5

AGGREGATES

There are two main uses of aggregates in civil engineering: as an underlying material for foundations and pavements and as ingredients in portland cement and asphalt concretes. By dictionary definition, aggregates are a combination of distinct parts gathered into a mass or a whole. Generally, in civil engineering the term *aggregate* means a mass of crushed stone, gravel, sand, etc., predominantly composed of individual particles, but in some cases including clays and silts. The largest particle size in aggregates may have a diameter as large as 150 mm (6 in.) and the smallest particle can be as fine as 5 to 10 microns. The balance of this chapter presents information about aggregates as used in construction. Information is not presented about the characteristics and properties of soils, as this is the purview of textbooks on geotechnical engineering.

5.1 Aggregate Sources

Natural sources for aggregates include gravel pits, river run deposits, and rock quarries. Generally, *gravel* comes from pits and river deposits, whereas *crushed stones* are the result of processing rocks from quarries. Usually, gravel deposits must also be crushed to obtain the needed size distribution, shape, and texture (Figure 5.1).

Manufactured aggregates can use slag waste from steel mills and expanded shale and clays to produce lightweight aggregates. Heavyweight concrete, used for radiation shields, can use steel slugs and bearings for the aggregate. Styrofoam beads can be used as an aggregate in lightweight concrete used for insulation.

FIGURE 5.1 Aggregate stockpiling.

5.2 Geological Classification

All natural aggregates result from the breakdown of large rock masses. Geologists classify rocks into three basic types: *igneous, sedimentary,* and *metamorphic.* Volcanic action produces igneous rocks by hardening or crystallizing molten material, magma. The magma cools either at the earth's surface, when it is exposed to air or water, or within the crust of the earth. Cooling at the surface produces *extrusive* igneous rocks, while cooling underground produces *intrusive* igneous rocks. In general, the extrusive rocks cool much more rapidly than the intrusive rocks. Therefore, we would expect extrusive igneous rocks to have a fine grain size and potentially to include air voids and other inclusions. Intrusive igneous rocks have larger grain sizes and fewer flaws. Igneous rocks are classified based on grain size and composition. Coarse grains are larger than 2 mm and fine grains are less than 0.2 mm. Classification based on composition is a function of the silica content, specific gravity, color, and the presence of free quartz.

Sedimentary rocks coalesce from deposits of disintegrated existing rocks or inorganic remains of marine animals. Wind, water, glaciers, or direct chemical precipitation transport and deposit layers of material that become sedimentary rocks, resulting in a stratified structure. Natural cementing binds the particles together. Classification is based on the predominant mineral present: calcareous (limestone, chalk, etc.), siliceous (chert, sandstone, etc.), and argillaceous (shale, etc.).

Metamorphic rocks form from igneous or sedimentary rocks that are drawn back into the earth's crust and exposed to heat and pressure, re-forming the grain structure. Metamorphic rocks generally have a crystalline structure, with grain sizes ranging from fine to coarse.

All three classes of rock are used successfully in civil engineering applications. The suitability of aggregates from a given source must be evaluated by a combination of tests to check physical, chemical, and mechanical properties, and must be supplemented by mineralogical examination. The best possible prediction of aggregate suitability for a given application is that based on historical performance in a similar design.

5.3 Evaluation of Aggregate Sources

Civil engineers select aggregates for their ability to meet specific project requirements, rather than their geologic history. The physical and chemical properties of the rocks determine the acceptability of an aggregate source for a construction project. These characteristics vary within a quarry or gravel pit, making it necessary to continually sample and test the materials as the aggregates are being produced.

Due to the quantity of aggregates required for a typical civil engineering application, the cost and availability of the aggregates are important when selecting an aggregate source. Frequently, one of the primary challenges facing the materials engineer on a project is how to use the locally available material in the most cost-effective manner.

Potential aggregate sources are usually evaluated for quality of the larger pieces, the nature and amount of fine material, and the gradation of the aggregate. The extent and quality of rock in the quarry is usually investigated by drilling cores and performing trial blasts (or shots) to evaluate how the rock breaks and by crushing some materials in the laboratory to evaluate grading, particle shape, soundness, durability, and amount of fine material. Cores are examined petrographically for general quality, suitability for various uses, and amount of deleterious materials. Potential sand and gravel pits are evaluated by collecting samples and performing sieve analysis tests. The amount of large gravel and cobble sizes determines the need for crushing, while the amount of fine material determines the need for washing. Petrographic examinations evaluate the nature of aggregate particles and the amount of deleterious material (Meininger and Nichols 1990).

Price and availability are universal criteria that apply to all uses of aggregates. However, the required aggregate characteristics depend on how they will be used in the structure; they may be used as base material, in asphalt concrete, or in portland cement concrete.

5.4 Aggregate Uses

As mentioned, aggregates are primarily used as an underlying material for foundations and pavements and as ingredients in portland cement and asphalt concretes. Aggregate underlying materials, or base courses, can add stability to a structure, provide a drainage layer, and protect the structure from frost damage (Figure 5.2). Stability is a function of the interparticle friction between the aggregates and the amount of clay and silt "binder" material in the voids between the aggregate particles. However, increasing the clay and silt content will block the drainage paths between the aggregate particles, thereby inhibiting the ability of the material to act as a drainage layer.

In portland cement concrete, 60% to 75% of the volume and 79% to 85% of the weight is made up of aggregates. The aggregates act as a filler to reduce the amount of cement paste needed in the mix. In addition, aggregates have greater volume stability than the cement paste. Therefore, maximizing the amount of aggregate, to a certain extent, improves the quality and economy of the mix.

In asphalt concrete, aggregates constitute over 80% of the volume and 92% to 96% of the mass. The asphalt cement acts as a binder to hold the aggregates together, but does not have enough strength to lock the aggregate particles into position. As a result, the strength and stability of asphalt

FIGURE 5.2 Compacted aggregate base before placing the hot-mix asphalt or portland cement concrete layer of a paved road.

concrete depends mostly on interparticle friction between the aggregates and, to a limited extent, on the binder.

5.5 Aggregate Properties

Aggregates' properties are defined by the characteristics of both the individual particles and the characteristics of the combined material. These properties can be further described by their physical, chemical, and mechanical characteristics, as shown in Table 5.1 (Meininger and Nichols, 1990). There are several individual particle characteristics that are important in determining if an aggregate source is suitable for a particular application. Other characteristics are measured for designing portland cement and asphalt concrete mixes (Goetz and Wood 1960).

5.5.1 Particle Shape and Surface Texture

The shape of the individual aggregate particles, Figures 5.3 and 5.4, determines how the material will pack into a dense configuration and also determines the mobility of the stones within a mix. There are two considerations in the shape of the material: *angularity* and *flakiness.* Crushing rocks produces angular particles with sharp corners. Due to weathering, the corners of the aggregates break down, creating *subangular* particles. When the aggregates tumble while being transported in water, the corners can become completely *rounded.* Generally, angular aggregates produce bulk materials with higher stability than rounded aggregates. However, the angular aggregates will be more difficult to work into place than rounded aggregates, since their shapes make it difficult for them to slide across each other. Flakiness describes the relationship between the smallest and largest dimensions of the aggregate.

The roughness of the aggregate surface plays an important role in the way the aggregate compacts and bonds with the binder material. Aggregates with a *rough* texture are more difficult to compact into a dense configuration than *smooth* aggregates. Rough texture generally improves bonding and increases interparticle friction. In general, natural gravel and sand have a smooth texture, whereas crushed aggregates have a rough texture.

For the purpose of preparing portland cement concrete, it is desirable to use rounded and smooth aggregate particles to improve the workability of fresh concrete during mixing. However, angular and rough particles are desirable for asphalt concrete and base courses in order to increase the stability of the materials in the field and to reduce rutting. Flaky and elongated aggregates are undesirable for asphalt concrete, since they are difficult to compact during construction and are easy to break.

Many specifications for aggregates used in asphalt concrete require a minimum percentage of aggregates with crushed faces as a surrogate *shape*

TABLE 5.1 Basic Aggregate Properties (Meininger and Nichols, 1990)

Property	Relative Importance for End Use*		
	Portland Cement Concrete	Asphalt Concrete	Base
PHYSICAL			
Particle shape (angularity)	M	V	V
Particle shape (flakiness, elongation)	M	M	M
Particle size—maximum	M	M	M
Particle size—distribution	M	M	M
Particle surface texture	M	V	V
Pore structure, porosity	V	M	U
Specific gravity, absorption	V	M	M
Soundness—weatherability	V	M	M
Unit weight, voids—loose, compacted	V	M	M
Volumetric stability—thermal	M	U	U
Volumetric stability—wet/dry	M	U	M
Volumetric stability—freeze/thaw	V	M	M
Integrity during heating	U	M	U
Deleterious constituents	V	M	M
CHEMICAL			
Solubility	M	U	U
Surface charge	U	V	U
Asphalt affinity	U	V	M
Reactivity to chemicals	V	U	U
Volume stability—chemical	V	M	M
Coatings	M	M	U
MECHANICAL			
Compressive strength	M	U	U
Toughness (impact resistance)	M	M	U
Abrasion resistance	M	M	M
Character of products of abrasion	M	M	U
Mass stability (stiffness, resilience)	U	V	V
Polishability	M	M	U

*V = Very important M = Moderately important U = Unimportant or importance unknown

and *texture requirement.* A crushed particle exhibits one or more mechanically induced fractured faces and typically has a rough surface texture. To evaluate the angularity and surface texture of coarse aggregate, the percentages of particles with one and with two or more crushed faces are counted in a representative sample.

