ACI Education Bulletin E1-99

AGGREGATES FOR CONCRETE

Developed by Committee E-701,
Materials for Concrete Construction

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, and blast-furnace slag that usually occupies approximately 60 to 75% of the volume of concrete. Besides reducing volume changes due to drying shrinkage of the cement-water paste, aggregate is an inexpensive filler that reduces the cost of the concrete. Aggregate properties significantly affect the workability of plastic concrete and 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" (deprecated term) has been replaced with "density" when used in reference to concrete, and with "bulk density" when used in reference to aggregates. However, as a convenience, most of the examples provided in the bulletin are in both SI and in.-lb units.

Frequent references are made to standards of the American Society for Testing and Materials (ASTM). 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 manual refer to the most recent edition. Other agencies 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 method of preparation. Natural sands and gravels are the product of weathering and the action of wind or water, while stone sands and crushed stone are produced by crushing natural stone. Screening and washing may be used to process aggregates from either of these categories. Aggregates may be produced from igneous, sedimentary, or metamorphic rocks, but the presence or absence of any 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 should be based upon specific information obtained from tests used to measure the aggregate quality, or upon its service record, or both. A typical consensus specification for concrete aggregate, both fine and coarse aggregate, is ASTM C 33.

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

Other classifications of aggregates may be based upon 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 sieves nested one above the other in order of size, with the sieve having the largest openings on top and the one having the smallest openings at the bottom (Fig. 1). These wire-cloth sieves have square openings. A pan is used to catch material passing the smallest sieve.

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) 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,

Fig. 1—Nest of sieves.

"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 is dependent upon the particle sizes present in the sample and the grading requirements specified.

After sieving, the mass of material retained on each sieve and on 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, total percent retained on each sieve, and total percent passing each sieve. For an accurate determination of the amount of material finer than the 75 µm (No. 200) sieve, the ASTM C 117 test method should be used.

Grading charts are drawn 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. Fig. 2 shows a typical grading chart for coarse and fine aggregates having gradings calculated in the following two examples.

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 below and the masses retained on each sieve are as shown.

Sieve size	Mass retained, g	Individual % retained	Total % retained	Total % passing
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	—	—

Table 1—Sieves commonly used for concrete aggregate sieve analysis

Standard sieve designation		Nominal sieve opening	
		mm	in.
Coarse sieves			
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
75 µm	No. 200	0.075	0.0029

*1000 µm = 1 mm.

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

Property		Typical ranges
Fineness modulus of fine aggregate		2.3 to 3.1
Nominal maximum size of coarse aggregate		37.5 to 9.5 mm (1-1/2 to 3/8 in.)
Absorption		0 to 8%
Bulk specific gravity		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.

Note that the total of masses retained may differ from the original sample mass. Since 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 was too great, a check would have been made for possible errors in mass determination, calculation, accidental spillage loss, or material stuck in the sieve openings.

The total mass of the material after sieving should check closely with the original mass of 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 by the sum of the masses retained on each sieve and the pan and multiplying by 100.

Total percent retained is calculated by successively summing the numbers in the individual percent retained column.

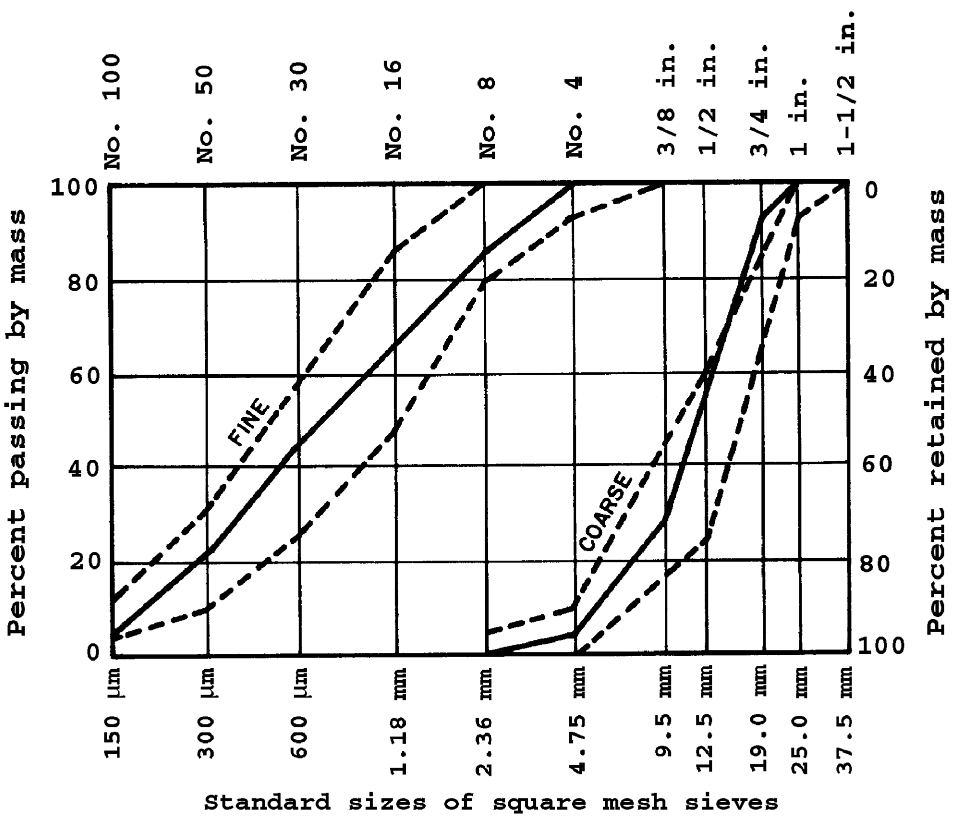

Fig. 2—Typical grading chart. Dashed lines indicate limits specified in ASTM C 33 for fine aggregates and for 25.0-mm (1-in.) coarse aggregate.

Total percent passing is calculated by subtracting the total 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 shown below 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 was too great.

All other calculations are carried out in a manner identical to that shown in Example 1.

If the test sample was first tested by the ASTM C 117 test method, 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 prior to washing as the basis for calculating all the percentages.

3.1.2 *Fineness modulus*—Using the sieve analysis results, a factor called the fineness modulus is often computed. The fineness modulus is the sum of the total percentages retained on each of a specified series of sieves, divided by 100. The specified sieves are the 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 fineness modulus. For sands used in concrete, the fineness modulus generally ranges from 2.3 to 3.1.

