ASTM International, West Conshohoken, Pa.

ASTM C 29/C 29M, "Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate."

ASTM C 33-03, "Standard Specifications for Concrete Aggregates."

ASTM C 40-04, "Standard Test Method for Organic Impurities in Fine Aggregates for Concrete."

ASTM C 70-94(2001), "Standard Test Method for Surface Moisture in Fine Aggregate."

ASTM C 87-03, "Standard Test Method for Effect of Organic Impurities in Fine Aggregate on Strength of Mortar."

ASTM C 88-99a, "Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate."

ASTM C 117-04, "Standard Test Method for Materials Finer than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing."

ASTM C 123-04, "Standard Test Method for Lightweight Particles in Aggregate."

ASTM C 127-04, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate."

ASTM C 128-04, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate."

ASTM C 131-03, "Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine."

ASTM C 136-04, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates."

ASTM C 142-97(2004), "Standard Test Method for Clay Lumps and Friable Particles in Aggregates."

ASTM C 227-03, "Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)."

ASTM C 289-03, "Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)."

ASTM C 294-04, "Standard Descriptive Nomenclature for Constituents of Concrete Aggregates."

ASTM C 295-03, "Standard Guide for Petrographic Examination of Aggregates for Concrete."

ASTM C 330-04, "Standard Specification for Lightweight Aggregates for Structural Concrete."

ASTM C 331-04, "Standard Specification for Lightweight Aggregates for Concrete Masonry Units."

ASTM C 332-99, "Standard Specification for Lightweight Aggregates for Insulating Concrete."

ASTM C 535-03$^{\varepsilon 1}$, "Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine."

ASTM C 566-97(2004), "Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying."

ASTM C 637-98a(2003), "Standard Specification for Aggregates for Radiation-Shielding Concrete."

ASTM C 638-92(2002), "Standard Descriptive Nomenclature of Constituents of Aggregates for Radiation-Shielding Concrete."

ASTM C 641-98$^{\varepsilon 1}$, "Standard Test Method for Staining Materials in Lightweight Concrete Aggregates."

ASTM C 586-99, "Standard Test Method for Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregates (Rock Cylinder Method)."

ASTM C 702-98(2003), "Standard Practice for Reducing Samples of Aggregate to Testing Size."

ASTM C 1137-97, "Standard Test Method for Degradation of Fine Aggregate Due to Attrition."

ASTM C 1252-03, "Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)."

ASTM C 1260-01, "Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)."

ASTM C 1293-01, "Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction."

ASTM C 1524/C 1524M-02a, "Standard Test Method for Water-Extractable Chloride in Aggregate (Soxhlet Method)."

ASTM C 1567-04, "Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate."

ASTM D 75-03, "Standard Practice for Sampling Aggregates."

ASTM D 448-03a, "Standard Classification for Sizes of Aggregate for Road and Bridge Construction."

ASTM STP 169 C, "Significance of Tests and Properties of Concrete and Concrete-Making Materials," ASTM International, West Conshohocken, Pa., 1994.

IS 413, "Diagnosis and Control of Alkali-Aggregate Reactions in Concrete," Portland Cement Association, Skokie, Ill., 1997.

TB014, "Recycling Concrete Pavement," American Concrete Pavement Association," Skokie, Ill., 1993.

CHAPTER 9—GLOSSARY

Abrasion resistance—Ability of a surface to resist being worn away by rubbing and friction.

Absorption—The mass of water contained in the pores of a saturated surface-dry aggregate expressed as a percentage of the oven-dry mass of the aggregate; also the process by which a liquid is drawn into a porous solid body.

Admixture—A material other than water, aggregates, and hydraulic cement that is used as an ingredient in concrete or mortar and is added to the batch immediately before or during mixing.

Aggregate—Granular material such as natural sand, manufactured sand, gravel, crushed stone, and blast furnace slag that, when bound together by cement paste, forms concrete.

Air entrainment—The inclusion of air in the form of very small bubbles during the mixing of concrete.

Alkali-aggregate reaction—Chemical reaction in mortar or concrete between alkalis from portland cement or other sources and certain constituents of some aggregates; under certain conditions, harmful expansion of the concrete or mortar may result.

Batch—Quantity of concrete or mortar mixed at one time.

Blast-furnace slag—The nonmetallic product, consisting essentially of silicates and aluminosilicates of calcium and of other bases, which is developed in a molten condition simultaneously with iron in a blast furnace.

Bleeding—The flow of mixing water toward the surface of newly placed concrete caused by the settlement of solid materials.

Bulk density (replaces deprecated term "unit weight")—For aggregate, the mass of a unit volume of aggregate material (the unit volume includes the volume of individual particles and the volume of the voids between the particles).

Cement, portland—The product obtained by pulverizing clinker consisting essentially of hydraulic calcium silicates with calcium sulfates as an interground addition; when mixed with water it forms the binder in portland cement concrete or other hydraulic cement concretes.

Coarse aggregate—Aggregate predominantly retained on the 4.75 mm (No. 4) sieve.

Colorimetric test—A procedure used to indicate the amount of organic impurities present in fine aggregate.

Concrete—A material consisting of a binder within which aggregate particles are imbedded; in hydraulic cement concrete, the binder is a mixture of hydraulic cement and water.

Crushed gravel—The product resulting from the artificial crushing of gravel with nearly all fragments having at least one face resulting from fracture.