For fine aggregate, angularity and surface texture can be measured indirectly using the ASTM C1252 method, Test Method for Uncompacted Void Content of Fine Aggregate. In this test a sample of fine aggregate is poured into a small cylinder by flowing it through a standard funnel, as shown in

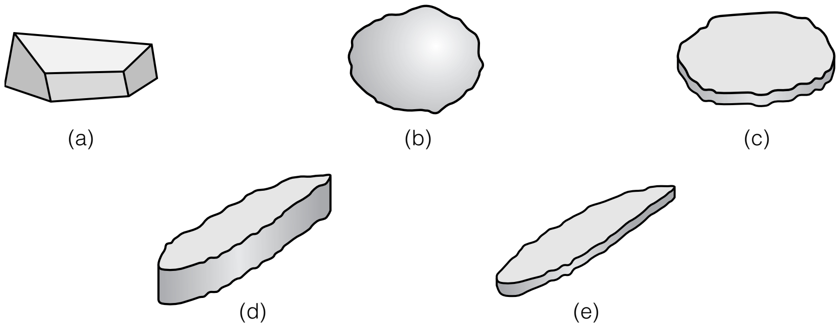


FIGURE 5.3 Particle shapes: (a) angular, (b) rounded, (c) flaky, (d) elongated, and (e) flaky and elongated.

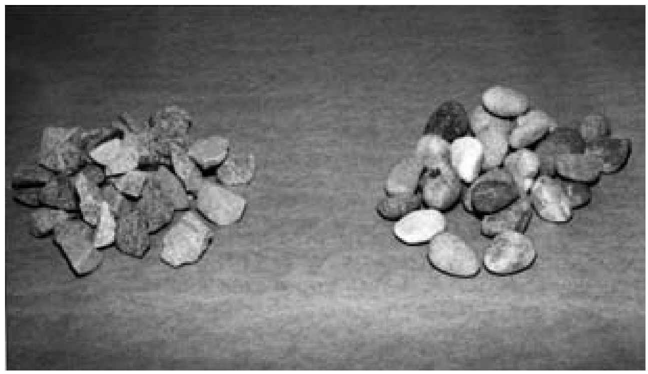


FIGURE 5.4 Angular and rounded aggregates.

Figure 5.5. By determining the weight of the fine aggregate in the filled cylinder of known volume, the void content can be calculated as the difference between the cylinder volume and the fine aggregate volume collected in the cylinder. The volume of the fine aggregate is calculated by dividing the weight of the fine aggregate by its bulk density. The higher the amount of void content, the more angular and the rougher will be the surface texture of the fine aggregate.

5.5.2 Soundness and Durability

The ability of aggregate to withstand weathering is defined as soundness or durability. Aggregates used in various civil engineering applications must be sound and durable, particularly if the structure is subjected to severe climatic conditions. Water freezing in the voids of aggregates generates stresses that can fracture the stones. The soundness test (ASTM C88) simulates weathering by soaking the aggregates in either a sodium sulfate or a magnesium

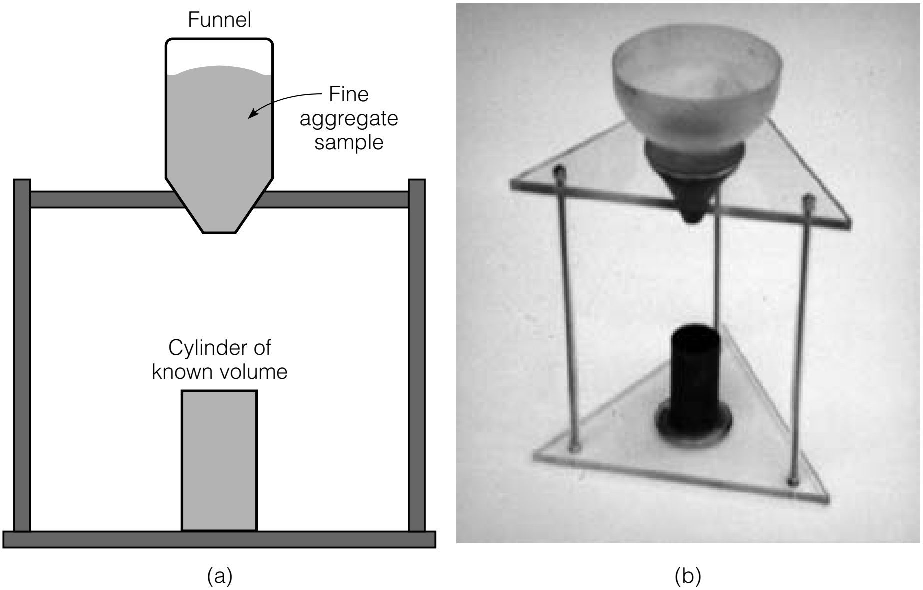


FIGURE 5.5 Apparatus used to measure angularity and surface texture of fine aggregate.

sulfate solution. These sulfates cause crystals to grow in the aggregates, simulating the effect of freezing. The test starts with an oven-dry sample separated into different sized fractions. The sample is subjected to cycles of soaking in the sulfate for 16 hours followed by drying. Typically, the samples are subjected to five cycles. Afterwards, the aggregates are washed and dried, each size is weighed, and the weighted average percentage loss for the entire sample is computed. This result is compared with allowable limits to determine whether the aggregate is acceptable. This is an empirical screening procedure for new aggregate sources when no service records are available.

The soundness by freeze thaw (AASHTO T103) and potential expansion from hydrated reactions (ASTM D4792) are alternative screening tests for evaluating soundness. The durability of aggregates in portland cement concrete can be tested by rapid freezing and thawing (ASTM C666), critical dilation by freezing (ASTM C671), and by frost resistance of coarse aggregates in air-entrained concrete by critical dilation (ASTM C682).

5.5.3 Toughness, Hardness, and Abrasion Resistance

The ability of aggregates to resist the damaging effect of loads is related to the hardness of the aggregate particles and is described as the toughness or abrasion resistance. The aggregate must resist crushing, degradation, and disintegration when stockpiled, mixed as either portland cement or asphalt concrete, placed and compacted, and exposed to loads.

FIGURE 5.6 Los Angles abrasion machine.

The Los Angeles abrasion test (ASTM C131, C535) evaluates the aggregates' toughness and abrasion resistance. In this test, aggregates blended to a fixed size distribution are placed in a large steel drum with standard sized steel balls that act as an abrasive charge (see Figure 5.6). The drum is rotated, typically for 500 revolutions. The material is recovered from the machine and passed through a sieve that retains all of the original material. The percentage weight loss is the LA abrasion number. This is an empirical test; that is, the test results do not have a scientific basis and are meaningful only when local experience defines the acceptance criteria.

5.5.4 Absorption

Although aggregates are inert, they can capture water and asphalt binder in surface voids. The amount of water the aggregates absorb is important in the design of portland cement concrete, since moisture captured in the aggregate voids is not available to improve the workability of the plastic concrete and to react with the cement. There is no specific level of aggregate absorption that is desirable for aggregates used in portland cement concrete, but aggregate absorption must be evaluated to determine the appropriate amount of water to mix into the concrete.

Absorption is also important for asphalt concrete, since absorbed asphalt is not available to act as a binder. Thus, highly absorptive aggregates require greater amounts of asphalt binder, making the mix less economical.

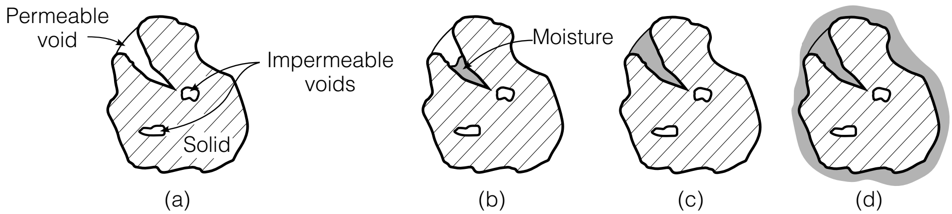


FIGURE 5.7 Voids and moisture absorption of aggregates: (a) bone dry, (b) air dry, (c) saturated surface-dry (SSD), and (d) moist.