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

Sieve size	Total % retained
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

Although fineness modulus is most commonly computed for fine aggregates, the fineness modulus of coarse aggregate is needed for some proportioning methods. It is calculated in the same manner but care must be taken 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*

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. Since 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 fineness modulus 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*

Three aggregates are combined in the mass percentages indicated. For the given individual aggregate gradings, determine the grading of the combined aggregate.

Sieve size	% 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	—	—
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:

For the 9.5-mm (3/8-in.) sieve:
100% 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% of Aggregate 2 and 3, respectively, are used. Therefore,

% passing of Aggregate 1
in the combined aggregate = 35% × 100 = 35%
% passing of Aggregate 2
in the combined aggregate = 25% × 89 = 22%
% passing of Aggregate 3
in the combined aggregate = 40% × 2 = 1%
% passing the 9.5 mm (3/8 in.)
sieve for the combined aggregate = 58%
% retained on the 9.5 mm (3/8 in.)
sieve for the combined aggregate = 100 − 58 = 42%

Sieve size	Aggregate 1	Aggregate 2	Aggregate 3	% passing	% retained	Individual % retained
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	~~37~~	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 fineness modulus 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. Therefore,

Fineness modulus = 560/100 = 5.60

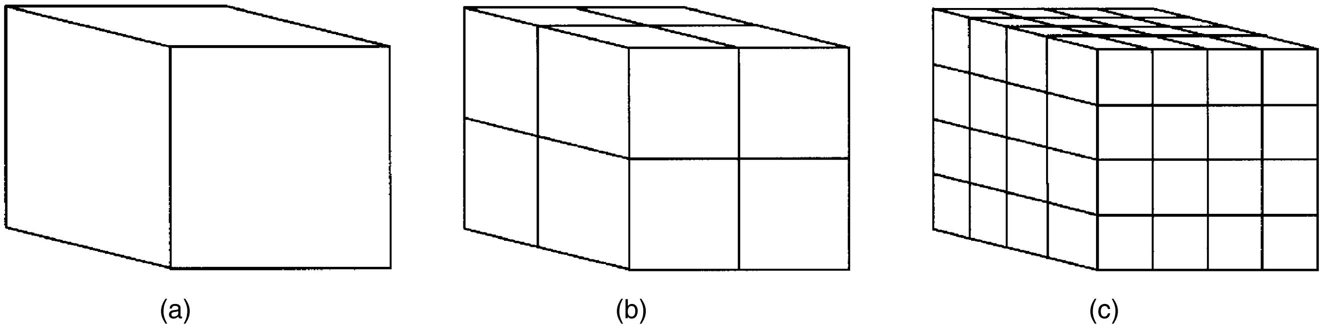

Fig. 3—Effect of particle size on aggregate surface area:
(a) one 25.0 mm (1-in.) cube of aggregate [surface area= 6 x 25.0 x 25.0 = 3750 mm^2 (6 in.^{2})];
(b) eight 12.5 mm (1/2 in.) cubes of aggregate [surface area= 6 x 12.5 x 12.5 x 8 = 7500 mm^2 (12 in.^{2})]; and
(c) sixty-four 6.25 mm (1/4 in.)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

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 the 25.0 mm (1-in.) sieve = 80%
% passing the 19.0 mm (3/4 in.) sieve = 70%
% of material between the 25.0
and 19.0 mm (1 and 3/4 in.) sieves = 80 – 70 = 10%

This is the individual percent retained on the 19.0 mm (3/4 in.) sieve.

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

Sieve size	Specification limits 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 will generally produce mixtures with fewer voids between particles. Since 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 sand to fill the voids between coarse aggregate particles, the space must be filled with cement paste. These undersanded mixes also tend to be harsh and difficult to finish. On the other hand, aggregate combinations with excessive amounts of sand or excessively fine sands may produce uneconomical concretes because of the larger surface area of finer particles.

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 mm^2 (6 in.^{2}) and a volume of 15,625 mm^3 (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 mm^2 (12 in.^{2}). By reducing a large coarse aggregate particle to particles one half its original size, the surface area of an equal volume (or mass) is twice as great. If it were further reduced to fine sand size particles, the same volume 15,625 mm^3 (1 in.^{3}) 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. We 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 a cheap diluent; or 3) he can buy more paint. Each of these options has at least one disadvantage. It takes more effort to paint the side with a thinner layer, the cheap diluent will reduce the quality of the paint and buying more paint will increase the cost. Similarly, when the aggregate surface area increases, if we leave the cement paste content constant, the thinner layers of paste surrounding the aggregate particles result in a stiffer concrete that is harder to place and compact. If we make the paste 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 sand to a concrete mixture and to avoid using an extremely fine sand.

The maximum size of coarse aggregate used in concrete also has an effect upon 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. This is 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 nominal maximum size of aggregate that can be used will be determined by the size and shape of the concrete member and by the clear spacing between reinforcing bars. In general, it 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 size, consistent with placing requirements, is sometimes recommended in order to minimize the amount of cement required and to minimize shrinkage.

Aggregates of different maximum sizes, however, may give different concrete strengths for the same water-cementitious material ratio. *In many instances, at the same water-cementitious material ratio, concrete with smaller maximum size aggregate has the higher compressive strength. This is especially true in higher strength ranges.* If compressive strengths in excess of 35 MPa (5100 psi) are required, 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 also 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, provided:

1. The aggregate is used in air-entrained concrete containing more than 250 kg/m^3 (420 lb/yd^3) of cement and an air content of more than 3%;
2. More than 300 kg/m^3 (506 lb/yd^3) of cement are used in non-air-entrained concrete; or
3. An approved mineral admixture is used to supply the deficiency in material passing these sieves.

The lower limits given may be adequate for easy placing conditions or for mechanically finished concrete, but for hand-finished concrete floors or where a smooth texture is needed, 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. It should be remembered, however, that with a fixed water-cementitious material ratio, use of greater than the previously stated amounts of these finer fractions will increase the surface area and therefore increase the amount of paste needed to maintain a given slump for the concrete. This is particularly true for high-strength concrete with a high cement content.

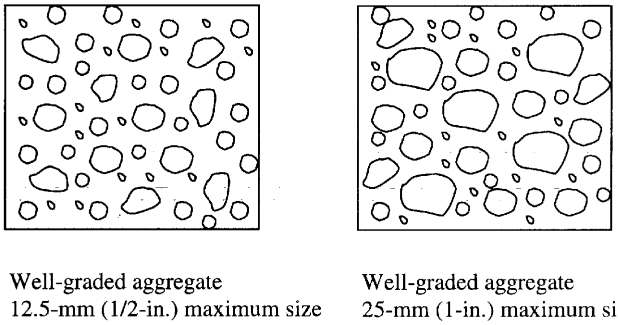

Fig. 4—Effect of increasing maximum size on void content of well-graded aggregate.

