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Aggregates for Concrete

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Aggregates for Concrete

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Aggregate properties and gradation significantly affect workability and finishability of freshly placed concrete and properties of hardened concrete including compressive strength, durability and abrasion resistance. Properties and accepted test methods discussed in this bulletin include: aggregate gradation; fine and coarse aggregate fineness moduli; relative bulk densities of wet, saturated surface dry, air-dry, and oven-dry aggregates; moisture absorption; shape angularity and surface texture; abrasion and impact resistance; permeability resistance to freeze thaw cycles and alkali-silica reaction; and chemical stability. Aggregate types including normalweight, lightweight and heavyweight natural aggregate; blast furnace slag aggregates; and recycled aggregates from crushed reclaimed concrete pavements are covered. Examples are provided on how to calculate and evaluate fineness modulus, batch mixture proportions adjusted for aggregate absorption, batch mixing water proportions, water cementitious ratios and bulk densities. Sampling aggregate methods to estimate average aggregate properties of large volumes or stockpiles, batches, or truckloads of aggregates are also covered.

Keywords: abrasion resistance, absorption, aggregate angularity, aggregate gradation, aggregate surface texture, air-dry bulk density, alkali-silica reaction, batch mixture proportioning, blast-furnace slag aggregate, bulk density, compaction, fineness modulus, heavyweight aggregate, lightweight aggregate, mixing water, normalweight aggregate, oven-dry bulk density, recycled aggregate, relative bulk density, saturated surface-dry bulk density, sampling, surface moisture, water-cementitious ratio.

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CONTENTS

CHAPTER 1—INTRODUCTION, p. 2

CHAPTER 2—CLASSIFICATION OF AGGREGATES, p. 2

CHAPTER 3—AGGREGATE PROPERTIES AND TEST METHODS, p. 2

- 3.1—Grading, p. 2
- 3.2—Relative density (specific gravity), p. 8
- 3.3—Absorption and surface moisture, p. 10
- 3.4—Bulk density, p. 16
- 3.5—Particle shape and surface texture, p. 17
- 3.6—Abrasion and impact resistance, p. 18
- 3.7—Soundness, p. 19
- 3.8—Chemical stability, p. 20
- 3.9—Harmful substances, p. 21

CHAPTER 4—SAMPLING AGGREGATES, p. 22

- 4.1—Variability in aggregates, p. 22
- 4.2—Sampling, p. 22

CHAPTER 5—BLAST-FURNACE SLAG AND LIGHTWEIGHT AGGREGATES, p. 23

- 5.1—Blast-furnace slag, p. 23
- 5.2—Lightweight aggregates, p. 23
- 5.3—Recycled aggregates, p. 25

CHAPTER 6—REFERENCES, p. 26

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CHAPTER 1—INTRODUCTION

Concrete is a mixture of hydraulic cement, aggregates, and water, with or without admixtures, fibers, or other cementitious materials. Aggregates are granular materials such as sand, gravel, crushed stone, crushed hydraulic-cement concrete, or iron blast-furnace slag. Coarse aggregate is that portion retained on the 4.75 mm (No. 4) sieve. Fine aggregate is that portion passing the 4.75 mm (No. 4) sieve and predominantly retained on the 75 μ m (No. 200) sieve. Aggregate classifications include normalweight, lightweight, or heavyweight. The selection of aggregate to be used for concrete mixtures depends on the intended concrete properties. For instance, heavyweight aggregates such as barite, magnetite, hematite, limonite, ilmenite, iron, or steel are used in heavyweight concrete mixtures. Heavyweight concrete is used for applications such as radiation shielding, ballast for offshore pipelines, or other similar applications. Lightweight aggregate, such as expanded or sintered clay, shale, slate, diatomaceous shale, perlite, vermiculite, slag, pumice, scoria, volcanic cinders, tuff, diatomite, sintered fly ash, or industrial cinders, are used in lightweight concrete applications.

Coarse and fine aggregate constitute approximately 60 to 75 percent of the concrete mixture. Therefore, the properties of the aggregates have a significant influence on the properties of the concrete mixture. Aggregate properties significantly affect the workability of plastic concrete, and the durability, strength, volume stability, 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, lightweight, and heavyweight aggregates are discussed.

CHAPTER 2—CLASSIFICATION OF AGGREGATES

Aggregates may be broadly classified as natural or manufactured, 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 whereas manufactured crushed fine aggregate and crushed stone are produced by crushing natural stone. Screening and washing may be used to process either natural or manufactured aggregates. 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 or in a specification should be based on specific information obtained from tests used to measure the aggregate quality, its service record, or both. A typical consensus specification for both fine and coarse concrete aggregate is [ASTM C33/C33M](#).

Manufactured aggregates may be either by-products 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 on bulk density (previously termed unit weight) ([ASTM C33/C33M](#); [ASTM C330/C330M](#); and [ASTM C637](#)), mineralogical composition ([ASTM C294](#)), and particle shape; 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 C136/C136M](#), “Sieve Analysis of Fine and Coarse Aggregates.” A representative sample of the aggregate that has been properly prepared 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. 3.1.1a](#)). 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 3.1.1a](#), and various physical properties of normalweight aggregates, with typical range values, are shown in [Table 3.1.1b](#).

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 μ m (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 C33/C33M](#), “Standard Specification for Concrete Aggregates,” lists several such size groups using the simplified practice



Fig. 3.1.1a—Nest of sieves.

Table 3.1.1a—Sieves commonly used for concrete aggregate sieve analysis

ASTM E11 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

*Note: 1000 μm = 1 mm.

Table 3.1.1b—Ranges in physical properties for normalweight aggregates used in concrete

Property		Typical ranges
Fineness modulus of fine aggregate		2.0 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 percent
Bulk relative density (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 percent
	Fine aggregate	0 to 10 percent

*Previously dry-rodded unit weight.

recommendation (SPR) number designation. The number and size of sieves selected for a sieve analysis depends on the particle sizes present in the sample and the grading requirements specified. After sieving, the mass of material retained on each sieve and in the pan is obtained using a balance accurate to 0.1 percent of the test-sample mass. Results are recorded in tabular form and typically reported as mass retained on each sieve, individual percent retained on each sieve, cumulative percent retained, and cumulative percent passing each sieve. For an accurate determination of the amount of material finer than the 75 μm (No. 200) sieve, a specimen is tested in accordance with [ASTM C117](#).

Grading charts are drawn to show the results of a sieve analysis graphically. The percent passing is usually plotted on the vertical axis whereas the sieve sizes are plotted on the horizontal axis. Upper and lower limits specified for the allowable percentage of material passing each sieve may also be included on the grading chart. [Figure 3.1.1b](#) shows a typical grading chart for coarse and fine aggregates having grading calculated in [3.1.1.1](#) and [3.1.1.2](#). Combined gradation charts, which illustrate the particle size distribution for a mixture of fine and coarse aggregate, are useful in concrete mixture optimization. Combined gradation charts can identify gaps or deficiencies and an excess in a particular size range.

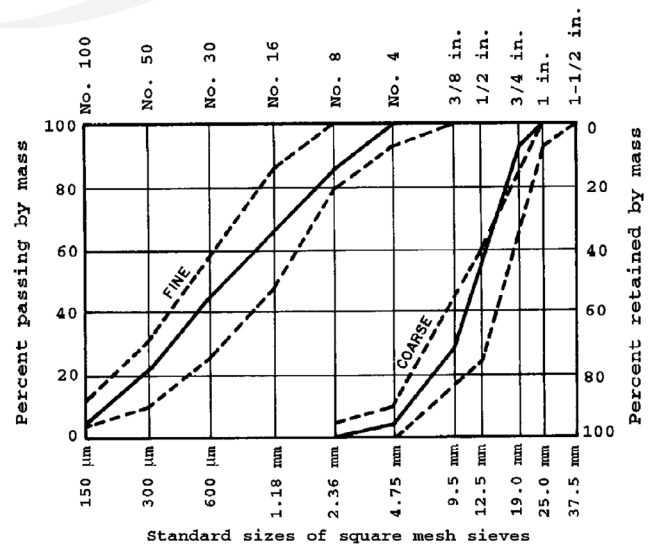


Fig. 3.1.1b—Typical grading chart. Dashed lines indicate limits specified in [ASTM C33/C33M](#) for fine aggregates and for 25.0 mm (1 in.) coarse aggregate.