On the other hand, some asphalt absorption is desired to promote bonding between the asphalt and the aggregate. Therefore, low-absorption aggregates are desirable for asphalt concrete.

Figure 5.7 demonstrates the four moisture condition states for an aggregate particle. *Bone dry* means the aggregate contains no moisture; this requires drying the aggregate in an oven to a constant mass. In an *air dry* condition, the aggregate may have some moisture but the saturation state is not quantified. In a *saturated surface–dry (SSD)* condition, the aggregate's voids are filled with moisture but the main surface area of the aggregate particles is dry. *Absorption* is defined as the moisture content in the SSD condition. Moist aggregates have a moisture content in excess of the SSD condition. Free moisture is the difference between the actual moisture content of the aggregate and the moisture content in the SSD condition.

Sample Problem 5.1

A sample of sand has the following properties:

Wet mass = 625.2 g
Dry mass = 589.9 g
Absorption = 1.6%

Determine: (a) total moisture content, and (b) free moisture content

Solution

a. Mass of water = 625.2 − 589.9 = 35.3 g

$$\text{Total moisture content} = \frac{35.3}{589.9} \times 100 = 6.0\%$$

b. Free moisture = 6.0 − 1.6 = 4.4%

5.5.5 Specific Gravity

The weight–volume characteristics of aggregates are not an important indicator of aggregate quality, but they are important for concrete mix design. *Density*, the mass per unit volume, could be used for these calculations. However, *specific gravity* (Sp. Gr.), the mass of a material divided by the mass of an equal volume of distilled water, is more commonly used. Four types of specific gravity are defined based on how voids in the aggregate particles are considered. Three of these types—*bulk-dry, bulk-saturated surface–dry,* and *apparent* specific gravity—are widely accepted and used in portland cement and asphalt concrete mix design. These are defined as

$$\text{Bulk Dry Sp. Gr.} = \frac{\text{Dry Weight}}{(\text{Total Particle Volume})\gamma_w} = \frac{W_s}{(V_s + V_i + V_p)\gamma_w} \quad (5.1)$$

$$\text{Bulk SSD Sp. Gr.} = \frac{\text{SSD Weight}}{(\text{Total Particle Volume})\gamma_w} = \frac{W_s + W_p}{(V_s + V_i + V_p)\gamma_w} \quad (5.2)$$

$$\text{Apparent Sp. Gr.} = \frac{\text{Dry Weight}}{(\text{Volume Not Accessible to Water})\gamma_w} = \frac{W_s}{(V_s + V_i)\gamma_w} \quad (5.3)$$

where

W_s = weight of solids
V_s = volume of solids
V_i = volume of water impermeable voids
V_p = volume of water permeable voids
W_p = weight of water in the permeable voids when the aggregate is in the SSD condition
γ_w = unit weight of water

Figure 5.8 shows that, when aggregates are mixed with asphalt binder, only a portion of the water-permeable voids are filled with asphalt. Hence, a fourth type of specific gravity—the *effective specific gravity*—is defined as

$$\text{Effective Sp.Gr.} = \frac{\text{Dry weight}}{(\text{Volume not accessible to asphalt})\gamma_w} = \frac{W_s}{(V_s + V_c)\gamma_w} \quad (5.4)$$

where V_c is volume of voids not filled with asphalt cement.

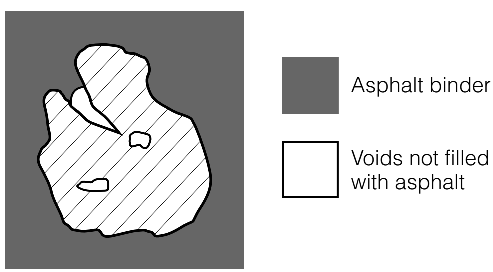


FIGURE 5.8 Aggregate particle submerged in asphalt cement; not all voids are filled with asphalt.

At present, there is no standard method for determining the effective specific gravity of aggregates directly. The U.S. Corps of Engineers has defined a method for determining the effective specific gravity of aggregates that absorb more than 2.5% water.

The specific gravity and absorption of coarse aggregates are determined in accordance with ASTM C127. In this procedure, a representative sample of the aggregate is soaked for 24 hours and weighed suspended in water. The sample is then dried to the SSD condition and weighed. Finally, the sample is dried to a constant weight and weighed. The specific gravity and absorption are determined by

$$\text{Bulk Dry Sp. Gr.} = \frac{A}{B - C} \tag{5.5}$$

$$\text{Bulk SSD Sp. Gr.} = \frac{B}{B - C} \tag{5.6}$$

$$\text{Apparent Sp. Gr.} = \frac{A}{A - C} \tag{5.7}$$

$$\text{Absorption (\%)} = \frac{B - A}{A}(100) \tag{5.8}$$

where

A = dry weight
B = SSD weight
C = submerged weight

ASTM C128 defines the procedure for determining the specific gravity and absorption of fine aggregates. A representative sample is soaked in water for 24 hours and dried back to the SSD condition. A 500-g sample of the SSD material is placed in a *pycnometer,* a constant volume flask; water is added to the constant volume mark on the pycnometer and the weight is determined again. The sample is then dried and the weight is determined. The specific gravity and absorption are determined by

$$\text{Bulk Dry Sp. Gr.} = \frac{A}{B + S - C} \tag{5.9}$$

$$\text{Bulk SSD Sp. Gr.} = \frac{S}{B + S - C} \tag{5.10}$$

$$\text{Apparent Sp. Gr.} = \frac{A}{B + A - C} \tag{5.11}$$

$$\text{Absorption (\%)} = \frac{S - A}{A}(100) \tag{5.12}$$

where

A = dry weight
B = weight of the pycnometer filled with water
C = weight of the pycnometer filled with aggregate and water
S = saturated surface—dry weight of the sample

5.5.6 Bulk Unit Weight and Voids in Aggregate

The bulk unit weight of aggregate is needed for the proportioning of portland cement concrete mixtures. According to ASTM C29 procedure, a rigid container of known volume is filled with aggregate, which is compacted either by rodding, jigging, or shoveling. The bulk unit weight of aggregate (γ_b) is determined as

$$\gamma_b = \frac{W_s}{V} \tag{5.13}$$

where W_s is the weight of aggregate (stone) and V is the volume of the container.

If the bulk dry specific gravity of the aggregate (G_{sb}) (ASTM C127 or C128) is known, the percentage of voids between aggregate particles can be determined as follows:

$$\%V_s = \frac{V_s}{V} \times 100 = \frac{W/\gamma_s}{W/\gamma_b} \times 100 = \frac{\gamma_b}{\gamma_s} \times 100 = \frac{\gamma_b}{G_{sb} \cdot \gamma_w} \times 100$$

$$\%\text{Voids} = 100 - \%V_s \tag{5.14}$$

where

V_s = volume of aggregate
γ_s = unit weight of aggregate
γ_b = bulk unit weight of aggregate
γ_w = unit weight of water

Sample Problem 5.2

Coarse aggregate is placed in a rigid bucket and rodded with a tamping rod to determine its unit weight. The following data are obtained:

Volume of bucket = 1/3 ft^3
Weight of empty bucket = 18.5 lb
Weight of bucket filled with dry rodded coarse aggregate = 55.9 lb

a. Calculate the dry-rodded unit weight
b. If the bulk dry specific gravity of the aggregate is 2.630, calculate the percent voids in the aggregate.

Solution

a. Dry-rodded unit weight = (55.9 − 18.5)/0.333 = 112.3 lb/ft^3

b. Percent volume of particles $= \dfrac{112.3}{2.630 \times 62.3} \times 100 = 68.5\%$

Percent voids = 100 − 68.5 = 31.5%

5.5.7 Strength and Modulus

The strength of portland cement concrete and asphalt concrete cannot exceed that of the aggregates. It is difficult and rare to test the strength of aggregate particles. However, tests on the parent rock sample or a bulk aggregate sample provide an indirect estimate of these values. Aggregate strength is generally important in high-strength concrete and in the surface course on heavily traveled pavements. The tensile strength of aggregates ranges from 0.7 MPa to 16 MPa (100 psi to 2300 psi), while the compressive strength ranges from 35 MPa to 350 MPa (5000 psi to 50,000 psi) (Meininger and Nichols 1990; Barksdale 1991). Field service records are a good indication of the adequacy of the aggregate strength.