3.1.5 *Permissible variations in grading*—A relatively wide range of grading for both fine and coarse aggregates is permitted by many specifications. ASTM C 33 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 mix 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, its 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 is different 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.

3.2—Specific gravity

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. Since the aggregate mass will vary with its moisture content, specific gravity is deter-

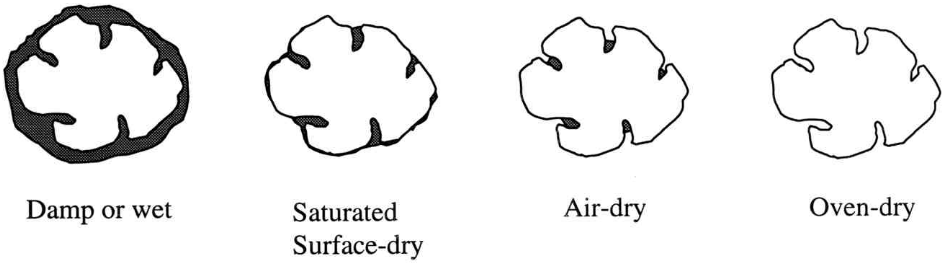

Fig. 5—Moisture condition of aggregates.

mined at a fixed moisture content. Four moisture conditions are defined for aggregates depending upon 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 upon 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 bulk specific gravity SSD is the saturated surface-dry mass divided by the mass of a volume of water equal to the aggregate volume. Most normal mass aggregates have a bulk specific gravity SSD between 2.4 and 2.9.

3.2.2 *Specific gravity test methods*—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 constant mass at 100 to 110 C (212 to 230 F), cooled in air and immersed in water for 24 hr.[*] 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.

The mass of the sample in air is determined and then it is placed in a sample container for determination of its mass in water. The mass of the sample in water will be 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 mass determined again. 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 = mass of oven-dry sample in air;
B = mass of saturated surface-dry mass in air; and
C = mass of saturated sample.

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

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

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

Fine aggregate is dried to a constant mass at 100 to 110 C (212 to 230 F), cooled in air and immersed in water for 24 hr.[*] Excess water is drained off and the sample is spread on a flat surface exposed to a gently moving current of warm air. The sample is stirred frequently until it approaches a free flowing condition and then 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. This indicates that it has reached a saturated surface-dry condition. Next, about 500 g of the surface-dried material is placed in a jar or flask, and water is added to fill it to its calibrated capacity. The total mass of the jar, specimen, and water is determined. The fine aggregate is then removed from the jar, oven-dried and its mass determined. Finally, the mass of the jar filled with water to its calibrated capacity is determined. The specific gravity values are then calculated as follows:

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[*] 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-hr 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.

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

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

where

A = mass of oven-dry sample in air;

B = mass of saturated surface-dry sample in air;

C = mass of jar or flask filled with water; and

D = mass of jar or flask with specimen and water to the calibration or filling mark.

Example 7: *Specific gravity calculation 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

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

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

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 not including the voids between particles.

Substituting one aggregate for another in a concrete when the aggregates have differing specific gravities will cause the yield or volume of concrete to increase or decrease if batch masses remain constant. And since concrete is often sold by volume, this change means that either the purchaser is receiving less concrete than ordered or the producer is supplying more concrete than is being purchased. Changes in the aggregate specific gravity will also cause the concrete density to change. This is undesirable if a minimum density is specified, for example, in concrete for nuclear radiation shielding.

The specific gravity of an aggregate *is not a measure of aggregate quality,* but within an aggregate source, a variation in the specific gravity may indicate a change in the aggregate characteristics.

3.2.4 *Absolute volume calculations*—To calculate absolute volume, the mass of aggregate is divided by the absolute density (previously termed absolute “unit weight”), which is the specific gravity times the density of water. If the mass is in kg, the specific gravity is multiplied by 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. What is 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:

$$\text{Absolute volume} = \frac{105.0}{2.60 \times 62.4} = \frac{105.0}{162.2} = 0.647\ \text{ft}^3$$

In a batch of concrete, the sum of the absolute volumes of cement, 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. What is 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	760	2.60 (bulk SSD)
SSD coarse aggregate	1044	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	Absolute volume, m^3
Cement	279	3.15	3150	0.089
Water	166	1.00	1000	0.166
SSD fine aggregate	760	2.60	2600	0.292
SSD coarse aggregate	1044	2.63	2630	0.397
		Total absolute volume = 0.944 m^3		

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

$$V_c = 0.944 + V_a$$

By definition of air content, $V_a = 0.03V_c$

so $V_c = 0.944 + 0.03V_c$.

Therefore, $0.97V_c = 0.944$

and $V_c = 0.944 / 0.97 = 0.973\ \text{m}^3$.

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	Absolute volume, ft^3
Cement	470	3.15	196.6	2.39
Water	280	1.00	62.4	4.49
SSD fine aggregate	1280	2.60	162.2	7.89
SSD coarse aggregate	1760	2.63	164.1	10.73
		Total absolute volume = 25.50 ft^3		

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

$$V_c = 25.5 + V_a$$

By definition of air content, $V_a = 0.03V_c$,

so $V_c = 25.5 + 0.03V_c$.

Therefore, $0.97V_c = 25.5$

and $V_c = 25.5 / 0.97 = 26.3$ 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 specific gravity calculations. However, aggregates stockpiled on the job are seldom in either of these states. The aggregates usually carry some free or surface moisture that becomes part of the mixing water. Freshly-washed coarse aggregates contain free water, but since they dry quickly, they are sometimes in an air-dry state when used. In this state, they will absorb some of the mixing water when used.

At this point, it is necessary to define the terms mixing water and water-cementitious material ratio. 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 batches at the plant or through a truck mixer system. Mixing water is the water available to come in contact with cement particles during the initial phases of the chemical reaction between cement and water that takes place in concrete.

The water-cementitious material ratio is the mass ratio of mixing water to cementitious material. In the past, this ratio was frequently expressed in gallons of water per sack of cementitious material. Today, most agencies express quantities of cementitious material and water in kg or lb, and water-cementitious material ratio 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 content 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.

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

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

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

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 = mass of the original sample, and

W_{OD} = 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.

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

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

If an aggregate is air-dry (surface is dry but pores are partially filled with water), the total moisture content will be less than the absorption and the surface moisture content will be a negative value. This means that the aggregate will absorb water when mixed in concrete. 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 water-cementitious material ratio and consistency. However, it is difficult to determine precisely how much water will be absorbed while the concrete is still in a plastic state because the absorption is calculated after a 24-hr soaking period, although concrete typically sets sooner than this period.