3.1.1.1 Example calculation for sieve analysis of fine aggregate—A sample of fine aggregate with a mass of

Table 3.1.1.1—Example calculation for sieve analysis of fine aggregate

Sieve size	Individual mass retained, g (lb)	Individual percent retained	Cumulative percent retained	Cumulative percent passing
9.50 mm (3/8 in.)	0 (0)	0	0	100
4.75 mm (No. 4)	9.2 (0.020)	2	2	98
2.36 mm (No. 8)	67.6 (0.149)	13	15	85
1.18 mm (No. 16)	101.2 (0.223)	20	35	65
600 µm (No. 30)	102.2 (0.225)	20	55	45
300 µm (No. 50)	120.5 (0.266)	24	79	21
150 µm (No. 100)	93.1 (0.205)	18	97	3
75 µm (No. 200)	10.2 (0.022)	2	99	1
Pan	4.5 (0.010)	1	100	0
Total	508.5 (1.120)	100	—	—

Notes: Total of masses retained may differ from original sample mass. Because mass of material on each sieve is determined to within 0.1 percent of the total sample mass, maximum difference should not exceed 0.1 percent times the number of mass determinations. In this example, seven mass determinations were made, so the difference should not exceed 0.7 percent. The total of masses retained differs from the mass of the original sample by 2 g, or only 0.4 percent. 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 sieve openings. Normally, sieve analysis calculations are recorded to the nearest 0.1 percent and then reported to the nearest 1 percent, except for the percent passing the No. 200 (75 µm), which is reported to the nearest 0.1 percent.

Table 3.1.1.2—Example calculation for sieve analysis of coarse aggregate

Sieve size	Individual mass retained, g (lb)	Individual percent retained	Cumulative percent retained	Cumulative percent passing
25.0 mm (1 in.)	0 (0)	0	0	100
19.0 mm (3/4 in.)	405 (0.89)	5	5	95
12.5 mm (1/2 in.)	2850 (6.28)	35	40	60
9.5 mm (3/8 in.)	2435 (5.37)	30	70	30
4.75 mm (No. 4)	2030 (4.48)	25	95	5
2.36 mm (No. 8)	375 (0.83)	5	100	0
Pan	35 (0.08)	0	100	0
Total	8130 (17.93)	100	—	—

510.5 g (1.125 lb) is passed through the sieves shown in [Table 3.1.1.1](#) and the masses retained on each sieve are as shown.

The total mass of the material after sieving should check closely with the original mass of the sample placed on the sieves. If the amounts differ by more than 0.3 percent, 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.

Cumulative percent retained is calculated by successively summing the numbers in the individual percent retained column. The cumulative percent passing is calculated by subtracting the cumulative percent retained from 100.

3.1.1.2 Example calculation for sieve analysis of coarse aggregate—A sample of coarse aggregate with a mass of 8145 g (17.96 lb) is passed through the sieves shown in [Table 3.1.1.2](#) and the masses retained on each sieve are as shown.

The total of masses retained differs from the original sample mass. Six mass determinations were made so the difference should not exceed 0.6 percent of the total sample mass. The total of masses retained differs from the original sample mass by 15 g (0.033 lb) or only 0.2 percent. Refer to [3.1.1.1](#) 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 [3.1.1.1](#).

If the test sample was first tested by the [ASTM C117](#) 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—Fineness modulus is often computed using the sieve analysis results. The fineness modulus is the sum of the total percentages coarser than 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, 1-1/2, 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 in the following. 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 per [ASTM C33/C33M](#). In some regions, finer or coarser sands are used in concrete mixtures with fineness modulus of 2.0 and 3.1, respectively.

3.1.2.1 Example calculation of fineness modulus for fine aggregate—Although fineness modulus is most commonly computed for fine aggregates ([Table 3.1.2.1](#)), 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 [1 and 1/2 in.] sieves) and to include all of the specified finer sieves.

3.1.2.2 Example calculation of fineness modulus for coarse aggregate is shown in [Table 3.1.2.2a](#)—Although the 25 and 12.5 mm (1 and 1/2 in.) sieves were used in the sieve

Table 3.1.2.1—Example calculation of fineness modulus of fine aggregate

Sieve size	Total percent retained
9.5 mm (3/8 in.)	0
4.75 mm (No. 4)	2
2.36 mm (No. 8)	15
1.18 mm (No. 16)	35
600 μ m (No. 30)	55
300 μ m (No. 50)	79
150 μ m (No. 100)	97
Sum	283

Notes: Fineness modulus = $283/100 = 2.83$.

All of the sieve sizes for determining fineness modulus below the maximum size (in this case nothing retained on the 9.50 mm [3/8 in.]) should be included and all other sieves not used for determining fineness modulus should be excluded. For example, if a 75 μ m (No. 200) or 12.5 mm (1/2 in.) sieve were included in the sieve analysis, the cumulative percent retained on those sieves would not be included in the fineness modulus calculation.

analysis, they are not included in the calculation. Because the total percent retained on the 2.36 mm (No. 8) sieve was 100 percent, 100 percent will also be retained on the smaller sieves specified in the fineness modulus definition. Thus, the calculation is as shown in Table 3.1.2.2b.

3.1.2.3 Example calculation of grading when two or more aggregates are combined—Three aggregates as shown in Table 3.1.2.3a are combined in the mass percentages indicated. For the given individual aggregate grading, determine the grading of the combined aggregate.

The combined grading is shown in Table 3.1.2.3b. The percent passing is calculated for each of the sieve sizes as follows. Using the 9.5 mm (3/8 in.) sieve as an example, 100 percent of Aggregate 1 passes the 9.5 mm (3/8 in.) sieve, but only 35 percent of this aggregate is used in the mixture. Similarly, only 25 and 40 percent of Aggregate 2 and 3, respectively, are used. Therefore,

- Percent passing of Aggregate 1 in the combined aggregate = 35 percent \times 100 = 35 percent
- Percent passing of Aggregate 2 in the combined aggregate = 25 percent \times 89 = 22 percent
- Percent passing of Aggregate 3 in the combined aggregate = 40 percent \times 2 = 1 percent
- Percent passing the 9.5 mm (3/8 in.) sieve in the combined aggregate = 58 percent
- Percent retained on the 9.5 mm (3/8 in.) sieve in the combined aggregate = $100 - 58 = 42$ percent

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 μ m (No. 200) sieves should not be included in the calculation. Therefore

$$\text{Fineness modulus} = 560/100 = 5.60$$

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

- Percent passing the 25.0 mm (1 in.) sieve = 80 percent
- Percent passing the 19.0 mm (3/4 in.) sieve = 70 percent

Table 3.1.2.2a—Example calculation of fineness modulus of coarse aggregate

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

Table 3.1.2.2b—Example calculation of cumulative percent retained of coarse aggregate

Sieve size	Cumulative percent 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 μ m (No. 30)	100
300 μ m (No. 50)	100
150 μ m (No. 100)	100
Sum	670

Note: Fineness modulus = $670/100 = 6.70$.

- Percent of material between the 25.0 and 19.0 mm (1 and 3/4 in.) sieves = $80 - 70 = 10$ percent
10 percent would be the individual percent retained on the 19.0 mm (3/4 in.) sieve.

3.1.3 Maximum size and nominal maximum size—ACI defines the maximum size as the smallest sieve opening through which the entire amount of aggregate is required to pass. The nominal maximum size of aggregate is defined as the smallest sieve opening through which the entire amount of the aggregate is permitted to pass. Aggregate meeting the specification limits in Table 3.1.3 would have a maximum size of 37.5 mm (1-1/2 in.) and a nominal maximum size of 25.0 mm (1 in.).

3.1.4 Significance of aggregate grading—There are several reasons for specifying both grading limits and maximum aggregate size. The aggregate gradation and content will impact properties such as finishability, workability, pumpability, strength, permeability, and shrinkage. Aggregates having a smooth grading curve and neither a deficiency nor an excess of any one particle size will generally produce mixtures with fewer voids between particles. Because cementitious materials are typically more expensive than aggregates, and the cementitious paste requirement for concrete increases with increasing void content of the combined aggregates, it is desirable to keep the void content as low as possible. If there is not enough fine aggregate to fill the voids between coarse aggregate particles, the space must be filled with cementitious paste. These under-sanded mixtures also tend to be harsh and difficult to finish. On the other hand, aggregate combinations with excessive amounts of fine aggregate or excessively fine sands may produce undesirable concretes because of the larger specific surface area of finer particles.