The modulus of elasticity of aggregates is not usually measured. However, new mechanistic-based methods of pavement design require an estimate of the modulus of aggregate bases. The response of bulk aggregates to stresses is nonlinear and depends on the confining pressure on the material. Since the modulus is used for pavement design, dynamic loads are used in a test to simulate the magnitude and duration of stresses in a pavement base caused by a moving truck. During the test, as the stresses are applied to the sample, the deformation response has two components, a recoverable or resilient deformation, and a permanent deformation. Only the resilient portion of the strain is used with the applied stress level to compute the modulus of the aggregate. Hence, the results are defined as the resilient modulus M_R.

In the resilient modulus test (AASHTO T292), a prepared cylindrical sample is placed in a triaxial cell, as shown in Figure 5.9. A specimen with large aggregates is typically 0.15 m (6 in.) in diameter by 0.30 m (12 in.) high, while soil samples are 71 mm (2.8 in.) in diameter by 142 mm (5.6 in.) high. The specimen is subjected to a specified confining pressure and a repeated axial load. Accurate transducers, such as LVDTs, measure the axial deformation. The test requires a determination of the modulus over a range of axial loads and confining pressures. The resilient modulus equals the repeated axial stress divided by the resilient strain for each combination of load level and confining pressure. The resilient modulus test requires the measurement of very small loads and deformations and is, therefore, difficult to perform. Currently, the test is mostly limited to research projects.

5.5.8 Gradation and Maximum Size

Gradation describes the particle size distribution of the aggregate. The particle size distribution is an important attribute of the aggregates. Large aggregates are economically advantageous in portland cement and asphalt concrete, as they have less surface area and, therefore, require less binder. However, large aggregate mixes, whether asphalt or portland cement concrete, are harsher and more difficult to work into place. Hence, construction considerations, such as equipment capability, dimensions of construction members, clearance between reinforcing steel, and layer thickness, limit the maximum aggregate size.

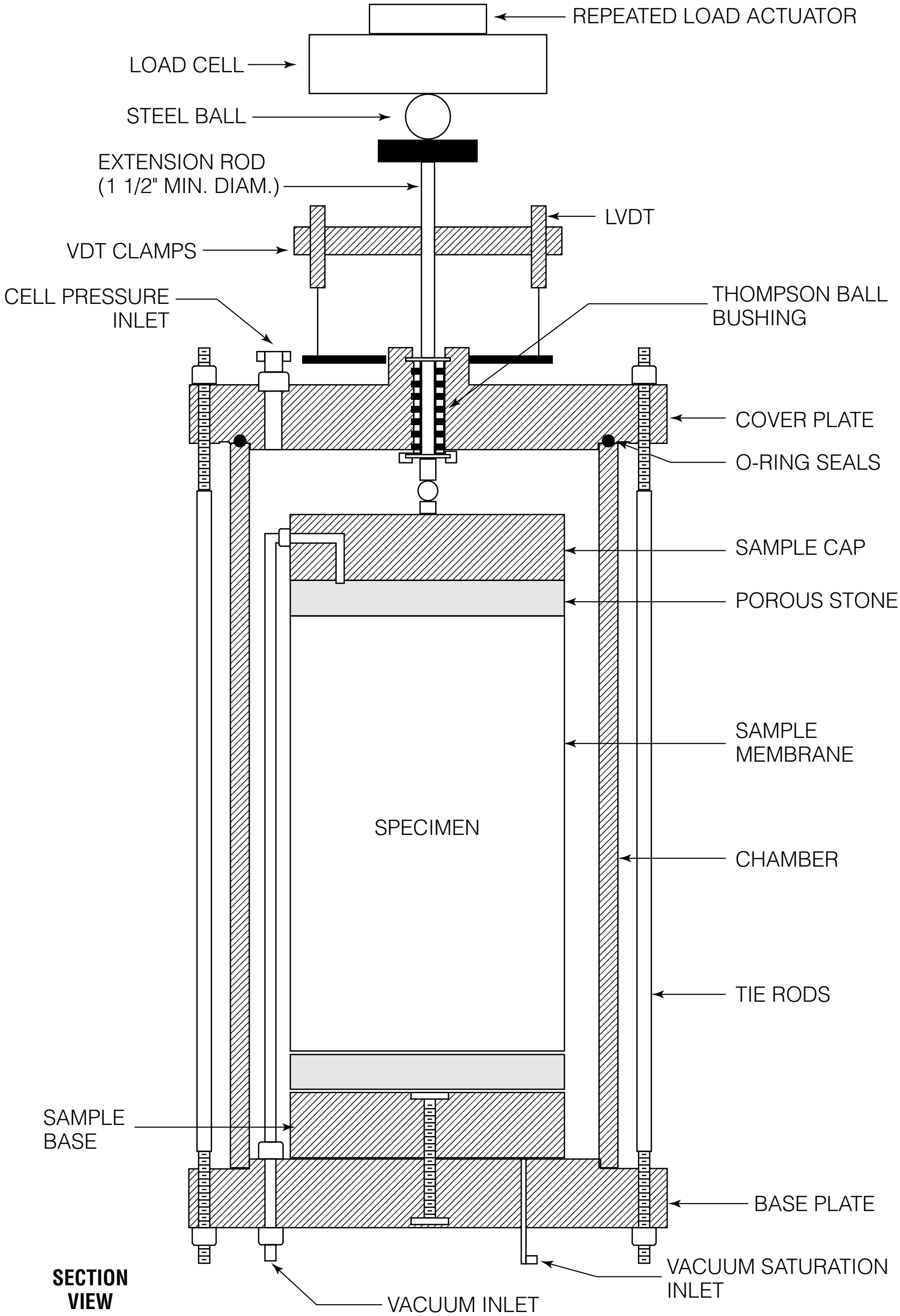


FIGURE 5.9 Triaxial chamber with external LVDT's and load cell.

Two definitions are used to describe the maximum particle size in an aggregate blend:

Maximum aggregate size—the smallest sieve size through which 100% of the aggregates sample particles pass.
Nominal maximum aggregate size—the largest sieve that retains any of the aggregate particles, but generally not more than 10%.

Some agencies define the maximum aggregate size as two sizes larger than the first sieve to retain more than 10% of the material, while the nominal maximum size is one size larger than the first sieve to retain more than 10% of the material (The Asphalt Institute 1995; McGennis et al. 1995).

Sieve Analysis Gradation is evaluated by passing the aggregates through a series of sieves, as shown in Figure 5.10 (ASTM C136, E11). The sieve retains particles larger than the opening, while smaller ones pass through. Metric sieve descriptions are based on the size of the openings measured in millimeters. Sieves smaller than 0.6 mm can be described in either millimeters or micrometers. In U.S. customary units, sieves with openings greater than 1/4 in. are designated by the size of the opening; the lengths of the sides of the square openings of a 2-in. sieve are 2 in. measured between the wires. This equals the diameter of a sphere that will exactly touch each side of the square at the midpoints. Sieves smaller than 1/4 in. are specified by the number of uniform openings per linear inch (a No. 8 sieve has 8 openings per inch, or 64 holes per square inch).

Gradation results are described by the cumulative percentage of aggregates that either pass through or are retained by a specific sieve size. Percentages are

FIGURE 5.10 Sieve shaker for large samples of aggregates.

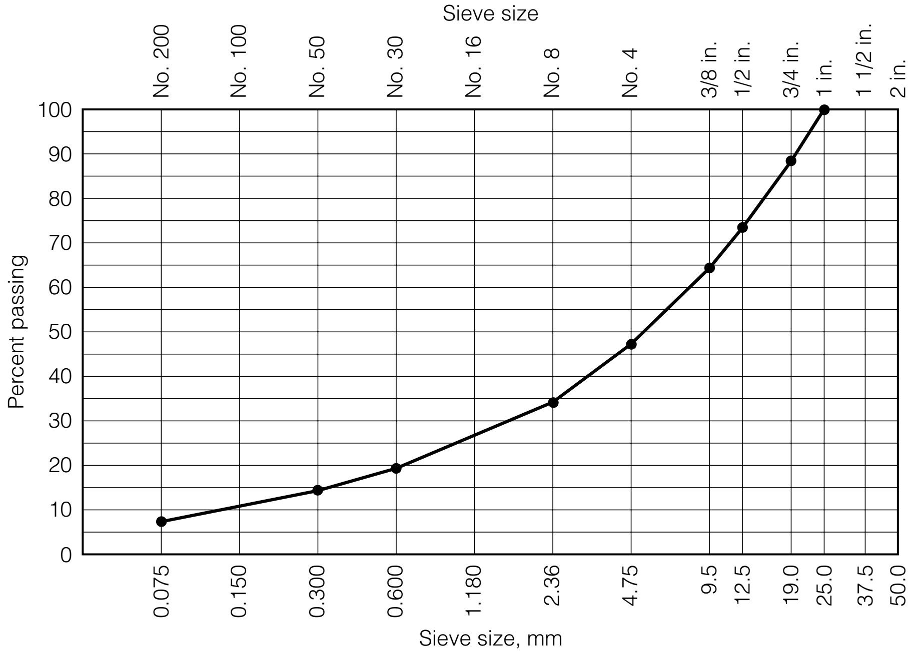


FIGURE 5.11 Semi-log aggregate gradation chart showing a gradation example. See Table 5.2.

reported to the nearest whole number, except that if the percentage passing the 0.075-mm (No. 200) sieve is less than 10%, it is reported to the nearest 0.1%. Gradation analysis results are generally plotted on a semilog chart, as shown in Figures 5.11 and A.21.