For techniques to be used in controlling the mixing water and water-cementitious material ratio for mixtures containing highly absorptive aggregates, the reader is referred to ACI Standard 211.2-98, "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 water-cementitious material ratio 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 water-cementitious material ratio 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

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 =

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

$$943 - W_{OD} = 0.061 W_{OD}$$

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

For gravel:
Total moisture content =

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

$$1092 - W_{OD} = 0.013 W_{OD}$$

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

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 = 45.3 kg
Free moisture on gravel = 0.006 ×1078 = 6.5 kg
Total free moisture on aggregate = 45.3 + 6.5 = 51.8 kg
Mixing water = 146 + 51.8 =197.8 kg
or 198 kg
Water-cementitious material ratio= 198 / (267 + 89) = 0.55

These calculations are summarized in the following table.

Material	Batch mass, kg	Total moisture, %	Dry mass, kg	Surface moisture, %	Mixing water, kg
Cement	267	0	267	0	—
Fly ash	89	0	89	0	—
Sand	943	6.1	889	5.1	45.3
Gravel	1092	1.3	1078	0.6	6.5
Water	146	—	—	—	146.0
				Total:	197.8 (198)

In in.-lb units:

What is the mixing water content and water-cementitious material ratio 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

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 =

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

$$1590 - W_{OD} = 0.061 W_{OD}$$

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

For gravel:
Total moisture content =

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

$$1840 - W_{OD} = 0.013 W_{OD}$$

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

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 = 76 lb
Free moisture on gravel = 0.006 × 1816 = 11 lb
Total free moisture on aggregate = 76 + 11 = 87 lb
Mixing water = 242 + 87 = 329 lb
Water-cementitious material ratio = 329 / (450 + 150) = 0.55

These calculations are summarized in the following table.

Material	Batch mass, lb	Total moisture, %	Dry mass, lb	Surface moisture, %	Mixing water, lb
Cement	450	0	450	0	—
Fly ash	150	0	150	0	—
Sand	1590	6.1	1498	5.1	76
Gravel	1840	1.3	1816	0.6	11
Water	242	—	—	—	242
				Total:	329

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. However, since aggregates as batched into the mixtures are very seldom oven-dry or saturated surface-dry, adjustments must be made in both the masses of aggregates and the quantity of water to be added.

Since 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 are given below. In the first, batch quantities are given in terms of oven-dry aggregates 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	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

However, at the batch plant, 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.

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.

Mass of fine aggregate = (0.06 × 770) + 770 = 816 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.

Mass of coarse aggregate = (0.03 × 1127) + 1127 = 1161 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 = 38.5 kg
Coarse aggregate
free moisture content = 0.01 × 1127 = 11.3 kg
Total aggregate
free moisture content = 38.5 + 11.3 = 49.8 kg
Water to be added
at the mixer = 190 – 49.8 = 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 table below summarizes these calculations.

Material	Batch mass, kg	Total moisture, %	Dry mass, kg	Surface moisture, %	Mixing water, kg
Cement	267	—	267	—	—
Fly ash	89	—	89	—	—
Fine aggregate	816	6.0	770	5.0	38.5
Coarse aggregate	1161	3.0	1127	1.0	11.3
Water	140	—	—	—	140
				Total:	189.8 (190)

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

However, at the batch plant, 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.

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.

Mass of fine aggregate = (0.06 × 1300) + 1300 = 1378 lb

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

Coarse aggregate mass is calculated the same way.

Mass of coarse aggregate = (0.03 × 1900) + 1900 = 1957 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
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 × 1300 = 65 lb
Coarse aggregate free moisture content = 0.01 × 1900 = 19 lb
Total aggregate free moisture content = 65 + 19 = 84 lb
Water to be added at the mixer = 320 – 84 = 236 lb

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 table below summarizes these calculations.

Material	Batch mass, lb	Total moisture, %	Dry mass, lb	Surface moisture, %	Mixing water, lb
Cement	450	—	450	—	—
Fly ash	150	—	150	—	—
Fine aggregate	1378	6.0	1300	5.0	65
Coarse aggregate	1957	3.0	1900	1.0	19
Water	236	—	—	—	236
				Total:	320

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 since moisture contents and absorption are percentages of oven-dry masses.

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

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

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

Free moisture content = total moisture content – absorption
Sand = 6.0 – 1.0 = 5.0% free moisture
Stone = 3.0 – 2.0 = 1.0% free moisture
Sand free moisture content = 0.05 × 771 = 38.5 kg
Stone free moisture content = 0.01 × 1127 = 11.3 kg
Total aggregate free moisture content = 38.5 + 11.3 = 49.8 kg
Water to be added at the mixer = 190 – 49.8=140.2 kg
Wet fine aggregate mass =779 (SSD) + 38.5 =817 kg
Wet coarse aggregate mass =1150 (SSD) + 11.3 =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 table below summarizes these calculations.

Material	SSD mass, kg	Batch mass, kg	Total moisture, %	Dry mass, kg	Surface moisture, %	Mixing water, kg
Cement	267	267	—	267	—	—
Fly ash	89	89	—	89	—	—
Sand	779	816	6.0	771	5.0	38.5
Stone	1150	1161	3.0	1127	1.0	11.3
Water	190	140	—	—	—	140.0
					Total:	189.8 (190)

In in.-lb 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, 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 since moisture contents and absorption are percentages of oven-dry masses.

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

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

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

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

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 table below summarizes these calculations.

Material	SSD mass, lb	Batch mass, lb	Total moisture, %	Dry mass, lb	Surface moisture, %	Mixing water, lb
Cement	450	450	—	450	—	—
Fly ash	150	150	—	150	—	—
Sand	1313	1378	6.0	1300	5.0	65
Stone	1938	1957	3.0	1900	1.0	19
Water	320	236	—	—	—	236
					Total:	320

3.3.6 *Alternate definition of surface moisture*—Some agencies that state desired 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 = original sample mass; usually a wet or damp mass; and
W_{SSD} = 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 through the use of 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:

$$P = \frac{V_S - V_d}{W_S - V_S}$$

where
P = surface moisture in terms of saturated surface-dry fine aggregate, percent;
V_S = mass of water displaced (determined either by a

mass determination or volumetric method);
V_d = mass of the sample divided by the bulk specific gravity SSD; and
W_S = 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 surface moisture content determination. 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 will displace 1 g of water for each 1 g of surface moisture. Therefore, the wet sample will displace 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 – 200 = 203 mL
Mass of water displaced = 203 mL × 1 g/mL = 203 g
Surface moisture content, %, =

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

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: *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 = 26.8 kg
Coarse aggregate free moisture = 0.008 × 902 = 7.2 kg
Total aggregate free moisture = 26.8 + 7.2 = 34 kg
Water to be added at the mixer = 193 – 34 = 159 kg
Wet fine aggregate mass = 765 + 26.8 = 791.8 kg (792 kg)
Wet coarse aggregate mass = 902 + 7.2 = 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 table below summarizes these calculations.