Table 3.1.2.3a—Example grading of aggregates to be combined

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

Table 3.1.2.3b—Calculations for determining mixture proportions from aggregate given in Table 3.1.2.3a

Sieve size	Aggregate 1	Aggregate 2	Aggregate 3	Combined cumulative percent passing	Combined cumulative percent retained	Individual percent retained for combined aggregate
50 mm (2 in.)	35	25	40	100	0 (not included in fineness modulus calculation)	0
37.5 mm (1-1/2 in.)	35	25	38	98	2	2
25.0 mm (1 in.)	35	25	20	80	20 (not included in fineness modulus calculation)	18
19.0 mm (3/4 in.)	35	25	10	70	30	10
12.5 mm (1/2 in.)	35	25	3	63	37 (not included in fineness modulus calculation)	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 μ m (No. 30)	13	—	—	13	87	9
300 μ m (No. 50)	5	—	—	5	95	8
150 μ m (No. 100)	1	—	—	1	99	4
75 μ m (No. 200)	0	—	—	0	100 (not included in fineness modulus calculation)	1
				Sum	560	

To understand how surface area increases with increasing aggregate fineness, visualize a 25 mm (1 in.) cube of aggregate. As shown in Fig. 3.1.4a, this cube has a surface area of 3750 mm² (6 in.²) and a volume of 15,625 mm³ (1 in.³). If it is cut into eight 12.5 mm (0.5 in.) cubes, the volume does not

change, but the surface area increases to 7500 mm² (12 in.²). 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 mm³ (1 in.³)

Table 3.1.3—Typical specification limits for percent passing of aggregates

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

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 cheap diluents; 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 diluents will reduce the quality of the paint, and buying more paint will increase the cost. Similarly, when the aggregate surface area increases, if the cement paste content is left constant, the thinner layers of paste surrounding the aggregate particles results in a stiffer concrete that is harder to place and compact. If the paste is made more fluid by adding water, the concrete strength and durability will suffer, whereas if more cement and water are added, the cost of the concrete increases. Consequently, it is best to avoid adding too much fine aggregate to a concrete mixture and to avoid using extremely fine sand.

The maximum size of coarse aggregate used in concrete also has an effect on 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. 3.1.4b. 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. An intermediate aggregate can be used to fill gaps that exist in combined coarse and fine aggregates. 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, the nominal maximum aggregate 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 to

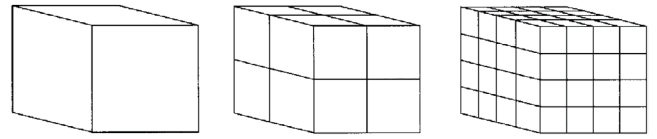
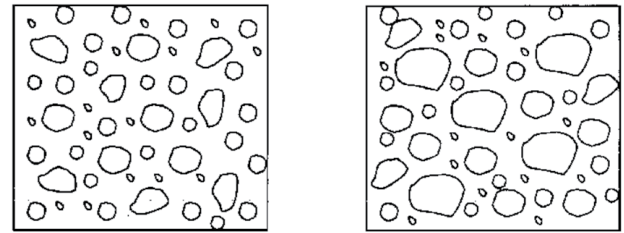


Fig. 3.1.4a—Effect of particle size on aggregate surface area: (a) one 25.0 mm (1 in.) cube of aggregate (surface area = $6 \times 25.0 \times 25.0 = 3750 \text{ mm}^2$ [6 in.²]); (b) eight 12.5 mm (1/2 in.) cubes of aggregate (surface area = $6 \times 12.5 \times 12.5 \times 8 = 7500 \text{ mm}^2$ [12 in.²]); and (c) sixty-four 6.25 mm (1/4 in.) cubes of aggregate (surface area = $6 \times 6.25 \times 6.25 \times 64 = 15,000 \text{ mm}^2$ [24 in.²]).



Well-graded aggregate
12.5 mm (1/2 in.) maximum size

Well-graded aggregate
25 mm (1 in.) maximum size

Fig. 3.1.4b—Effect of increasing maximum size on void content of well-graded aggregate.

minimize the amount of cement required and to minimize shrinkage of the paste.

Aggregates of different maximum sizes, however, may give different concrete strengths for the same water-cementitious materials ratio (w/cm). In many instances, at the same w/cm , 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. Larger aggregate sizes, however, can be used in these instances if the combined aggregate gradation is optimized by using intermediate sizes to fill void spaces between coarse aggregates.

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 material 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 percent to pass the 300 μm (No. 50) sieve, and 2 to 10 percent to pass the 150 μm (No. 100) sieve. **ASTM C33/C33M** permits the lower limits for percent passing the 300 and 150 μm (No. 50 and 100) sieves to be reduced to 5 and 0, respectively. A precautionary note in **ASTM C33/C33M** states that the addition of entrained air, additional cement, or the addition of an approved supplemental cementitious material to supply the deficient fines are methods used to alleviate potential problems with decreased fines.

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 percent passing the 300 μm (No. 50) sieve and 3 percent 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 percent should pass the 300 μm (No. 50) sieve, and 5 to 10 percent should pass the 150 μm (No. 100) sieve. It should be remembered, however, that with a fixed w/cm , 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 workability for the concrete. This is particularly true for high-strength concrete with a high cementitious content.

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 C33/C33M** states that fine aggregate failing to meet the sieve analysis requirements may be accepted. In these cases, the concrete containing the fine aggregate under consideration must demonstrate that the relevant properties are at least equal to those of similar concrete containing another fine aggregate that conforms to the specification requirements. Additionally, the fine aggregate must be selected from a source having an acceptable performance record in similar concrete construction. Once a specific grading is selected, close control should be exercised to minimize variation. If wide variations in coarse aggregate grading occur on a given project, it may be necessary to adjust mixture proportions to produce workable concrete.

Somewhat smaller variations in fine aggregate grading can affect the concrete workability due to the higher surface area. For this reason, **ASTM C33/C33M** states that, for continuing shipments from a given source, the fineness modulus of fine aggregate should not vary by more than 0.20 from the value that is typical of the source (base fineness modulus). If the base fineness modulus 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 will increase. It is often more economical to maintain uniformity in producing and handling aggregates than to adjust proportions for variations in grading.

3.2—Relative density (specific gravity)

3.2.1 Definition—The relative density (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 relative density of 2.50 would thus be two and a half times denser than an equal volume of water.

Each aggregate particle is made up of solid matter and voids that may or may not contain water. Because the aggregate mass will vary with its moisture content, relative density is determined at a constant moisture content. Four moisture conditions are defined for aggregates depending on

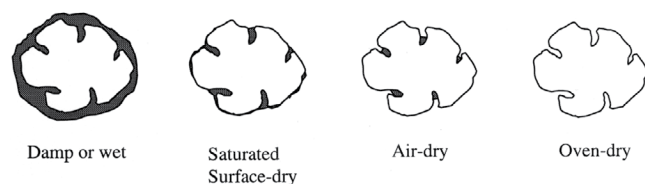


Fig. 3.2.1—Moisture condition of aggregates.

the amount of water held in the pores or on the surface of the particles. These conditions are shown in Fig. 3.2.1 and described as follows:

- Damp or wet—Aggregate in which the pores connected to the surface are filled with water and with free water also on the surface;
- Saturated surface-dry (SSD)—Aggregate in which the pores connected to the surface are filled with water but with no free water on the surface;
- Air-dry—Aggregate that has a dry surface but contains some water in the pores; and
- 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 relative density may be calculated depending on whether the mass used is an oven-dry or an SSD mass. Bulk relative density is the oven-dry mass divided by the mass of a volume of water equal to the SSD aggregate volume whereas bulk relative density SSD is the SSD mass divided by the mass of a volume of water equal to the aggregate volume. Most normalweight (normal density) aggregates have a bulk specific gravity SSD between 2.4 and 2.9.

3.2.2 Relative density test methods—Test methods for finding relative density of aggregates are described in **ASTM C127**, “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregates,” and **ASTM C128**, “Standard Test Method for Density, Relative Density (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 hours. Where the relative density values are to be used in proportioning concrete mixtures in which the aggregates will be in their naturally moist condition, the requirement for initial drying to constant mass may be eliminated, and, if the surfaces of the particles in the sample have been kept continuously wet until test, the 24-hour soaking may also be eliminated. Values for relative density in the SSD condition may be significantly higher for aggregate not oven-dried before soaking and the variation in procedure should be noted in reporting the results. It is then removed from the water and dried to an SSD 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 coarse aggregate sample in air is determined and then placed in a wire basket suspended in water from the bottom of the scale for determination of its mass in water. The mass of the sample in water will be less than that in air and the difference in mass is equal to the mass of the

water displaced. Therefore, the difference 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 relative density and bulk relative density SSD are calculated as follows:

$$\text{Bulk relative density} = \frac{A}{B - C}$$

$$\text{Bulk relative density SSD} = \frac{B}{B - C}$$

where A is the mass of oven-dry sample in air; B is the mass of SSD sample in air; and C is the mass of saturated sample suspended in water.