Aggregates are usually classified by size as coarse aggregates, fine aggregates, and mineral fillers (fines). ASTM defines coarse aggregate as particles retained on the 4.75-mm (No. 4) sieve, fine aggregate as those passing the 4.75-mm sieve, and mineral filler as material mostly passing the 0.075-mm (No. 200) sieve.

Maximum Density Gradation The density of an aggregate mix is a function of the size distribution of the aggregates. In 1907 Fuller established the relationship for determining the distribution of aggregates that provides the maximum density or minimum amount of voids as

$$P_i = 100\left(\frac{d_i}{D}\right)^n \tag{5.15}$$

where

P_i = percent passing a sieve of size d_i
d_i = the sieve size in question
D = maximum size of the aggregate

The value of the exponent n recommended by Fuller is 0.5. In the 1960s, the Federal Highway Administration recommended a value of 0.45 for n and introduced the "0.45 power" gradation chart, Figures 5.12 and A.22, designed to produce a straight line for maximum density gradations (Federal Highway Administration 1988). Table 5.2 presents a sample

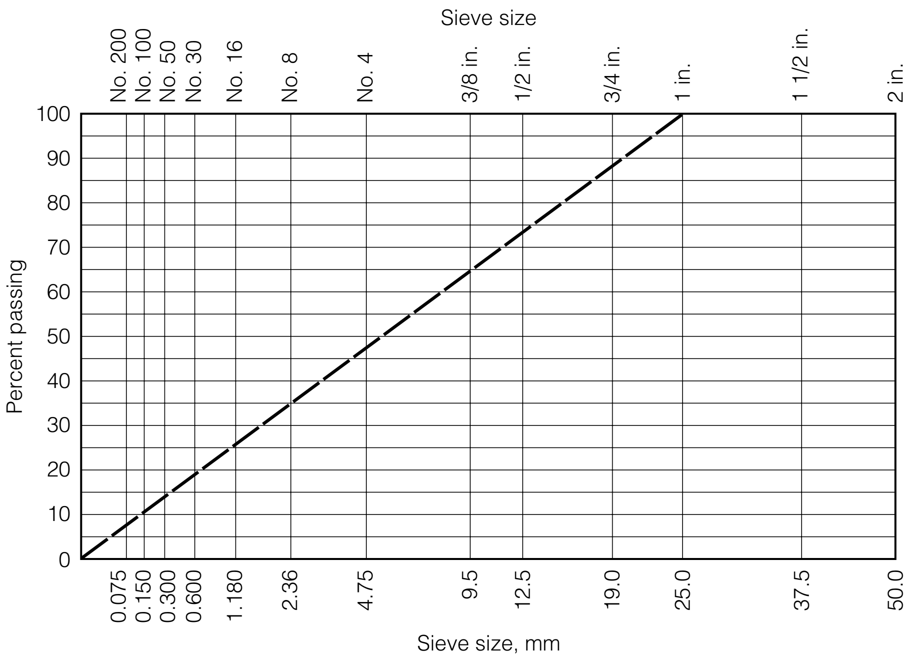


FIGURE 5.12 Federal Highway Administration 0.45 power gradation chart showing the maximum density gradation for a maximum size of 25 mm. See Table 5.2.

TABLE 5.2 Sample Calculations of Aggregate Distribution Required to Achieve Maximum Density

Sieve	$P_i = 100(d_i/D)^{0.45}$
25 mm (1 in.)	100
19 mm (3/4 in.)	88
12.5 mm (1/2 in.)	73
9.5 mm (3/8 in.)	64
4.75 mm (No. 4)	47
2.36 mm (No. 8)	34
0.60 mm (No. 30)	19
0.30 mm (No. 50)	14
0.075 mm (No. 200)	7.3

calculation of the particle size distribution required for maximum density. Note that the gradation in Table 5.2 is plotted on both gradation charts in Figures 5.11 and 5.12.

Frequently, a *dense* gradation, but not necessarily the maximum possible density, is desired in many construction applications, because of its high stability. Using a high-density gradation also means the aggregates occupy most of the volume of the material, limiting the binder content and thus reducing the cost. For example, aggregates for asphalt concrete must be dense, but must also have sufficient voids in the mineral aggregate to provide room for the binder, plus room for voids in the mixture.

Sample Problem 5.3

A sieve analysis test was performed on a sample of fine aggregate and produced the following results:

Sieve, mm	4.75	2.36	2.00	1.18	0.60	0.30	0.15	0.075	pan
Amount retained, g	0	33.2	56.9	83.1	151.4	40.4	72.0	58.3	15.6

Calculate the percent passing each sieve, and draw a 0.45 power gradation chart with the use of a spreadsheet program.

Solution

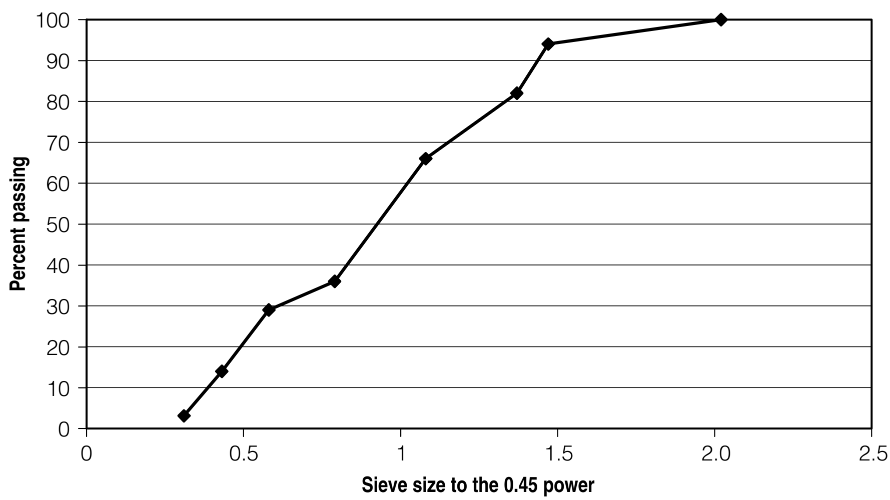
Sieve size	Amount Retained, g (a)	Cumulative Amount Retained, g (b)	Cumulative Percent Retained (c) = (b) × 100/Total	Percent Passing* (d) = 100 − (c)
4.75 mm (No. 4)	0	0	0	100
2.36 mm (No. 8)	33.2	33.2	6	94
2.00 mm (No. 10)	56.9	90.1	18	82
1.18 mm (No. 16)	83.1	173.2	34	66
0.60 mm (No. 30)	151.4	324.6	64	36
0.30 mm (No. 50)	40.4	365.0	71	29
0.15 mm (No. 100)	72.0	437.0	86	14
0.075 mm (No.200)	58.3	495.3	96.9	3.1
Pan	15.6	510.9	100	
Total	510.9			

*Percent passing is computed to a whole percent, except for the 0.075 mm (No. 200) material, which is computed to 0.1 %.