Material	SSD mass, kg	Surface moisture SSD basis, %	Mixing water, kg	Wet batch mass, kg
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	1290
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 = 45 lb

Coarse aggregate free moisture = 0.008 × 1520 = 12 lb
Total aggregate free moisture = 45 + 12 = 57 lb
Water to be added at the mixer = 325 − 57 = 268 lb
Wet fine aggregate mass = 1290 + 45 = 1335 lb
Wet coarse aggregate mass= 1520 + 12 = 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 table below summarizes these calculations.

Material	SSD mass, lb	Surface moisture SSD basis, %	Mixing water, lb	Wet batch mass, lb
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 deprecated term "unit weight")

3.4.1 *Definition and test method*—The bulk density (previously unit weight and sometimes called 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. 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 and determination of its mass.

The bulk density is used in estimating quantities of materials and in some mixture proportioning calculations.

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

$$\text{Bulk density} = \frac{36.8 - 13.1}{0.0141} = \frac{23.7}{0.0141} = 1681 \text{ kg/m}^3$$

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

$$\text{Bulk density} = \frac{81.1 - 28.8}{0.498} = \frac{52.3}{0.498} = 105 \text{ lb/ft}^3$$

3.4.2 *Factors affecting bulk density*—If the moisture content of the aggregate varies, its bulk density will also vary. For coarse aggregate, increasing moisture content increases the bulk density, but for fine aggregate, increasing the moisture content beyond the saturated surface-dry condition can cause the bulk density to decrease. 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 is called bulking and is of little importance if the aggregates for a concrete mixture are batched by mass. However, if volumetric batching is used, bulking must be taken into account when 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 will usually have a higher bulk density than those with a preponderance of one size particles present. Higher specific gravity of the particles results in higher bulk density for a particular grading, and smooth rounded aggregates will 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 normal-weight concrete generally ranges from 1200 to 1760 kg/m^3 (75 to 110 lb/ft^3).

3.5—Particle shape and surface texture

3.5.1 *Definition*—Particle shape includes two properties: sphericity and roundness. Sphericity is a measure of whether the particle is compact in shape. That is, if it is close to being a sphere or a cube as opposed to being flat (disk-like) or elongated (needle-like). Roundness refers to the relative sharpness or angularity of the particle edges and corners. The higher the sphericity (the closer the particle is to a sphere or cube), the lower will be its surface area and, therefore, lower will be its demand for mixing water in concrete and lower will be the amount of sand needed in the mixture to provide workability. More angular and less spherical coarse aggregates will require higher mixing water and fine aggregate content to provide the needed workability.

Surface texture refers to the degree of roughness or irregularity of the aggregate particle surface. Usually, terms such as rough, granular, crystalline, smooth, or glassy are used to describe surface texture rather than using any quantitative method. Smooth particles will require less mixing water and therefore less cementitious material at a fixed water-cementitious material ratio to produce concrete with a given workability, but will have less bonding area with the cement paste than rougher particles.

3.5.2 *Test methods*—There have been a number of test methods used to provide a measure of some function of sphericity, angularity, and/or surface texture. No one method has gained universal acceptance, but the procedures summarized below (or variations thereof) have been used reasonably widely. Three methods have been adopted as ASTM standard procedures: 1) ASTM C 1252; 2) ASTM D 3398; and 3) ASTM D 4791, developed by the U. S. Army Corps of Engineers. 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 agencies have also used this procedure (sometimes using a ratio of length-to-thickness) termed "flat and elongated" particles of 5 instead of 3. This method is feasible only for coarse aggregate sizes. It is a tedious procedure involving the handling of each individual particle in the sample portion. Also, it does not provide any measurement of the angularity or roundness of the corners and edges, and it does not measure the surface texture.

Another test, the flakiness index, was developed in Britain and involves determining what percentage of a closely sized sieve fraction, such as 19.0 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, the average size of the 19.0 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 are indicative of aggregates with a high degree of sphericity. This procedure is also time consuming since each particle is handled to see if it can be fitted through the appropriate slot; again, only coarse aggregate is considered. Angularity and surface texture are not measured by this method.

Both fine and coarse aggregate characteristics relating to shape, angularity, and surface texture can 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 an 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. 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 is, the greater the percentage of voids will be. In addition, the grading of the sample affects the percentage of voids, so 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 it also includes a procedure using a fixed grading for both fine and coarse aggregates to obtain companion void percentages related to shape and texture. The concrete mixing water requirement for a given slump level can be related to shape and texture, as indirectly measured by voids in the fine aggregate. Flow rate of aggregate through a funnel-like orifice has also been used as a measure of shape and texture. Orifice flow has been found to be highly related to percent voids.

Particle index, ASTM D 3398, is a test method that involves 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. Particle index is determined by the formula below for each size and then a weighted index is calculated for the overall grading.

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

where

I = particle index;

V_{10} = percent voids at 10 drops compaction; and

V_{50} = percent voids at 50 drops compaction.

Another somewhat tedious procedure involving the handling of each particle is the counting of particles with more than one (or sometimes two) crushed faces. This is a method applicable to usually only coarse aggregate and is subject to 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 and surface texture*—The shape and surface texture of the individual particles of sand, rock, gravel, slag, or lightweight aggregate making up an aggregate will have an important influence on the workability of freshly mixed concrete and the strength of hardened concrete. Fine aggregate particle shape and texture affects concrete in one major way—through its influence on the workability of fresh concrete. Angular rough sands will require more mixing water in concrete than rounded smooth fine aggregates to obtain the same level of slump or workability, with other factors being equal. This, in turn, will affect the water-cementitious material ratio if the cementitious content is held constant; or it will require an adjustment in the cementitious content if a certain water-cementitious material ratio is needed.

The influence of fine aggregate shape and texture on the strength of hardened concrete is almost entirely related to its influence on the resulting water-cementitious material ratio of the concrete if the fine aggregate has a grading within the normally accepted limits and its grading is taken into account in selecting concrete proportions.