3.2.2.1 Example relative density 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

$$\text{Bulk relative density} = \frac{3168.5}{3190 - 1972} = 2.60$$

$$\text{Bulk relative density SSD} = \frac{3190}{3190 - 1972} = 2.62$$

Fine aggregate is dried to a constant mass at 100 to 110°C (212 to 230°F), cooled in air, and either moistened to at least 6 percent total moisture and sealed for 24 hours or immersed in water for 24 hours. Where the relative density values are to be used in proportioning concrete mixtures in which the aggregates will be in their naturally moist condition, the requirement for initial drying to constant mass may be eliminated, and, if the surfaces of the particles in the sample have been kept continuously wet until test, the 24-hour soaking may also be eliminated. Values for relative density in the SSD condition may be significantly higher for aggregate not oven-dried before soaking and the variation in procedure should be noted in reporting the results. Immersion has the disadvantage of the potential for losing fines and requires more drying time. 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 an SSD condition. Next, approximately 500 g of the surface-dried material is placed in a glass container and water is added to fill it to its calibrated capacity. The total mass of the glass container, specimen, and water is determined. The fine aggregate is then carefully transferred from the glass container into a pan, oven-dried, and its mass deter-

mined. Finally, the mass of the glass container that is filled with water to its calibrated capacity is determined. The relative density values are then calculated as follows:

$$\text{Bulk relative density} = \frac{A}{B + C - D}$$

$$\text{Bulk relative density SSD} = \frac{B}{B + C - D}$$

where A is the mass of the oven-dry sample in air; B is the mass of the SSD sample in air; C is the mass of the jar or flask filled with water; and D is the mass of the jar or flask with specimen and water to the calibration or filling mark.

3.2.2.2 Example relative density 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

$$\text{Bulk relative density} = \frac{490.7}{501.4 + 647.2 - 953.5} = 2.51$$

$$\text{Bulk relative density SSD} = \frac{501.4}{501.4 + 647.2 - 953.5} = 2.57$$

3.2.3 Significance of relative density (specific gravity)—

The relative density of an aggregate is used in concrete 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 relative densities will cause the yield or volume of concrete to increase or decrease if batch masses remain constant. And because 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 relative density 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. While the relative density of an aggregate is not a measure of aggregate quality, a variation in the relative density may indicate a change in the aggregate characteristics.

3.2.4 Absolute volume calculations—To calculate absolute volume that an aggregate occupies in the concrete mixture, the mass of aggregate is divided by the absolute density (previously termed absolute unit weight), which is the relative density times the density of water, which is 1000 kg/m³ (62.4 lb/ft³).

3.2.4.1 Example 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?

$$\text{Absolute volume} = \frac{47.7}{2.60 \times 1000} = \frac{47.7}{2600} = 0.018 \text{ m}^3 \quad (\text{SI units})$$

$$\text{Absolute volume} = \frac{105.0}{2.60 \times 62.4} = \frac{105.0}{162.2} = 0.647 \text{ ft}^3 \quad (\text{in.-lb units})$$

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

3.2.4.2 Example calculation of volume of a batch of concrete—The masses of materials used to produce a batch of concrete are given in Table 3.2.4.2a. What is the volume of the concrete if the air content is 3 percent? (Air content is the volume of air expressed as a percentage of the concrete volume.)

In in.-lb units:

Table 3.2.4.2a—Mixture proportions for example in 3.2.4.2 (in.-lb units)

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

Table 3.2.4.2b shows calculated absolute volumes.

Table 3.2.4.2b—Calculated absolute volumes

Material	Mass, lb	Relative density	Absolute density, lb/ft ³ = relative density × density of water	Absolute volume, ft ³ = mass/relative density/62.4 lb/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, $V_a = 0.03V_c$; therefore, $V_c = 25.5 + 0.03V_c$.

Therefore, $0.97V_c = 25.5$ and $V_c = 25.5/0.97 = 26.3 \text{ ft}^3$. This batch yields less than 27 ft^3 ; the concrete mixture has under-yielded. To adjust the mixture to obtain 27 ft^3 , additional aggregate, air, or all of the ingredients could be added proportionally.

In SI units:

Table 3.2.4.2a—Mixture proportions for example in 3.2.4.2 (SI units)

Material	Mass, kg	Relative density
Cement	279	3.15
Water	166	1.00
SSD fine aggregate	760	2.60 (bulk SSD)
SSD coarse aggregate	1044	2.63 (bulk SSD)

Table 3.2.4.2b shows calculated absolute volumes.

Table 3.2.4.2b—Calculated absolute volumes

Material	Mass, kg	Relative density	Absolute density, kg/m ³ = relative density × density of water	Absolute volume, m ³ = mass/relative density/1000 kg/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 volume of air content, $V_a = 0.03V_c$; therefore, $V_c = 0.944 + 0.03V_c$.

Therefore, $0.97V_c = 0.944$ and $V_c = 0.944/0.97 = 0.973 \text{ m}^3$. This batch yields less than 1 m^3 ; the concrete mixture has under-yielded. To adjust the mixture to obtain 1 m^3 , either more aggregate, more air, or more of all of the ingredients could be added proportionally.

3.3—Absorption and surface moisture

3.3.1 Mixing water and w/cm—The various moisture conditions in which an aggregate may exist have been described previously. Two of these, oven-dry and saturated surface-dry (SSD), are used as the basis for relative density calculations. Aggregates stockpiled on the job, however, 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 because 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 w/cm. The mixing water in a batch of concrete is all the water present in the concrete with the exception of absorbed water within aggregate particles. Mixing water is the sum of the masses of free or surface moisture on the fine and coarse aggregate and the mass of water added separately, such as through a water meter or weigh batcher at the plant or through a truck mixer water system or added to the mixer by some other means.

The w/cm is the mass ratio of mixing water to cementitious materials. The w/cm is expressed as a decimal fraction by mass, kilogram (pound) of water (excluding that absorbed by the aggregate) divided by kilogram (pound) of cementitious materials.

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

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

Absorption is a measure of the total pore volume accessible to water and is usually calculated using the results from a relative density determination (ASTM C127; ASTM C128).

3.3.2.1 Example 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

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

Total moisture content is measured in accordance with ASTM C566, “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 is the mass of the original sample and W_{OD} is the mass of the dried sample.

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

3.3.3.1 Example calculation of total and surface moisture—An aggregate sample has an absorption of 1.2 percent 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.

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

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

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. This can cause unexpectedly rapid slump loss in the concrete and stiffening of concrete paving mixtures when nonagitating delivery systems are used. For aggregates with unusually high absorption that are batched in an unusually dry state, water equal to the amount absorbed should be added to maintain the intended w/cm and consistency. 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-hour soaking period, although concrete typically sets sooner than this. The use of moisture probes to monitor the aggregate moisture content is useful in adjusting the water in the concrete mixture to compensate for water that will be absorbed by the aggregates.

For techniques to be used in controlling the mixing water and w/cm for mixtures containing highly absorptive aggregates, refer to ACI 211.2-03, “Standard Practice for Selecting Proportions for Structural Lightweight Concrete.”

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

3.3.4.1 Example calculation of mixing water and water-cementitious materials ratio

In in.-lb units:

What is the mixing water content and w/cm for 1 yd³ batch of concrete for the values given in Table 3.3.4.1a?

Table 3.3.4.1a—Mixture proportions for calculating mixing water content and w/cm in in.-lb units

Material	Batch mass, lb
Cement	450
Fly ash	150
Wet sand (absorption 1.0 percent, total moisture content 6.1 percent)	1590
Wet gravel (absorption 0.7 percent, total moisture content 1.3 percent)	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 =

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

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

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

For gravel:

Total moisture content =

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

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

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

Surface moisture content of sand = $6.1 - 1.0 = 5.1$ percent

Surface moisture content of gravel = $1.3 - 0.7 = 0.6$ percent

Free moisture on sand = $0.051 \times 1498 = 76$ lb

Free moisture on gravel = $0.006 \times 1816 = 11$ lb

Total free moisture on aggregate = $76 + 11 = 87$ lb

Mixing water = $242 - 87 = 155$ lb

Water-cementitious materials ratio = $242 / (450 + 150) = 0.40$

These calculations are summarized in [Table 3.3.4.1b](#).

Table 3.3.4.1b—Summary of calculations for example 3.3.4.1 (in.-lb units)

Material	Batch mass, lb	Total moisture, percent	Dry mass, lb	Surface moisture, percent	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

In SI units:

What is the mixing water content and w/cm for the following 1 m³ batch of concrete?

Table 3.3.4.1a—Mixture proportions for calculating mixing water content and w/cm in SI units

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

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

For sand:

Total moisture content =

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

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

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

For gravel:

Total moisture content =

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

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

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

Surface moisture content of sand = $6.1 - 1.0 = 5.1$ percent

Surface moisture content of gravel = $1.3 - 0.7 = 0.6$ percent

Free moisture on sand = $0.051 \times 889 = 45.3$ kg

Free moisture on gravel = $0.006 \times 1078 = 6.5$ kg

Total free moisture on aggregate = $45.3 + 6.5 = 51.8$ kg

Mixing water = $146 + 51.8 = 198$ kg

Water-cementitious materials ratio = $198 / (267 + 89) = 0.55$

These calculations are summarized in [Table 3.3.4.1b](#).

Table 3.3.4.1b—Summary of calculations for example 3.3.4.1 (SI units)

Material	Batch mass, kg	Total moisture, percent	Dry mass, kg	Surface moisture, percent	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
Total:					197.8 (198)

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 SSD masses, and the amount of water indicated is the total mixing water. Because aggregates as batched into the mixtures are very seldom oven-dry or SSD, adjustments must be made in both the masses of aggregates and the quantity of water to be added.