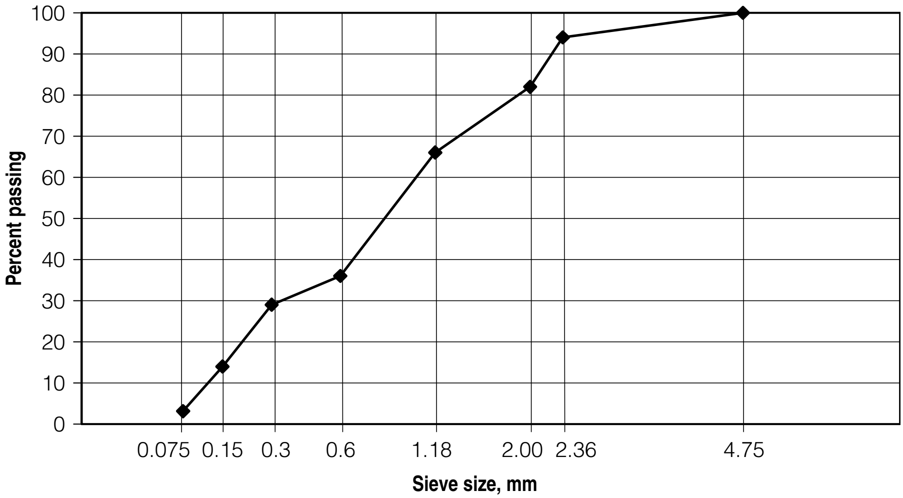
The first step in drawing the graph is to compute the sieve size to the 0.45 power, using the metric sieve sizes:

Sieve Size (mm)	Sieve to the 0.45 power	Percent Passing
4.75	2.02	100
2.36	1.47	94
2	1.37	82
1.18	1.08	66
0.6	0.79	36
0.3	0.58	29
0.15	0.43	14
0.075	0.31	3.1

Then the x-y scatter graph function is used to plot the percent passing on the y axis versus the sieve size to the 0.45 power:



Since the sieve size raised to the 0.45 power is not a meaningful number, the values on the axis are deleted and the text box feature is used to label the x-axis with the actual sieve values. In addition, the drawing tool is used to add vertical lines between the axis and the data points. The resulting graph is as follows:



Other Types of Gradation In addition to maximum density (i.e., *well-graded*), aggregates can have other characteristic distributions, as shown in Figure 5.13. A *one-sized* distribution has the majority of aggregates passing one sieve and being retained on the next smaller sieve. Hence, the majority of the aggregates have essentially the same diameter; their gradation curve is nearly vertical. One-sized graded aggregates will have good permeability, but poor stability, and are used in such applications as chip seals of pavements. *Gap-graded* aggregates are missing one or more sizes of material. Their gradation curve has a near horizontal section indicating that nearly the same portions of the aggregates pass two different sieve sizes. *Open-graded* aggregates are missing small aggregate sizes that would block the voids between the larger aggregate. Since there are a lot of voids, the material will be highly permeable, but may not have good stability.

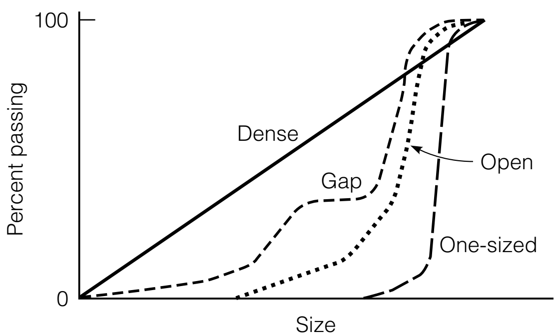


FIGURE 5.13 Types of aggregate grain size distributions plotted on a 0.45 gradation chart.

TABLE 5.3 Effect of Amount of Fines on the Relative Properties of Aggregate Base Material

Characteristic	No fines (Open or Clean)	Well-Graded (Dense)	Large Amount of Fines (Dirty or Rich)
Stability	Medium	Excellent	Poor
Density	Low	High	Low
Permeability	Permeable	Low	Impervious
Frost Susceptibility	No	Maybe	Yes
Handling	Difficult	Medium	Easy
Cohesion	Poor	Medium	Large

As shown in Table 5.3, the amount of fines has a major effect on the characteristics of aggregate base materials. Aggregates with the percentage of fines equal to the amount required for maximum density have excellent stability and density, but may have a problem with permeability, frost susceptibility, handling, and cohesion.

Gradation Specifications Gradation specifications define maximum and minimum cumulative percentages of material passing each sieve. Aggregates are commonly described as being either coarse or fine, depending on whether the material is predominantly retained on or passes through a 4.75-mm (No. 4) sieve.

Portland cement concrete requires separate specifications for coarse and fine aggregates. The ASTM C33 specifications for fine aggregates for concrete are given in Table 5.4. Table 5.5 shows the ASTM C33 gradation specifications for coarse concrete aggregates.

TABLE 5.4 ASTM Gradation Specifications for Fine Aggregates for Portland Cement Concrete (Copyright ASTM, reprinted with permission)

Sieve	Percent Passing
9.5 mm (3/8″)	100
4.75 mm (No. 4)	95–100
2.36 mm (No. 8)	80–100
1.18 mm (No. 16)	50–85
0.60 mm (No. 30)	25–60
0.30 mm (No. 50)	10–30
0.15 mm (No. 100)	2–10

TABLE 5.5 Coarse Aggregate Grading Requirements for Concrete (ASTM C-33) (Copyright ASTM, reprinted with permission)

		Amounts Finer Than Each Laboratory Sieve (Square Openings), Weight Percent												
Size No.	**Nominal Size**	**4 in. (100 mm)**	**3 1/2 in. (90 mm)**	**3 in. (75 mm)**	**2 1/2 in. (63 mm)**	**2 in. (50 mm)**	**1 1/2 in. (37.5 mm)**	**1 in. (25.0 mm)**	**3/4 in. (19.0 mm)**	**1/2 in. (12.5 mm)**	**3/8 in. (9.5 mm)**	**No. 4 (4.75 mm)**	**No. 8 (2.36 mm)**	**No. 16 (1.18 mm)**
1	3 1/2 to 1 1/2 in. (90 to 37.5 mm)	100	90 to 100	...	25 to 60	...	0 to 15	...	0 to 5	...	...	...	...	...
2	2 1/2 to 1 1/2 in. (63 to 37.5 mm)	...	...	100	90 to 100	35 to 70	0 to 15	...	0 to 5	...	...	...	...	...
3	2 to 1 in. (50 to 25.0 mm)	...	...	...	100	90 to 100	35 to 70	0 to 15	...	0 to 5	...	...	...	...
357	2 in. to No. 4 (50 to 4.75 mm)	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	...	0 to 5	...	...
4	1 1/2 to 3/4 in. (37.5 to 19 mm)	...	...	...	...	100	90 to 100	20 to 55	0 to 15	...	0 to 5	...	...	...
467	1 1/2 in. to No. 4 (37.5 to 4.75 mm)	...	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	0 to 5	...	...

TABLE 5.5 (Continued)

Size No.	Nominal Size	Amounts Finer Than Each Laboratory Sieve (Square Openings), Weight Percent												
		4 in. (100 mm)	3 1/2 in. (90 mm)	3 in. (75 mm)	2 1/2 in. (63 mm)	2 in. (50 mm)	1 1/2 in. (37.5 mm)	1 in. (25.0 mm)	3/4 in. (19.0 mm)	1/2 in. (12.5 mm)	3/8 in. (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)
5	1 to 1/2 in. (25.0 to 12.5 mm)	...	...	...	...	...	100	90 to 100	20 to 55	0 to 10	0 to 5	...	...	...
56	1 to 3/8 in. (25.0 to 9.5 mm)	...	...	...	...	...	100	90 to 100	40 to 85	10 to 40	0 to 15	0 to 5	...	...
57	1 in. to No. 4 (25.0 to 4.75 mm)	...	...	...	...	...	100	95 to 100	...	25 to 60	...	0 to 10	0 to 5	...
6	3/4 in. to 3/8 in. (19.0 to 9.5 mm)	...	...	...	...	...	...	100	90 to 100	20 to 55	0 to 15	0 to 5	...	...
67	3/4 in. to No. 4 (19.0 to 4.75 mm)	...	...	...	...	...	...	100	90 to 100	...	20 to 55	0 to 10	0 to 5	...
7	1/2 in. to No. 4 (12.5 to 4.75 mm)	...	...	...	...	...	...	...	100	90 to 100	40 to 70	0 to 15	0 to 5	...
8	3/8 in. to No. 8 (9.5 to 2.36 mm)	...	...	...	...	...	...	...	...	100	85 to 100	10 to 30	0 to 10	0 to 5

TABLE 5.6 Aggregate Grading Requirements for Superpave Hot Mix Asphalt (AASHTO MP-2)

Sieve Size, mm (in.)	Nominal Maximum Size (mm)					
	37.5	25	19	12.5	9.5	4.75
50 (2 in.)	100	—	—	—	—	—
37.5 (1 1/2 in.)	90–100	100	—	—	—	—
25 (1 in.)	90 max	90–100	100	—	—	—
19 (3/4 in.)	—	90 max	90–100	100	—	—
12.5 (1/2 in.)	—	—	90 max	90–100	100	100
9.5 (3/8 in.)	—	—	—	90 max	90–100	95–100
4.75 (No. 4)	—	—	—	—	90 max	90–100
2.36 (No. 8)	15–41	19–45	23–49	28–58	32–67	—
1.18 (No. 16)	—	—	—	—	—	30–60
0.075 (No. 200)	0.0–6.0	1.0–7.0	2.0–8.0	2.0–10.0	2.0–10.0	6.0–12.0

Generally, local agencies develop their own specifications for the gradation of aggregates for asphalt concrete. Table 5.6 gives the aggregate grading requirements for Superpave hot mix asphalt (McGennis et al. 1995). These specifications define the range of allowable gradations for asphalt concrete for mix design purposes. Note that the percentage of material passing the 0.075-mm (No. 200) sieve, the fines or mineral filler, is carefully controlled for asphalt concrete due to its significance to the properties of the mix.