Coarse aggregate shape and texture also affect mixing water requirement and water-cementitious material ratio in a manner similar to that of fine aggregate. However, coarse aggregate particles, due to their much smaller ratio of surface area to volume, affect strength through a more complex relationship of aggregate to cement paste bonding properties and concrete water-cementitious material ratio. Therefore, the effects of aggregate shape and texture on the strength of hardened concrete should not be overgeneralized.

It has been demonstrated that the 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 to similar size rounded particles. 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 type of surface texture of the largest pieces, which affects its bond strength per unit of surface area. The mineralogy and crystal structure of these pieces will affect bond strength.

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

4. Maximum size of the aggregate. For a given water-cementitious material ratio, as the size of the larger particles is increased, the likelihood of a paste to aggregate bond failure increases since stresses at the interface will be 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 to rounded sands are of no particular benefit to bond strength. This leads to the conclusion that fine aggregate shape and texture affect the amount of mixing water required for a given slump level and that the effects of different fine aggregates on concrete strength can be predicted from a knowledge of their effects on mixing water and water-cementitious material ratio.

For a coarse aggregate, 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 will produce different water-cementitious material ratio versus strength curves. For example, in very high strength concrete mixtures where coarse aggregate bond is critical, it has been found that angular cubical-shaped coarse aggregate will generally give better strengths than either rounded smooth aggregates or those with a large proportion of flat or elongated pieces, and that smaller maximum size aggregates, such as the 12.5 or 19 mm (1/2 or 3/4 in.) fractions, will give better results than 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 water-cementitious material ratio required to provide the needed strength.

3.6—Abrasion and impact resistance

3.6.1 *Definition and significance*—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 degradation of coarse aggregate by abrasion and impact is the Los Angeles machine method [ASTM C 131 for aggregate smaller than 37.5 mm (1-1/2 in.) but greater than 2.36 mm (No. 8 sieve opening), and ASTM C 535 for aggregates larger than 19 mm (3/4 in.) but less than 75 mm (3 in.)]. This test 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 standard size steel balls. The drum is rotated for 500 or 1000 revolutions with a shelf inside the drum causing a tumbling and dropping of 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 percent mass loss. ASTM C 33, "Concrete Aggregates," specifies a maximum mass loss of 50% for gravel, crushed gravel, or crushed stone. However, comparisons of results of aggregate abrasion tests with those of abrasion resistance of concrete do not generally show a direct correlation. The abrasion resistance of concrete is generally related to compressive strength.

3.7—Soundness

3.7.1 *Definition and mechanism of deterioration*—Soundness of an aggregate refers to its ability to withstand the aggressive actions, particularly those due to weather, to which the concrete containing it might be exposed. 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 the pores are nearly completely filled, it would 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. The amount of pressure developed will depend upon the rate of freezing and the particle size above which the particle will fail if completely saturated. This critical size will depend upon the porosity or 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 chert), the critical particle size may be in the range of normal aggregate sizes. It is higher for coarse-grained ma-

Fig. 6—Popout due to unsound aggregate particle.

terials 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.

3.7.2 *Test methods*—Several methods have been used to predict the performance of aggregates under exposure to freezing and thawing. Evaluation of past performance is one method. If aggregates from the same source have previously given satisfactory service when used in concrete, the aggregate may be considered suitable. 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 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 a number of cycles of immersion of a sample of the aggregate in a sulfate solution, oven-drying the sample, and determining the percentage of mass loss. This test sometimes produces inconsistent results. Aggregates behaving satisfactorily in the test may produce concrete having low freeze-thaw 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 confined in cement paste as they would be in a field situation.

3.7.3 *Popouts*—A popout is the breaking away of a small portion of a concrete surface due to internal pressure which leaves a shallow, usually conical depression, as shown in Fig. 6. Popouts result from freezing and thawing of porous aggregate that is critically saturated or from alkali-silica reaction. Due to the critical size effect mentioned earlier, popouts caused by freezing can sometimes be minimized by reducing the maximum aggregate size used. In other instances, however, it is necessary to remove harmful substances such as chert, coal, or lignite that also cause popouts.

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

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, primarily from the cement. 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 solution and react with the 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 chert, 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, and acid to intermediate glassy volcanic rocks. Some phyllites, argillites, micaceous 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 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. 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 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, there are several ASTM tests for identifying reactive aggregates.

ASR tests:

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. The mortar bar test can be used for either fine or coarse aggregates, but three to six months must elapse before conclusions can be drawn.

ASTM C 289, known as the quick chemical test, is used for identifying potentially reactive siliceous aggregates. It can be completed in 24 hr. 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 that was developed to supplement lengthier test methods. In this test, mortar bars are stored in a strong alkaline solution of sodium hydroxide at an elevated temperature. The potential for reactivity is based on the length change of the mortar bars after two weeks of immersion in the alkaline solution.

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 75 x 75 x 250 mm (3 x 3 x 10 in.), are placed in containers at a prescribed temperature and humidity, similar to that used in ASTM C 227. Expansion measurements are carried out for 1 year, although longer test periods have sometimes been used.

There is considerable controversy about the decision that might be reached regarding the potential reactivity of an aggregate by these test methods. ASTM C 227 seems to correlate well with field performances for rapidly reacting siliceous aggregates, but it has been known to give false indications with slowly reactive aggregates (showing distress in field structures) within the test period. 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. It will identify slow reacting aggregates that are not so identified by ASTM C 227, but it has also caused aggregates with a good service record to be identified as potentially reactive. 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.

ACR tests:

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 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 alkalies. It has been proven in laboratory tests and field performance 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. However, some pozzolans have shown lesser ability to prevent excessive expansion. It is necessary to evaluate, by testing, the ability of a given pozzolanic material or ground granulated blast-furnace slag to control ASR, and an accelerated test, ASTM C 441, is usually used to determine the reduction in expansion of a bar made from mortar containing pozzolans or slag. Another option to control ASR expansion is to use a low-alkali cement. The rejection of a potentially reactive aggregate should be resorted to after all other available options are exhausted. In very rare instances, the best course of action may be to choose a different aggregate.

On the other hand, expansions due to ACR cannot be easily controlled by modifying the concrete mixture. Pozzolans and slag do not seem to control excessive expansions due to ACR. Cement with an alkali content less than 0.4% (sodium oxide equivalent) has been recommended in some cases. Controlling expansions due to ACR is best handled 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

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 be naturally occurring constituents in the aggregate or can be contaminants resulting from the transportation of aggregates in gondola cars, barges, and trucks that were previously used to haul coal or other harmful substances.