Because total moisture content of the aggregate and absorption are given on the basis of oven-dry aggregate mass, SSD masses should be converted to oven-dry masses before making adjustments. Two examples are given in the following. 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 SSD masses and total mixing water.

3.3.5.1 Example adjustment of batch masses for aggregate moisture

The mass of materials required for 1 yd³ of concrete are given in **Table 3.3.5.1a**.

In in.-lb units:

Table 3.3.5.1a—Mass of materials used for example 3.3.5.1 (in.-lb units)

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

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

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

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

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

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

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

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

Free moisture content = total moisture content – absorption

Fine aggregate = 6.0 – 1.0 = 5.0 percent free moisture

Coarse aggregate = 3.0 – 2.0 = 1.0 percent 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 shown in **Table 3.3.5.1b**.

Table 3.3.5.1c summarizes these calculations.

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

The mass of stockpiled fine aggregate required is calculated by multiplying the total moisture content, expressed as

Table 3.3.5.1b—Final batch masses (in.-lb units)

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

Table 3.3.5.1c—Calculation summary (in.-lb units)

Material	Batch mass, lb	Total moisture, percent	Dry mass, lb	Surface moisture, percent	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

In SI units:

Table 3.3.5.1a—Mass of materials used to for example 3.3.5.1 (SI units)

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

a decimal times the oven-dry mass, and adding this quantity to the oven-dry mass.

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

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

$$\text{Mass of coarse aggregate} = (0.03 \times 1127) + 1127 = 1161 \text{ kg}$$

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

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

Free moisture content = total moisture content – absorption

Fine aggregate = 6.0 – 1.0 = 5.0 percent free moisture

Coarse aggregate = 3.0 – 2.0 = 1.0 percent 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 kg

The final batch masses are shown in [Table 3.3.5.1b](#).

Table 3.3.5.1b—Final batch masses (SI units)

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

[Table 3.3.5.1c](#) summarizes these calculations.

Table 3.3.5.1c—Calculation summary for example in 3.3.5.1 (SI units)

Material	Batch mass, kg	Total moisture, percent	Dry mass, kg	Surface moisture, percent	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)	

3.3.5.2 Example adjustment of batch masses for aggregate moisture

In in.-lb units

The mass of materials required for 1 yd³ of concrete are given in [Table 3.3.5.2a](#). The stockpiled sand has a total moisture content of 6.0 percent and the stone has a total moisture content of 3.0 percent. Compute adjusted batch masses:

Table 3.3.5.2a—Mass of materials used for example in 3.3.5.2 (in.-lb units)

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

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

From the definition of absorption

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

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

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

Free moisture content = total moisture content – absorption

Sand = 6.0 – 1.0 = 5.0 percent free moisture

Stone = 3.0 – 2.0 = 1.0 percent free moisture

Free moisture content of sand = 0.05 × 1300 = 65 lb

Free moisture content of stone = 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

Mass of wet fine aggregate = 1313 (SSD) + 65 = 1378 lb

Mass of wet coarse aggregate = 1938 (SSD) + 19 = 1957 lb

The final batch masses to be used are shown in [Table 3.3.5.2b](#).

Table 3.3.5.2b—Final batch masses (in.-lb units)

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

[Table 3.3.5.2c](#) summarizes these calculations.

Table 3.3.5.2c—Calculation summaries for example given in 3.3.5.2 (in.-lb units)

Material	SSD mass, lb	Batch mass, lb	Total moisture, percent	Dry mass, lb	Surface moisture, percent	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

In SI units:

The following masses of material are required for 1 m³ of concrete. The stockpiled sand has a total moisture content of 6.0 percent and the stone has a total moisture content of 3.0 percent. Compute adjusted batch masses shown in [Table 3.3.5.2a](#).

Table 3.3.5.2a—Mass of materials used for example in 3.3.5.2 (SI units)

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

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

From the definition of absorption

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

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

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

Free moisture content = total moisture content – absorption

Sand = 6.0 – 1.0 = 5.0 percent free moisture

Stone = 3.0 – 2.0 = 1.0 percent free moisture

Free moisture content of sand = 0.05 × 771 = 38.5 kg

Free moisture content of rock = 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

Mass of wet fine aggregate = 779 (SSD) + 38.5 = 817 kg

Mass of wet coarse aggregate = 1150 (SSD) + 11.3 = 1161 kg

The final batch masses to be used are shown in **Table 3.3.5.2b**:

Table 3.3.5.2b—Final batch masses (SI units)

Material	Batch mass, kg
Cement	267
Fly ash	89
Wet fine aggregate	817
Wet coarse aggregate	1161
Water	140

Table 3.3.5.2c summarizes these calculations.

Table 3.3.5.2c—Calculation summaries for example given in 3.3.5.2 (SI units)

Material	SSD mass, kg	Batch mass, kg	Total moisture, percent	Dry mass, kg	Surface moisture, percent	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)

3.3.6 Alternate definition of surface moisture—Some agencies that state desired proportions in terms of SSD aggregate masses prefer to define surface moisture as a percentage of the SSD mass. If surface moisture is given in terms of the SSD mass, there is no need to convert SSD 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 is the original sample mass; usually a wet or damp mass; and W_{SSD} is the SSD mass of the sample.

A method for determining the surface moisture in fine aggregate is described in **ASTM C70**. To use this method, the bulk relative density 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 SSD mass. The formula is as follows:

$$P = \frac{V_s - V_d}{W_s - V_s}$$

where P is the surface moisture in terms of SSD fine aggregate, in percent; V_s is the mass of water displaced (determined either by a mass determination or volumetric method); V_d is the mass of the sample divided by the bulk relative density SSD; and W_s is the mass of the sample. The development of this formula is explained in the appendix to **ASTM C70**.

3.3.6.1 Example 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 relative density SSD of aggregate = 2.60

The bulk relative density 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

$$\text{Surface moisture content \%} = \frac{203 - \left(\frac{500}{2.60} \right)}{500 - 203} \times 100 =$$

$$\frac{203 - 192}{500 - 203} \times 100 = 3.7 \text{ percent}$$

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 relative density of fine aggregate.

3.3.6.2 Example adjustment of batch masses to take aggregate moisture into account given SSD masses

The masses of material required for 1 yd³ of concrete are given in **Table 3.3.6.2a**.

In in.-lb units:

Table 3.3.6.2a—Masses of material for 1 yd³ of concrete in example 3.3.6.2 (in.-lb units)

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 percent and the coarse aggregate surface moisture content (SSD basis) of 0.8 percent.

Compute the adjusted batch masses.

Fine aggregate free moisture = $0.035 \times 1290 = 45$ lb
 Coarse aggregate free moisture = $0.008 \times 1520 = 12$ 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 shown in [Table 3.3.6.2b](#):

Table 3.3.6.2b—Final batch masses (in.-lb units)

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

[Table 3.3.6.2c](#) summarizes these calculations.

Table 3.3.6.2c—Calculation summaries for example given in 3.3.6.2 (in.-lb units)

Material	SSD mass, lb	Surface moisture SSD basis, percent	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	

[Table 3.3.6.2a](#) shows the masses of material required for 1 m³ of concrete.

In SI units:

Table 3.3.6.2a—Masses of material for 1 m³ of concrete (SI units)

Material	Batch 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 percent and the coarse aggregate surface moisture content (SSD basis) is 0.8 percent.

Compute the adjusted batch masses.

Fine aggregate free moisture = $0.035 \times 765 = 26.8$ kg
 Coarse aggregate free moisture = $0.008 \times 902 = 7.2$ 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 = $765 + 26.8 = 792$ kg
 Wet coarse aggregate mass = $902 + 7.2 = 909$ kg

The final batch masses to be used are shown in [Table 3.3.6.2b](#).

Table 3.3.6.2b—Final batch masses (SI units)

Material	Mass, kg
Cement	320
SSD fine aggregate	792
SSD coarse aggregate	909
Total mixing water	159

[Table 3.3.6.2c](#) summarizes these calculations.

Table 3.3.6.2c—Calculation summaries for example given in 3.3.6.2 (SI units)

Material	SSD mass, kg	Surface moisture SSD basis, percent	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	

3.4—Bulk density

3.4.1 Definition and test method—The bulk density (also referred to as unit weight and 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 C29/C29M](#). 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 aggregates in stockpiles, bins, or the amount of aggregate needed in a

compacted aggregate base course, and in some mixture proportioning calculations.