Once aggregate gradation from asphalt concrete mix design is established for a project, the contractor must produce aggregates that fall within a narrow band around the single gradation line established for developing the mix design. For example, the Arizona Department of Transportation will give the contractor full pay only if the gradation of the aggregates is within the following limits with respect to the accepted mix design gradations:

Sieve Size	Allowable Deviations for Full Pay
9.5 mm (3/8 in.) and larger	±3%
2.36 to 0.45 mm (No. 8 to No. 40)	±2%
0.075 mm (No. 200)	±0.5%

TABLE 5.7 Sample Calculation of Fineness Modulus

Sieve Size	Percentage of Individual Fraction Retained, by Weight	Cumulative Percentage Retained by Weight	Percentage Passing by Weight
9.5 mm (3/8 in.)	0	0	100
4.75 mm (No. 4)	2	2	98
2.36 mm (No. 8)	13	15	85
1.18 mm (No. 16)	25	40	60
0.60 mm (No. 30)	15	55	45
0.30 mm (No. 50)	22	77	23
0.15 mm (No. 100)	20	97	3
pan	3	100	0
Total	100		

Fineness Modulus = 286/100 = 2.86

Fineness Modulus The *fineness modulus* is a measure of the fine aggregates' gradation and is used primarily for portland cement concrete mix design. It can also be used as a daily quality control check in the production of concrete. The fineness modulus is one-hundredth of the sum of the cumulative percentage weight retained on the 0.15-mm, 0.3-mm, 0.6-mm, 1.18-mm, 2.36-mm, 4.75-mm, 9.5-mm, 19.0-mm, 37.5-mm, 75-mm, and 150-mm (No. 100, 50, 30, 16, 8, and 4 and 3/8-in., 3/4-in., $1\frac{1}{2}$-in., 3-in., and 6-in.) sieves. When the fineness modulus is determined for fine aggregates, sieves larger than 9.5 mm (3/8 in.) are not used. The fineness modulus should be in the range of 2.3 to 3.1, with a higher number being a coarser aggregate. Table 5.7 demonstrates the calculation of the fineness modulus.

Sample Problem 5.4

Calculate the fineness modulus of the sieve analysis results of sample problem 5.1.

Solution

According to the definition of fineness modulus, sieves 2.00 and 0.075 mm (No. 10 and 200) are not included.

$$\text{Fineness modulus} = \frac{6 + 34 + 64 + 71 + 86}{100} = 2.61$$

Blending Aggregates to Meet Specifications Generally, a single aggregate source is unlikely to meet gradation requirements for portland cement or asphalt concrete mixes. Thus, blending of aggregates from two or more sources would be required to satisfy the specifications. Figure 5.14 shows a graphical method for selecting the combination of two aggregates to meet a specification. Table 5.8 presents the data used for Figure 5.14. Determining a satisfactory aggregate blend with the graphical method entails the following steps (The Asphalt Institute 1995):

1. Plot the percentages passing through each sieve on the right axis for aggregate A and on the left axis for aggregate B, shown as open circles in Figure 5.14.
2. For each sieve size, connect the left and right axes.
3. Plot the specification limits of each sieve on the corresponding sieve lines; that is, a mark is placed on the 9.5-mm (3/8 in.) sieve line corresponding to 70% and 90% on the vertical axis, shown as closed circles in Figure 5.14.
4. Connect the upper- and lower-limit points on each sieve line.
5. Draw vertical lines through the rightmost point of the upper-limit line and the leftmost point of the lower-limit line. If the upper- and lower-limit lines overlap, no combination of the aggregates will meet specifications.
6. Any vertical line drawn between these two vertical lines identifies an aggregate blend that will meet the specification. The intersection with the upper axis defines the percentage of aggregate B required for the blend. The projection to the lower axis defines the percentage of aggregate A required.
7. Projecting intersections of the blend line and the sieve lines horizontally gives an estimate of the gradation of the blended aggregate. Figure 5.14 shows that a 50-50 blend of aggregates A and B will result in a blend with 43% passing through the 2.36-mm (No. 8) sieve. The gradation of the blend is shown in the last line of Table 5.8.

When more than two aggregates are required, the graphical procedure can be repeated in an iterative manner. However, a trial and error process is generally used to determine the proportions. The basic equation for blending is

$$P_i = Aa + Bb + Cc + \dots \tag{5.16}$$

where

P_i = percent blend material passing sieve size i
$A, B, C, \dots$ = percent of aggregates A, B, C, … passing sieve i
$a, b, c, \dots$ = decimal fractions by weight of aggregates A, B, and C used in the blend, where the total is 1.00

Table 5.9 demonstrates these calculations for two aggregate sources. The table shows the required specification range and the desired (or target)

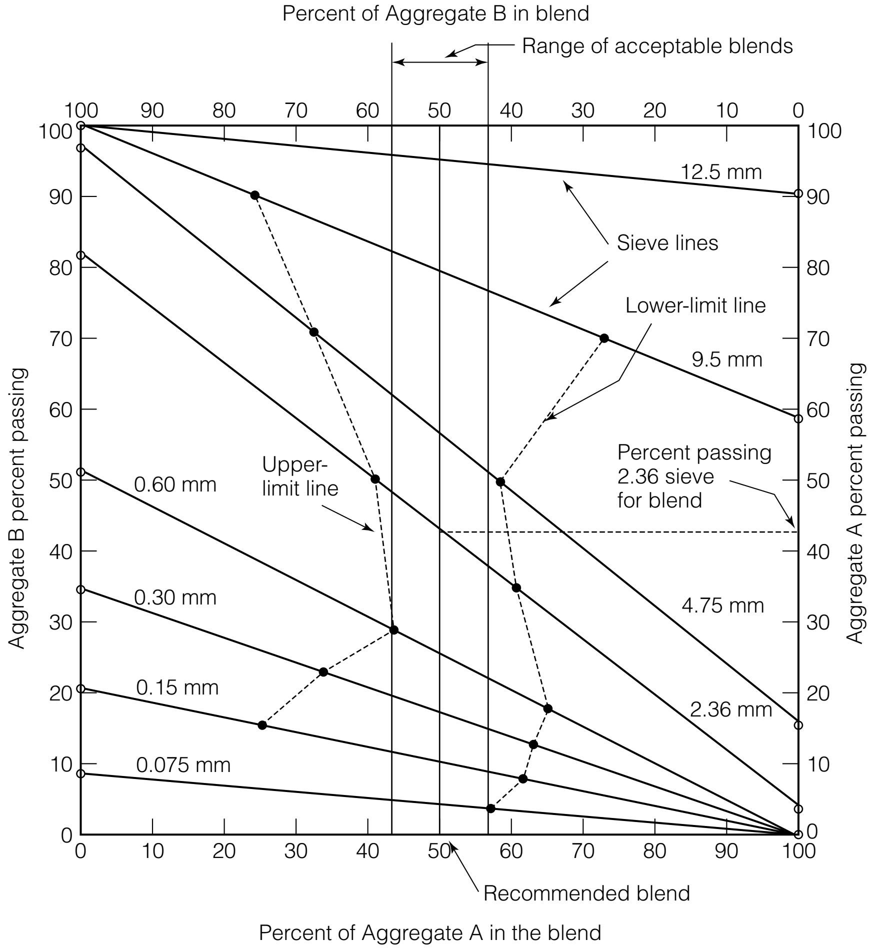


FIGURE 5.14 Graphical method for determining aggregate blend to meet gradation requirements. See Table 5.8.

TABLE 5.8 Example of Aggregate Blending Analysis by Graphical Method

Sieve	19 mm (3/4 in.)	12.5mm (1/2 in.)	9.5mm (3/8 in.)	4.75mm (No. 4)	2.36mm (No. 8)	0.60mm (No. 30)	0.30mm (No. 50)	0.15 mm (No.100)	0.075mm (No.200)
Specification	100	80–100	70–90	50–70	35–50	18–29	13–23	8–16	4–10
Agg. A	100	90	59	16	3	0	0	0	0
Agg. B	100	100	100	96	82	51	36	21	9
Blend	100	95	80	56	43	26	18	11	4.5

Note: Numbers shown are percent passing each sieve.

TABLE 5.9 Example of Aggregate Blending Analysis by Iterative Method.