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

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 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 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 hr. The color of the liquid above the sample is then compared with a standard color. If the liquid's color is darker than the standard, the sand is considered to contain injurious organic compounds and further tests should be made before approving it for use in concrete. Since all organic materials resulting in a positive reaction (dark color) are not necessarily harmful, a test (ASTM C 87) is usually conducted to determine the effect of the impurities on strength. Mortar cubes are made using the questionable sand, and a sample of the same sand that has been washed in sodium hydroxide to remove the organics. After 7 days of curing, the cubes are broken in compression. The strength of cubes containing the questionable sand is then divided by the strength of cubes containing washed sand, and if this strength ratio is at least 0.95, the sand is considered to be of suitable quality.

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 5% for fine aggregate used in all other concrete. However, for manufactured sands in which the fines are free of clay or shale, the limits are increased to 5 and 7%, respectively. Similarly, material passing the 75 μm (No. 200) sieve is limited to 1% for coarse aggregate, except that for crushed aggregates the percent may be increased to 1.5, provided that 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 with respect to 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 were 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 is used.

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 presented as evidence of 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 a pattern of variations in these properties. Knowledge of both the average properties and variability may be important. For example, suppose that there are two lots of sand and the fineness modulus of each is needed to be known. A single sample could be taken from each lot, a sieve analysis conducted, and the fineness modulus calculated. In both cases, assume the fineness modulus is 2.70. It can be now said that both samples have the same fineness modulus, but what can be said about the lots? Is it reasonable to say that the sand in each lot has a fineness modulus 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 moduli 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 a fineness modulus of 2.70. Something else about the lots must be found, 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 A, the fineness modulus ranges only from 2.63 to 2.75, while in Lot B, it ranges from 2.47 to 2.95. Concrete made with sand from this lot is likely to be variable in quality since aggregate fineness affects slump if water content is held constant. Thus, using the sand from Lot A would be preferable.

To repeat, test results on samples tell us about the average properties of an aggregate and may also indicate the variability in these properties. Decisions to accept or reject an aggregate must be made based upon the test results, and reasonable decisions can be made only if the sampling is done correctly and in accordance with a sampling plan.

4.2.3 *Sampling plans*—Detailed discussion of the formulation of a sampling plan is beyond the scope of this bulletin. The choice for a particular plan will be dependent upon the sampling situation and upon the information to be extracted from the measurements on the sample. For instance, one might be interested in finding only the average gradation or might want the average gradation and the variation in gradation within a lot of aggregate being tested. A mastery of the fundamentals of probability sampling is required, as well as knowledge of the product being sampled, to devise the plan. 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 References section of this bulletin.

4.2.4 *Sampling methods*—Methods of selecting samples of aggregates are described in ASTM D 75, "Standard Methods of Sampling Aggregates." Samples may be taken from conveyor belts, flowing aggregate streams, or stockpiles, but preferably from conveyor belts or flowing aggregate streams. In sampling from a conveyor belt, three approximately equal increments 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. Two templates are spaced and inserted such that the material contained between them yields an increment of the required weight. All material between the templates is carefully scooped into a suitable container and fines on the belt 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, and this usually requires the construction of a specially built pan large enough to intercept the entire cross section and to hold the required amount of material without overflowing.

Sampling from stockpiles should be avoided whenever possible, particularly when the sampling is done for the purpose of determining aggregates properties that may be dependent upon the grading of the sample. When it is mandatory to obtain samples 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 number of field samples required depends upon the criticality of, and variation in, the properties to be measured. Guidance for determining the number of samples required to obtain the desired level of confidence in test results may be found in the previously mentioned ASTM Recommended Practices E 105, E 122, and E 141. The unit of material represented by a single sample may vary widely, but usually, it is approximately 45 tonnes (50 tons).

Field sample size must be based upon the type and number of tests to which the material is to be subjected; sufficient material is necessary to provide for the proper execution of these tests. Minimum sample size varies with nominal maximum size of the aggregate and tentative 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 by 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 a small amount of some materials (such as that adhering to sugar or fertilizer sacks) may cause serious contamination. Also, the container should be tight to prevent either contamination or loss of fines. The sample should be identified clearly, inside and outside the container; information should be given as to the date, kind of aggregate, quantity represented by sample, location and other conditions of sampling, authority or reason for test, and kind of test desired.

CHAPTER 5—BLAST-FURNACE SLAG AND LIGHTWEIGHT AGGREGATES

5.1 Blast-furnace slag

5.1.1 *Definition*—Blast-furnace slag is a nonmetallic product that develops in a molten condition simultaneously with iron in a blast-furnace. Air-cooled slag is produced by pouring molten blast-furnace slag into pits or banks and permitting it to cool and solidify slowly under atmospheric conditions. It is usually crushed and screened into a variety of sizes. The application of a controlled amount of water, steam, or compressed air to molten slag produces expanded blast-furnace slag that is used as a lightweight aggregate. If the molten blast-furnace slag is suddenly quenched in water, granulated slag is produced. Only air-cooled and expanded slags are used as concrete aggregates. Expanded slags are discussed in the section on lightweight aggregates, and the remaining portion of this section deals with air-cooled slag.

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

Crushed slag is roughly cubical in shape and has a rough surface texture. ASTM C 33, "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).

Use of an air-entraining agent or air-entraining cements with slag is recommended as an aid to workability and for durability in concretes exposed to freezing and thawing. This is especially true when slag concrete is to be pumped. It is also desirable to have the slag close to a saturated surface-dry condition before adding mixing water to ensure that little of the mixing water is absorbed by the coarse aggregate.

5.1.3 *Availability*—Air-cooled blast-furnace slag is available primarily in areas around steel producing centers. The difference in price compared with natural aggregate is variable. In some slag producing areas, slag is more expensive, while in others, it costs less than natural aggregate.

5.2 Lightweight aggregates

5.2.1 *Definition of lightweight concrete*—Lightweight concrete is concrete of substantially lower bulk density than that made from gravel or crushed stone. The lower bulk density is produced by using lightweight aggregates that may be naturally occurring or processed materials. There are many types of aggregates available that are classed as lightweight, and they may be used in low-density, structural, or moderate strength concretes.

5.2.2 *Lightweight concrete types and aggregate production*—Low density concretes are especially light in mass, seldom exceeding 800 kg/m^3 (50 lb/ft^3), and are employed chiefly for insulation purposes. Thermal insulation values are high, but 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 platy 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 that contains sufficient combined water to generate steam internally when heated quickly; this causes disruptive expansion and breakage 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).

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). Insulation efficiency is lower than that for low-density concretes, but substantially better than that for normal-weight 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. Expanded slag is produced either by rapidly agitating molten blast-furnace slag in a machine with a controlled amount of water, or by treating the molten slag with a controlled amount of water forced into the mass in jets under high pressure. In both processes, the material is subsequently cooled and crushed.