3.4.1.1 Example calculation of the bulk density of an aggregate.

In in.-lb units:

Mass of aggregate and container = 81.1 lb

Mass of container = 28.8 lb

Volume of container = 0.498 ft³

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

In SI units:

Mass of aggregate and container = 36.8 kg

Mass of container = 13.1 kg

Volume of container = 0.0141 m³

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

3.4.2 Factors affecting bulk density—If the moisture content of the aggregate varies, so does its bulk density. For coarse aggregate, increasing moisture content increases the bulk density; however, for fine aggregate, increasing the moisture content beyond the saturated surface-dry (SSD) 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. If volumetric batching is used, however, bulking must be taken into account when moisture content varies.

Other properties that affect the bulk density of an aggregate include grading, relative density, 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 particle size. Higher relative density 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 normalweight concrete generally ranges from 1200 to 1760 kg/m³ (75 to 110 lb/ft³).

3.5—Particle shape and surface texture

3.5.1 Definition—Particle shape includes two properties: compactness and angularity. Compactness is a measure of whether the particle is compact in shape—that is, if it is close to being spherical or cubical as opposed to being flat (disk-like) or elongated (needle-like). Angularity refers to the relative sharpness or angularity of the particle edges and corners. The higher the compactness (the closer the particle is to a sphere or cube), the lower its surface area per unit weight and therefore the lower its demand for mixing water

in concrete and the lower the amount of sand needed in the mixture to provide workability. More angular and less spherical coarse aggregates will require higher mixing water and fine aggregate content to provide a given workability.

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

3.5.2 Test methods—A number of test methods are available to evaluate compactness or surface texture separately or in combination. While no one method has gained universal acceptance, the procedures summarized in the following (or variations thereof) have been widely used. Recently, computerized equipment has been developed to characterize the shape, angularity, and texture, which has been reported through a NCHRP study. In **ASTM D4791**, 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 three (flat particles), or the length-to-width ratio exceeds three (elongated particles).

Other agencies have also used this procedure, sometimes using a ratio of length-to-thickness, which they term flat and elongated particles. In these cases a minimum limit of five is used instead of three. 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 provides no measure of the angularity or roundness of the corners and edges, nor of surface texture.

Another test, the flakiness index, was developed in Britain and involves determining what percentage of a closely sized sieve fraction, such as 19 to 12.5 mm (3/4 to 1/2 in.) particles, will pass through a slotted opening that is only 60 percent of the average size of the size fraction. For example, the average size of the 19 to 12.5 mm (3/4 to 1/2 in.) fraction is 16 mm (5/8 in.), and 60 percent 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 compactness. This procedure is also time consuming because 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 C1252** provides a method for the determination of percent voids in fine aggregate and a similar AASHTO method is available for coarse aggregate.

gate. 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 relative density and the density of water. A percent void is the volume of the container minus the volume of the solid mass of the sample, expressed as a percentage of the container volume. The more angular and rough an aggregate, the greater the percentage of voids. In addition, 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 C1252 includes a procedure for fine aggregate involving the measurement of voids in three separate size fractions, and also a procedure using a fixed grading for both fine and coarse aggregates to obtain companion void percentages related to shape and texture. The concrete mixing water requirement for a given level of workability 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 closely related to percent voids.

Another somewhat tedious procedure involving the handling of each particle is the counting of particles with more than one (or sometimes two) crushed face. 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 D5821**.

3.5.3 Significance of particle shape and surface texture—The shape and surface texture of the individual particles of sand, crushed stone, gravel, slag, heavyweight aggregate, or lightweight aggregate making up the combined aggregate portion of a concrete mixture all have an important influence on the workability of freshly mixed concrete and the strength of hardened concrete. Fine aggregate particle shape and texture influences the workability of fresh concrete. Angular rough fine aggregate require more mixing water in concrete than rounded smooth fine aggregates to obtain the same level of slump or workability, all other factors being equal. This in turn affects the w/cm if the cementitious content is held constant, or an adjustment in the cementitious materials content is necessary if a certain w/cm 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 w/cm 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 and w/cm in a manner similar to that of fine aggregate. Due to their much smaller ratio of surface area to volume, however, coarse aggregate particles affect strength through a more complex relationship of aggregate to cement paste bonding properties as well as w/cm . Therefore, the effects of aggregate shape and texture on the strength of hardened concrete should not be over generalized.

The failure of a concrete strength specimen most often starts with microcracks between the paste or mortar and the surfaces of the largest coarse aggregate particles. This

is a bond failure mode. Angular rough-textured aggregates, for example, have an increased surface area for bond to the cement paste when compared with similar-size rounded particles. Considering all of the factors that have an effect on concrete strength, the following appear to be most important:

- The surface area available for bond to the cement paste; herein, the shape and texture of the largest particles is most important.
- 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 affects bond strength.
- 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, developed at particle surfaces.
- Maximum size of the aggregate; for a given w/cm , as the size of the larger particles is increased, the likelihood of a paste-to-aggregate bond failure increases because stresses at the interface are higher than those for smaller particles.

Factors that give higher intrinsic bond strength are relatively unimportant in fine aggregates because of the large total surface area available for bond and the lower stresses around small particles. Likewise, the larger surfaces of angular sands compared 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 workability level and that the effects of different fine aggregates on concrete strength can be predicted from a knowledge of their reactions on mixing water and w/cm .

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. Different maximum sizes of coarse aggregates, different grading, and different sources of coarse aggregate will produce different w/cm 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 strength 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 w/cm 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 C131/C131M](#) for aggregate smaller than 37.5 mm [1-1/2 in.] but greater than 2.36 mm [No. 8] sieve opening, and [ASTM C535](#) 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 percentage loss of mass. [ASTM C33/C33M](#), “Standard Specification for Concrete Aggregates,” specifies a maximum mass loss of 50 percent for gravel, crushed gravel, or crushed stone. Comparisons of results of aggregate abrasion tests with those of abrasion resistance of concrete do not generally show a direct correlation. The abrasion resistance of concrete is generally related to compressive strength.

The Micro-Deval test ([AASHTO TP 58](#)) for coarse and fine aggregate involves abrasion in water with a charge of steel balls in a rotating drum. The Durability Index of fine and coarse aggregate ([AASHTO T 210](#)) measures the amount of fines created during agitation of the aggregate in a solution.

3.7—Soundness

3.7.1 Definition and mechanism of deterioration—The 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 cycles of freezing and thawing. If an aggregate particle absorbs so much water that the pores are nearly completely filled, it may not accommodate the expansion that occurs when water turns to ice. As ice forms, the resulting expansion pushes unfrozen water through the aggregate pores and the resistance to this flow results in pressures that may be high enough to crack the particle. These pressures may not only cause cracking of the aggregate particle but, in concrete, this pressure may be high enough to also cause cracking throughout the concrete. This is known as D-cracking. The pressure developed depends on the rate of freezing, pore structure of the aggregate particles, and the particle size above which the particle will fail if completely saturated. This critical size depends on the porosity or total pore volume of the aggregate, pore size, 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

materials or those with pore systems interrupted by numerous pores too large to hold water by capillary action. For these materials, the critical size may be too large to be of consequence, even though absorption may be high. Also, if potentially vulnerable aggregates are dry when used or are used in concrete subjected to periodic drying while in service, they may never become sufficiently saturated to cause failure.

3.7.2 Test methods—Several methods have been used to predict the performance of aggregates under exposure to freezing and thawing. The evaluation of performance history 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 C666/C666M](#)), concrete specimens are subjected to alternate cycles of freezing, either in air or water, and thawing in water. The dynamic modulus of elasticity of the specimens is measured by the reduction in the frequency of an energy wave passed through the specimen.

Some specifications may require that resistance to weathering be demonstrated by the sodium sulfate or magnesium sulfate soundness test ([ASTM C88](#)). 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 freezing-and-thawing resistance; conversely, aggregates performing poorly may produce concrete with adequate resistance. This may be attributed in part to the fact that the aggregates in the test are not surrounded by cement paste as they would be in a field situation.

3.7.3 Popouts—Popouts are the breaking away of a small portion of a concrete surface due to internal pressure which leaves a shallow, usually conical depression, with the offending particle or portions of the offending particle at the apex of the conical depression, as shown in [Fig. 3.7.3](#). Popouts result from either freezing and thawing of porous aggregate that is critically saturated or from alkali-silica reaction (ASR). Due to the critical size effect mentioned previously, popouts caused by freezing can sometimes be minimized by reducing the maximum aggregate size used. In



Fig. 3.7.3—Popout due to unsound aggregate particles.

other instances, however, it is necessary to remove harmful substances such as opaline shale, chert, coal, or lignite that also cause popouts.

3.8—Chemical stability

3.8.1 Definition and reaction mechanisms—Aggregates that are chemically stable will not react chemically with cement in a harmful manner nor will they be affected chemically by normal external influences. In some areas, reactions can occur between aggregates made up of certain minerals and alkalis present in concrete, from either internal or external sources. One such reaction, alkali-silica reaction (ASR), involves certain silica minerals found in some aggregates. The process starts when alkalis (sodium and potassium oxide) from concrete ingredients enter the 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. 3.8.1). 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 due to strained or microcrystalline quartz. Refer to **ASTM C294** for a description of aggregate mineralogy.