Crushed stone—The product resulting from the mechanical crushing of rocks, boulders, etc., with substantially all faces of the particle having resulted from the crushing operation.

Elongated particle—A piece of aggregate having the ratio of length to width of its circumscribing prism greater than a specified value.

Fine aggregate—Aggregate passing the 9.5 mm (3/8 in.) sieve and almost entirely passing the 4.75 mm (No. 4) sieve and predominantly retained on the 75 μm (No. 200) sieve.

Fineness modulus—A factor obtained by adding the total percentages of an aggregate sample coarser than each of a specified series of sieves, and dividing the sum by 100; in the U.S., the sieves are 150 μm, 300 μm, 600 μm, 1.18 mm, 2.36 mm, 4.75 mm, 9.5 mm, 19.0 mm, 37.5 mm, 75 mm, and 150 mm (No. 100, No. 50, No. 30, No. 16, No. 8, No. 4, 3/8 in., 3/4 in., 1-1/2 in., 3 in., and 6 in.).

Flat particle—A piece of aggregate having the ratio of width to thickness of its circumscribing prism greater than a specified value.

Free moisture—Moisture not retained or absorbed by aggregate. Also called surface moisture.

Grading, Gradation—The distribution of particles of aggregate among various sizes; usually expressed in terms of total percentages larger or smaller than each of a series of sieve openings or the percentages between certain ranges of sieve openings.

Gravel—Granular material predominantly retained on the 4.75 mm (No. 4) sieve and resulting from natural disintegration and abrasion of rock or processing of weakly-bound conglomerate.

Harsh mixture—A concrete mixture that lacks desired workability and consistency due to a deficiency of mortar or aggregate fines.

Igneous rocks—Rocks that have solidified from a molten solution.

Lightweight aggregates—Aggregates that may range in dry loose mass (weight) from 96 to 1120 kg/m^3 (6 to 70 lb/ft^3) and are used in making lightweight concrete.

Los Angeles abrasion test—A procedure used to measure the abrasion resistance of aggregates.

Manufactured sand—See stone sand.

Maximum size of aggregate—In specifications for, or descriptions of, aggregate, the smallest sieve through which the entire amount of aggregate is required to pass.

Metamorphic rocks—Rocks altered and changed from their original igneous or sedimentary form by heat, pressure, or a combination of both.

Mineral admixture—Finely-divided mineral powder such as hydrated lime, fly ash, bentonite, and pulverized talc or stone used as an admixture for concrete.

Mortar bar test—A procedure used to determine whether an aggregate will expand excessively, due to the alkali-aggregate reaction, when used in concrete.

Nominal maximum size of aggregate—In specification for, or descriptions of, aggregate, the smallest sieve through which the entire amount of aggregate is permitted to pass.

Pop-out—The breaking away of small portions of a concrete surface due to internal pressure that leaves a shallow, typically conical, depression.

Pozzolan—A siliceous or siliceous and aluminous material that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form cementing compounds.

Pycnometer—a vessel for determination of specific gravity of liquids or solids

Reactive aggregate—Aggregate containing substances capable of reacting chemically with the products of solution or hydration of the portland cement in concrete or mortar under ordinary conditions of exposure, sometimes resulting in harmful expansion, cracking, or staining.

Roundness—A term referring to the relative sharpness or angularity of aggregate particle edges or corners.

Sand—Granular material passing the 9.5 mm (3/8 in.) sieve and almost entirely passing the 4.75 mm (No. 4) sieve and predominantly retained on the 75 µm (No. 200) sieve, and resulting from natural disintegration and abrasion of rock or processing of completely friable sandstone.

Saturated surface-dry—Condition of an aggregate particle when the permeable voids are filled with water and no water is on the exposed surfaces.

Sedimentary rock—Rocks formed by the deposition of plant and animal remains, and of materials formed by the chemical decomposition and physical disintegration of igneous, sedimentary, or metamorphic rocks.

Sieve analysis—Determination of the proportions of particles lying within selected size ranges in a granular material by separation on sieves of different size openings.

Slag—See blast-furnace slag.

Slump—A measure of consistency of freshly-mixed concrete obtained by placing the concrete in a truncated cone of standard dimensions, removing the cone, and measuring the subsidence of the concrete to the nearest 6 mm (1/4 in.).

Soundness—For aggregate, the ability to withstand the aggressive action to which concrete containing it might be exposed, particularly that due to weather.

Specific gravity—For aggregate, the mass of the aggregate divided by the mass of an equal volume of water. Now identified as relative density

Sphericity—A property of aggregate relating to the ratio of surface area to volume; spherical or cubical particles have a higher degree of sphericity than flat or elongated particles.

Stone sand—Fine aggregate produced by crushing rock, gravel, or slag. Also called manufactured sand.

Surface moisture—See free moisture.

Surface texture—Degree of roughness or irregularity of the exterior surfaces of aggregate particles or hardened concrete.

*Water-cementitious material ratio (*w/cm*)*—The ratio of the amount of water, exclusive only of that absorbed by the aggregates, to the amount of cementitious material in a concrete, preferably stated as a decimal by mass.

Workability—That property of freshly mixed concrete or mortar that determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished.

Yield—The volume of freshly mixed concrete produced from a known quantity of ingredients, usually calculated by dividing the total mass of ingredients by the density of the freshly mixed concrete.

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