In the sintering process, either crushed or pelletized aggregates can be produced. To form crushed aggregates, raw materials are used that contain either carbonaceous matter that serves 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 clinker formed is then cooled, crushed, and screened to required aggregate gradings. The finished product tends to be generally sharp and angular with a vesicular or porous surface texture. In a variation of the sintering process, clay, pulverized shale or fly ash is mixed with moisture and fuel and then pelletized or extruded before burning. The resultant product tends to be generally rounded or cylindrical in shape.

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 long nearly horizontal cylinder lined with refractory materials. Due to the slow rotation and slope of the kiln, the material progresses to the lower or burner end, and the heat causes a simultaneous softening and formation of gases that are trapped to form an internal cellular structure. In one variation of the process, the 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 to have a vesicular surface texture. In another variation, raw material is presized by crushing and screening or by pelletizing before introduction into the kiln and the individual particles are bloated without sticking together. The resultant particles tend to have a smooth shell over the cellular interior. Frequently, there is a combination of the two procedures in which most of the coarse aggregate will consist of uncrushed particles, obtained by screening, and most of the fine particles are obtained by crushing the fired product.

Moderate strength lightweight concretes fall approximately midway between low-density and structural concretes with respect to density and strength, and are sometimes designated as "fill" concrete. These are usually made with pumice or scoria as aggregates. Pumice is a spongy lava from which steam or gas escaped while it was still hot. Scoria is a volcanic cinder with pores chiefly in the form of vesicles or isolated cavities instead of the more tube-like, interconnected pores of the pumices.

5.2.3 *Properties*—Due to their cellular structure, the bulk specific gravity of lightweight aggregates is lower than that of normal weight aggregates. The bulk specific gravity of lightweight aggregates also varies with particle size, being highest for the fine particles and lowest for the coarse particles. This is because, during crushing, larger voids are destroyed and the finer lightweight aggregates thus have a 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 reproducing a saturated surface-dry state. Thus, in designing concretes using lightweight aggregates, a specific gravity factor is used in lieu of the bulk specific gravity. This factor is found in the same way as the bulk specific gravity SSD, previously described, except that the Mass B is the mass of the aggregate at the stockpile moisture, and mass of the sample in water is measured at a specific number of minutes after immersion.

The bulk density of structural lightweight aggregate is significantly lower than that of normal mass aggregates, normally ranging from 480 to 1040 kg/m^3 (30 to 65 lb/ft^3), while the fines generally weigh 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, that is, as specific gravity increases, bulk density increases. Since aggregates are usually batched by mass, but the volume occupied by the aggregate is the critical factor affecting yield or volume of concrete produced, bulk density of the lightweight aggregate is generally checked daily. Variations in bulk density indicate that the concrete yield may also vary since it is assumed that specific gravity changes are responsible for the variation in bulk density. However, it should be remembered that changes in grading or in particle shape can produce changes in bulk density, even though specific gravity of each individual size remains constant.

Particle shape and surface texture can vary considerably for lightweight aggregates produced by different methods. Shape will usually be reasonably equidimensional but may range from rounded to 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 will affect workability, water requirement, cement content, etc., just as they do for normal-weight aggregates.

In general, grading requirements for lightweight aggregates are similar to those for normal mass aggregates. However, lightweight aggregates require a larger percentage by mass of material retained on the finer sieve sizes since 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.). The sieve analysis is conducted as for normal aggregates, except that the mass of the fine aggregate test sample is reduced and the sieving time for mechanical sieving is only 5 min. These modifications are intended to prevent clogging of the smaller sieves with an excessive volume of material and to prevent breakage of the more friable particles during sieving. The size of the test sample for coarse aggregate is set at 3 L (0.10 ft^3) minimum.

Lightweight aggregates, due to their cellular structure, are capable of absorbing more water than normal mass aggregates. Based on a 24-hr 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 will not exceed two-thirds of the 24-hr absorption. This means that lightweight aggregates will usually absorb water when placed in the mix, and the rate of absorption is an important consideration in proportioning lightweight concrete. For further information on proportioning lightweight concrete, the reader is referred to ACI Standard 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 be dependent upon the aggregate itself. The concept of “strength ceiling” may be useful in this regard. A mix is near its strength ceiling when similar mixes containing the same aggregates and with higher cement contents have only slightly higher strengths. It is the 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. It has been found that the strength ceiling can be increased appreciably by reducing the maximum size of the coarse aggregate for most lightweight aggregates, especially the weaker and more friable ones. However, as maximum size of the aggregate is decreased, the density of the concrete will increase.

CHAPTER 6—SELECTED BIBLIOGRAPHY ON AGGREGATES

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C 29, “Test for Density (unit weight) of Aggregate.”

C 33, “Specifications for Concrete Aggregates.”

C 40, “Test for Organic Impurities in Sands for Concrete.”

C 87, “Test for Effect of Organic Impurities in Fine Aggregate on Strength of Mortar.”

C 88, “Test for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate.”

C 117, “Test for Materials Finer than No. 200 Sieve in Mineral Aggregates by Washing.”

C 123, “Test for Lightweight Pieces in Aggregate.”

C 131, “Test for Resistance to Abrasion of Small Size Coarse Aggregate by Use of the Los Angeles Machine.”

C 136, “Test for Sieve or Screen Analysis of Fine and Coarse Aggregates.”

C 142, “Test for Clay Lumps and Friable Particles in Aggregates.”

C 227, “Test for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method).”

C 289, “Test for Potential Reactivity of Aggregates (Chemical Method).”

C 295, “Recommended Practice for Petrographic Examination of Aggregates for Concrete.”

C 330, “Specifications for Lightweight Aggregates for Structural Concrete.”

C 342, “Test for Potential Volume Change of Cement-Aggregate Combinations.”

C 535, “Test for Resistance to Abrasion of Large Size Coarse Aggregates by Use of the Los Angeles Machine.”

C 586, “Test for Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregates (Rock Cylinder Method).”

D 75, “Sampling Aggregates.”

ASTM STP 169 C, “Significance of Tests and Properties of Concrete and Concrete-Making Materials,” American Society for Testing and Materials, Philadelphia, 1994.

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CHAPTER 7—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 which 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.

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 portland cement concrete, the binder is a mixture of portland 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 retained on 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.

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.

Popout—The breaking away of small portions of a concrete surface due to internal pressure which leaves a shallow, typically conical, depression.

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

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 certain 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.

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—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 which determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished.

Unit weight—For aggregate, the mass per unit volume (deprecated term—use preferred term “bulk density”).

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.