Another kind of harmful reaction is alkali-carbonate reaction (ACR), which normally results from de-dolomitization 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



Fig. 3.8.1—Cracking caused by abnormal expansion due to alkali-silica reaction.

materials used with the aggregate. If an aggregate has no service record, a petrographic examination (**ASTM C295/C295M**) 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. The ASTM tests that identify reactive aggregates are described in the following.

3.8.2.1 Alkali-silica reaction tests—**ASTM C227**, the mortar bar test, is used to determine the potentially expansive alkali-silica reactivity of cement-aggregate combinations. In this test, the expansion developed in mortar bars during storage under prescribed temperature and moisture conditions is measured. While the mortar bar test can be used for either fine or coarse aggregates, it takes at least 3 to 6 months for the results.

ASTM C289, known as the quick chemical test, is used for identifying potentially reactive siliceous aggregates. It can be completed in 24 hours. Results are based on the degree of reaction (change in alkalinity and amount of dissolved silica) when a crushed specimen of the aggregate in question is placed in a concentrated alkaline solution of sodium hydroxide at a high temperature.

ASTM C1260 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 2 weeks of immersion in the alkaline solution.

ASTM C1567 is similar to **ASTM C1260**, but tests combinations of cementitious materials such as cement, fly ash, natural pozzolans, and slag cement with the aggregates that are being evaluated. The sample preparation and storage conditions are similar to those of **ASTM C1260**.

ASTM C1293, 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 those used in **ASTM C227**. Expansion measurements are carried out for 1 year, although longer test periods have sometimes been used.

Industry consensus has not been reached on the usefulness of using these test methods to assess the potential reactivity of a particular source of aggregate. **ASTM C227** seems to correlate well with field performances for rapidly reacting siliceous aggregates, but it can fail to identify slowly reactive aggregates (showing distress in field structures). **ASTM C289** does not work well with carbonate and siliceous aggregates and is recommended for use only as a screening test. **ASTM C1260** is a severe test and is also recommended as a screening test. It can identify slowly reacting aggregates that are not identified by **ASTM C227**, but also can incorrectly identify aggregates with a good service record. **ASTM C1293** is considered to provide the best correlation with field performance. For the best indication of potential for aggregate

gate reactivity, ASR tests should be performed in conjunction with a petrographic examination of the aggregate. For more information on AAR refer to **ASTM C1778**.

3.8.2.2 Alkali-carbonate reaction tests—ASTM C586, 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 C1105 is a concrete prism test for ACR similar to **ASTM C1293** for ASR. The test is typically run for approximately 6 months, but a 1-year exposure is preferred. Dolomitic aggregates with the potential for causing concrete expansions due to ACR can be identified with relative assurance by an experienced petrographer.

3.8.3 Corrective measures—Several options are available for dealing with aggregates found to be potentially reactive with alkalis. It has been proven in laboratory tests and field performance that expansion due to ASR can be reduced by adding a pozzolan or ground slag as cementitious material to the concrete mixture in sufficient quantities, using a blended cement, or by using a lithium-based admixture. Some pozzolans, however, have shown lesser ability to prevent excessive expansion. It is necessary to evaluate, by testing, the ability of a given pozzolanic material or slag cement to control ASR. An accelerated test (**ASTM C441/C441M**; and **ASTM C1567**) is usually used to determine the reduction in expansion of a bar made from mortar containing pozzolans or slag. **ASTM C1293** is run for 2 years to show mitigation of ASR using pozzolans, slag cement, or blended cements. Although this is a long test, it has generally shown good correlation with field performance. 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.

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 percent (sodium oxide equivalent) has been recommended in some cases. Controlling expansions due to ACR is best handled by the choice of aggregate. Recommended methods include 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. Lubricating oil or grease that is dripped onto aggregates as

they are conveyed is an organic contaminant that can affect concrete properties.

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. Lubricating oil or grease can either increase or decrease the air content in concrete mixtures depending on the oxidation state of the lubricating oil or grease.

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

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

3.9.3 Test methods—The test for organic impurities in sands for concrete (**ASTM C40/C40M**) detects the presence of some injurious organic impurities. In this test, a sodium hydroxide solution is poured over a sample of the sand in a bottle that is then sealed with a stopper, shaken vigorously, and allowed to stand for 24 hours. The color of the liquid above the sample is then compared with a color standard. If the liquid's color is darker than the standard, the sand is considered to contain injurious organic compounds and further tests should be made before approving it for use in concrete. Because all organic materials resulting in a positive reaction (dark color) are not necessarily harmful, a test (**ASTM C87/C87M**) is usually conducted to determine the effect of the impurities on strength. Mortar cubes are made using the questionable sand and 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 C117**) and determining the resulting difference in mass as a percentage of the original sample weight. **ASTM C33/C33M** limits the percentage of material finer than a 75 μm (No. 200) sieve to 3 percent for fine aggregates used in concrete subject to abrasion, and 5 percent for fine aggregate used in all other concrete. For manufactured fine aggregate where the minus 75 μm (No. 200) fines can be shown to be free of clay or shale, the limits are increased to 5 and 7 percent, respectively. Similarly, material passing the 75 μm (No. 200) sieve is limited to 1 percent for coarse aggregate, except that for crushed aggregates the percentage 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 C123/C123M). 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 percent for both fine and coarse aggregates by ASTM C33/C33M whereas for all other concretes, the maximum is 1 percent. Requirements with respect to soft particles are given in Table 4 of ASTM C33/C33M.

CHAPTER 4—SAMPLING AGGREGATES

4.1—Variability in aggregates

In Chapter 3, methods for measuring aggregate properties were discussed. Aggregates vary from unit to unit and within each unit, however, and it is not practical to test entire units, whether that unit is a stockpile or a smaller batch. Thus, a sampling procedure is required.

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. 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 the fineness modulus is required from two lots of sand. 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. Both samples have the same fineness modulus, but is it reasonable to say that the sand in each lot has a fineness modulus of 2.70? 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 results in Table 4.2.2 might be obtained if five samples were taken from each lot.

Table 4.2.2—Fineness modules of five samples

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

The average of each five-sample set is still 2.70, so there would be more confidence in concluding that the sand in each lot has a fineness modulus of 2.70. Assuming that the correct sampling and testing procedures were used, Lot B is seemingly more variable than Lot A. For Lot A, the fineness modulus ranges from 2.63 to 2.75 whereas Lot B, ranges

from 2.47 to 2.95. Concrete made with sand from lot B is more likely to be variable in quality because aggregate fineness affects slump if water content is held constant. Thus, using the sand from Lot A would be preferable.

Test results on samples reveal 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 on 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—A detailed discussion of the formulation of a sampling plan is beyond the scope of this bulletin. The choice for a particular plan depends on the sampling situation and on the information to be extracted from the measurements on the sample. For instance, one might be interested in finding only the average gradation or 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 E141, “Standard Practice for Acceptance of Evidence on the Results of Probability Sampling.”

4.2.4 Sampling methods—Methods of selecting samples of aggregates are described in ASTM D75/D75M, “Standard Methods for 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 4.2.5. The conveyor belt is stopped while the sample increments are obtained. Two templates are spaced and inserted so 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 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 aggregate properties that may depend on 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 on 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 [ASTM E105](#), [ASTM E122](#), and [ASTM E141](#). The units of material represented by a single sample may vary widely, but usually, it is approximately 50 tons (45 metric tons).

Field sample size must be based on 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 recommendations are included in [Table 4.2.5](#).

Table 4.2.5—Minimum sample size recommendations

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 C702/C702M](#), “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's 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 slag is used for concrete aggregates. Expanded slag is discussed in [Section 5.2](#), and the remaining portion of this section deals with air-cooled slag.

5.1.2 Properties—Slag has a rather large number of disconnected internal voids that result in a structurally strong aggregate with low bulk relative density (specific gravity) and bulk density. Because the pores are coarse and are not interconnected, the resistance to damage from freezing and thawing is beneficial. Slag is not negatively 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 C33/C33M](#) 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/m³ (70 lb/ft³).

Use of an air-entraining agent or air-entraining cements with slag aggregates 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 (SSD) 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.

5.2—Lightweight aggregates

5.2.1 Definition of lightweight concrete—Lightweight concrete has a substantially lower bulk density than concrete 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/m³ (50 lb/ft³), and are used 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 micaceous material made up of dense parallel layers or sheets. When heated, water is combined in the layers and converts to steam, expanding the material like an accordion, creating lightweight and porous particles. This process is known as exfoliation. 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/m³ (6 to 12 lb/ft³).

Structural lightweight concretes have densities ranging from 1360 to 1920 kg/m³ (85 to 120 lb/ft³) and minimum compressive strengths of 17 MPa (2500 psi). Insulation efficiency is lower than that of low-density concretes, but substantially better than that for normalweight concretes. The most common aggregates used in this type of concrete are expanded slag; 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 formed clinker is then cooled, crushed, and screened to required aggregate grading. 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 resulting 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 resulting particles tend to be cubical or angular in shape and 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 resulting particles tend to have a smooth shell over the cellular interior. Frequently, the two procedures are combined to produce coarse aggregate consisting mostly of uncrushed particles obtained by screening and fine particles 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 relative density (specific gravity) of lightweight aggregates is lower than that of normalweight aggregates. The bulk

relative density 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 have a lower porosity. It is difficult to accurately determine bulk relative density and absorption for lightweight aggregates due to problems in consistently reproducing a saturated surface-dry (SSD) state. Thus, in designing concretes using lightweight aggregates, a relative density factor is used instead of the bulk relative density. This factor is found in the same way as the bulk relative density SSD, described in [Section 3.2](#), except that the SSD mass is the mass of the aggregate using the stockpile moisture, and the 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/m³ (30 to 65 lb/ft³), whereas the fines generally weigh 720 to 1120 kg/m³ (45 to 70 lb/ft³). For aggregates with the same gradation and particle shape, bulk density is essentially proportional to relative density—that is, as relative density increases, bulk density increases. Because 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 should be checked daily. Variations in bulk density indicate that the concrete yield may also vary because it is assumed that relative density changes are responsible for the variation in bulk density. Changes in grading or in particle shape can produce changes in bulk density, however, even though relative density of each individual size remains constant.

Particle shape and surface texture can vary considerably for lightweight aggregates produced by different methods. Shape is usually 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 affect workability, water requirement, and cement content just as with normalweight aggregates.

In general, grading requirements for lightweight aggregates are similar to those for normalweight aggregates. Lightweight aggregates, however, require a larger percentage by mass of material retained on the finer sieve sizes because the relative density 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 C330/C330M](#). 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 minutes. 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 ft³) minimum.

Due to their cellular structure, lightweight aggregates can absorb more water than normalweight aggregates. Based on a 24-hour absorption test, they generally absorb from 5 to 20 percent 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-hour absorption. This means that lightweight aggregates will usually absorb water when placed in the mixture, and the rate of absorption is an important consideration in proportioning lightweight concrete. For further information on proportioning lightweight concrete, refer to **ACI 211.2, "Recommended Practice for Selecting Proportions for Structural Lightweight Concrete."**

The maximum compressive strength attainable in concrete made with a given lightweight aggregate may depend on the aggregate itself. The concept of strength ceiling may be useful in this regard. A mixture is near its strength ceiling when similar mixtures containing the same aggregates and with higher cement contents have only slightly higher strengths. 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. As the maximum size of the aggregate is decreased, however, the density of the concrete increases.

5.3—Recycled aggregates

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

5.3.1 Definition—Recycling aggregate involves breaking old concrete (typically pavement), removing the reinforcement, and crushing to a specific size and gradation. While there is no restriction on the type of pavement that may be recycled, certain aggregate or certain types of mixtures may require investigation of the material to be recycled. For example, aggregates prone to D-cracking or concretes that have exhibited alkali-silica reaction (ASR) potential should be tested.

It is desirable to maximize the amount of coarse aggregate manufactured from the concrete to be recycled. Recycled fine aggregate will also be produced during the crushing operation, however, accounting for approximately 25 percent of the finished recycled material. New concrete mixtures can

contain both fine and coarse recycled aggregate. While up to 100 percent of the coarse aggregate can be recycled material, the percentage of fine aggregate is usually limited to 10 to 20 percent, with the remainder being virgin material.

5.3.2 Properties—Typical properties of interest when using recycled aggregates for concrete are listed in the following:

- a) **Surface condition and gradation**—It is possible to achieve almost any gradation with recycled materials. While the crushing operation may leave some residual dust on the aggregate surfaces, this does not pose a problem in most cases. Sometimes, however, it is necessary to wash the aggregate before use.
- b) **Relative density**—The crushed material has a lower relative density than virgin material. Usually, recycled coarse aggregate has a specific gravity of 2.2 to 2.5 in the saturated surface-dry (SSD) condition. As the size decreases, so does the relative density. Recycled sand has a relative density of approximately 2.0 to 2.3 SSD.
- c) **Absorption**—Absorption is much higher due to the cement mortar attached to particles. It is typically 2 to 6 percent for coarse aggregate and higher for sands. This can affect the workability of the concrete mixture. To prepare the recycled aggregate prior to mixing in concrete, it should be sprinkled with water to a moisture content that is greater than SSD, or it may be necessary to add extra water to the mixture to offset the water absorbed by the aggregate. Because sand made by crushing concrete is very angular and has a high absorption, it is generally necessary to limit it to approximately 10 to 20 percent of the sand content in a mixture.
- d) **Durability**—Abrasion loss is not a concern for recycled aggregate; nor is sulfate soundness. Residual chlorides in a mixture, as from application of deicing salts to a pavement, are usually below threshold values for both fine and coarse aggregates and are not a concern.

Concretes that contain known D-cracking aggregates should be tested before being used as recycled aggregates. Recycled aggregate can be used as coarse aggregate in new concrete pavements, but its ASR potential should be determined prior to such use. Several characteristics are helpful in determining the ability of this aggregate to perform without deleterious ASR during the pavement life. The alkali levels of both the old concrete and the new concrete can affect expansion of the recycled aggregate (old concrete refers to hardened concrete that is crushed and used as recycled aggregate). In this regard, the following characteristics of the recycled aggregate should be investigated: the original alkali level of the old concrete, the level of expansion of the old concrete, the remaining potential for expansion, and the alkali content of the new concrete. ASR in concrete containing recycled aggregates that have shown to be ASR reactive can be mitigated in many of the same ways as concrete made with virgin aggregates. Refer to **3.8.3**.

CHAPTER 6—REFERENCES

Committee documents are listed first by document number and year of publication followed by authored documents listed alphabetically.

American Association of State Highway and Transportation Officials

AASHTO TP 58-99—Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus

AASHTO T 210-15—Standard Method of Test for Aggregate Durability Index

American Concrete Institute

ACI 211.2-98—Standard Practice for Selecting Proportions for Structural Lightweight Concrete (Reapproved 2004)

ACI 213R-14—Guide for Structural Lightweight-Aggregate Concrete

ACI 221R-96—Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete (Reapproved 2001)

ASTM International

ASTM C29/C29M-09—Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate

ASTM C33/C33M-13—Standard Specification for Concrete Aggregates

ASTM C40/C40M-11—Standard Test Method for Organic Impurities in Fine Aggregates for Concrete

ASTM C70-13—Standard Test Method for Surface Moisture in Fine Aggregate

ASTM C87/C87M-10—Standard Test Method for Effect of Organic Impurities in Fine Aggregate on Strength of Mortar

ASTM C88-13—Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate

ASTM C117-13—Standard Test Method for Materials Finer than 75- μ m (No. 200) Sieve in Mineral Aggregates by Washing

ASTM C123/C123M-14—Standard Test Method for Lightweight Particles in Aggregate

ASTM C127-15—Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate

ASTM C128-15—Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate

ASTM C131/C131M-14—Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

ASTM C136/C136M-14—Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates

ASTM C666/C666M-15—Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing

ASTM C227-10—Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)

ASTM C289-07—Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method) (Withdrawn 2016)

ASTM C294-12—Standard Descriptive Nomenclature for Constituents of Concrete Aggregates

ASTM C295/C295M-12—Standard Guide for Petrographic Examination of Aggregates for Concrete

ASTM C330/C330M-14—Standard Specification for Lightweight Aggregates for Structural Concrete

ASTM C441/C441M-11—Standard Test Method for Effectiveness of Pozzolans or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction

ASTM C535-12—Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

ASTM C566-13—Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying

ASTM C586-11—Standard Test Method for Potential Alkali Reactivity of Carbonate Rocks as Concrete Aggregates (Rock-Cylinder Method)

ASTM C637-14—Standard Specification for Aggregates for Radiation-Shielding Concrete

ASTM C702/C702M-11—Standard Practice for Reducing Samples of Aggregate to Testing Size

ASTM C1105-08—Standard Test Method for Length Change of Concrete Due to Alkali-Carbonate Rock Reaction

ASTM C1252-06—Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading) (Withdrawn 2015)

ASTM C1260-14—Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)

ASTM C1293-08(2015)—Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction

ASTM C1567-13—Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)

ASTM C1778-14—Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete

ASTM D75/D75M-14—Standard Practice for Sampling Aggregates

ASTM D4791-10—Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate

ASTM D5821-13—Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate

ASTM E105-10—Standard Practice for Probability Sampling of Materials

ASTM E122-09—Standard Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process

ASTM E141-10—Standard Practice for Acceptance of Evidence Based on the Results of Probability Sampling



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