Sieve	12.5 mm (1/2 in.)	9.5 mm (3/8 in.)	4.75 mm (No. 4)	2.00 mm (No. 10)	0.425 mm (No. 40)	0.180 mm (No. 80)	0.075 mm (No. 200)
Specification	100	95–100	70–85	55–70	20–40	10–20	4–8
Target gradation	100	98	77.5	62.5	30	15	6
% Agg. A (A)	100	100	98	90	71	42	19
% Agg. B (B)	100	94	70	49	14	2	1
30% A (a)	30	30	29.4	27	21.3	12.6	5.7
70% B (b)	70	65.8	49	34.3	9.8	1.4	0.7
Blend (P_i)	100	96	78	61	31	14	6.4

gradation, usually the midpoint of the specification. A trial percentage of each aggregate source is assumed and is multiplied by the percentage passing each sieve. These gradations are added to get the composite percentage passing each sieve for the blend. The gradation of the blend is compared to the specification range to determine if the blend is acceptable. With practice, blends of four aggregates can readily be resolved. These calculations are easily performed by a spreadsheet computer program.

Properties of Blended Aggregates When two or more aggregates from different sources are blended, some of the properties of the blend can be calculated from the properties of the individual components. With the exception of specific gravity and density, the properties of the blend are the simple weighted averages of the properties of the components. This relationship can be expressed as

$$X = P_1X_1 + P_2X_2 + P_3X_3 + \cdots \tag{5.17a}$$

where

X = composite property of the blend
X_1, X_2, X_3 = properties of fractions 1, 2, 3
P_1, P_2, P_3 = decimal fractions by weight of aggregates 1, 2, 3 used in the blend, where the total is 1.00

This equation applies to properties such as angularity, absorption, strength, and modulus.

Sample Problem 5.5

Coarse aggregates from two stockpiles having coarse aggregate angularity (crushed faces) of 40% and 90% were blended at a ratio of 30:70 by weight, respectively. What is the percent of crushed faces of the aggregate blend?

Solution

Crushed faces of the blend = (0.3)(40) + (0.7)(90) = 75%

Equation 5.17a is used for properties that apply to the whole aggregate materials in all stockpiles that are blended. However, some properties apply to either coarse aggregate only or fine aggregate only. Therefore, the percentage of coarse or fine aggregate in each stockpile has to be considered. The relationship in this case is expressed as

$$X = \frac{(x_1P_1p_1 + x_2P_2p_2 + \cdots + x_nP_np_n)}{(P_1p_1 + P_2p_2 + \cdots + P_np_n)} \tag{5.17b}$$

where,

X = the test value for the aggregate blend
x_i = the test result for stockpile i
P_i = the percent of stockpile i in the blend
p_i = the percent of stockpile i that either passes or is retained on the dividing sieve

Sample Problem 5.6

Aggregates from two stockpiles, A and B having coarse aggregate angularity (crushed faces) of 40% and 90% were blended at a ratio of 30:70 by weight, respectively. The percent material passing the 4.75 mm sieve was 25% and 55% for stockpiles A and B, respectively. What is the percent of crushed faces of the aggregate blend?

Solution

Crushed faces of the blend =

$$X = \frac{(x_1P_1p_1 + x_2P_2p_2 + \cdots + x_nP_np_n)}{(P_1p_1 + P_2p_2 + \cdots + P_np_n)}$$

$$= \frac{(40 \times 30 \times (100 - 25) + 90 \times 70 \times (100 - 55))}{(30 \times (100 - 25) + 70 \times (100 - 55))} = 69\%$$

Note that the percentage of coarse aggregate in each stockpile was calculated by subtracting the percentage passing the 4.75 mm sieve from 100.

Asphalt concrete mix design requires that the engineer knows the composite specific gravity of all aggregates in the mix. The composite specific gravity of a mix of different aggregates is obtained by the formula

$$G = \frac{1}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \frac{P_3}{G_3} + \ldots} \quad (5.18)$$

where

G = composite specific gravity
G_1, G_2, G_3 = specific gravities of fractions 1, 2, and 3
P_1, P_2, P_3 = decimal fractions by weight of aggregates 1, 2, and 3 used in the blend, where the total is 1.00

Note that Equation 5.18 is used only to obtain the combined specific gravity and density of the blend, whereas Equation 5.17 is used to obtain other combined properties.

Sample Problem 5.7

Aggregates from three sources having bulk specific gravities of 2.753, 2.649, and 2.689 were blended at a ratio of 70:20:10 by weight, respectively. What is the bulk specific gravity of the aggregate blend?

Solution

$$G = \frac{1}{\frac{0.7}{2.753} + \frac{0.2}{2.649} + \frac{0.1}{2.689}} = 2.725$$

5.5.9 Deleterious Substances in Aggregate

A deleterious substance is any material that adversely affects the quality of portland cement or asphalt concrete made with the aggregate. Table 5.10 identifies the main deleterious substances in aggregates and their effects on portland cement concrete. In asphalt concrete, deleterious substances are clay lumps, soft or friable particles, and coatings. These substances decrease the adhesion between asphalt and aggregate particles.

TABLE 5.10 Main Deleterious Substances and Their Affects on Portland Cement Concrete

Substance	Harmful Effect
Organic impurities	Delay settling and hardening, may reduce strength gain, may cause deterioration
Minus 0.075 mm (No. 200) materials	Weaken bond, may increase water requirements
Coal, lignite or other low-density materials	Reduce durability, may cause popouts or stains
Clay lumps and friable particles	Popouts, reduce durability and wear resistance
Soft particles	Reduce durability and wear resistance, popouts

5.5.10 Alkali–Aggregate Reactivity

Some aggregates react with portland cement, harming the concrete structure. The most common reaction, particularly in humid and warm climates, is between the active silica constituents of an aggregate and the alkalis in cement (sodium oxide, Na_2O, and potassium oxide, K_2O). The alkali–silica reaction results in excessive expansion, cracking, or popouts in concrete as shown in Figure 5.15. Other constituents in the aggregate, such as carbonates, can also react with the alkali in the cement; however, their reaction is less harmful. The alkali–aggregate reactivity is affected by the amount, type, and particle size of the reactive material, as well as by the soluble alkali and water content of the concrete.

The best way to evaluate the potential for alkali–aggregate reactivity is by reviewing the field service history. For aggregates without field service history, several laboratory tests are available to check the potential alkali–aggregate reactivity. The ASTM C227 test can be used to determine the potentially expansive alkali–aggregate reactivity of cement–aggregate combinations. In this test, a mortar bar is stored under a prescribed temperature and moisture conditions and its expansion is determined. The quick chemical test (ASTM C289) can be used to identify potentially reactive siliceous aggregates. ASTM C586 is used to determine potentially expansive carbonate rock aggregates (alkali–carbonate reactivity).

If alkali-reactive aggregate must be used, the reactivity can be minimized by limiting the alkali content of the cement. The reactivity can also be reduced by keeping the concrete structure as dry as possible. Fly ash, ground granulated blast furnace slag, silica fume, or natural pozzolans can be used to control the alkali–silica reactivity. Lithium-based admixtures have also been used for the same purpose. Finally, replacing about 30% of a reactive

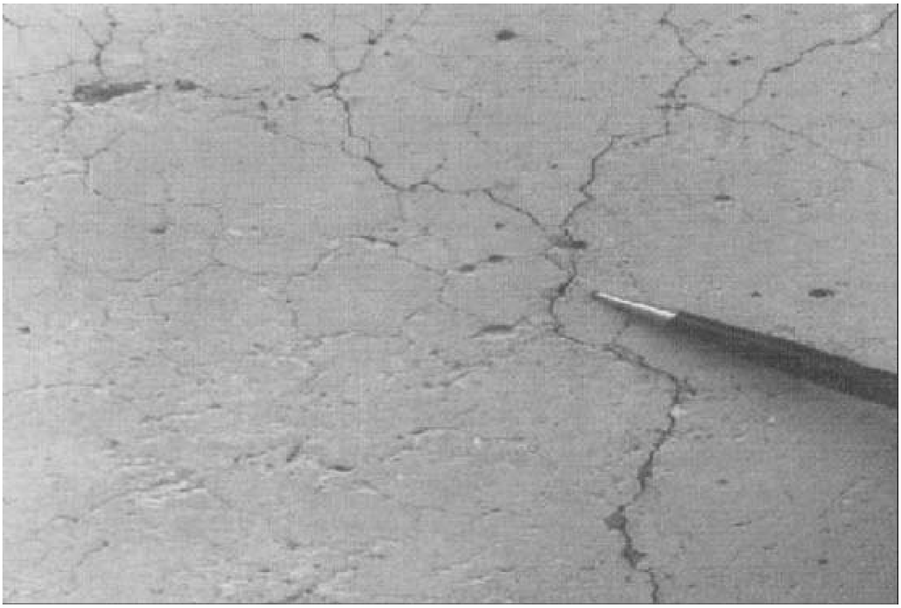


FIGURE 5.15 Example of cracking in concrete due to alkali-silica reactivity.

sand–gravel aggregate with crushed limestone (limestone sweetening) can minimize the alkali reactivity (Kosmatka et al. 2002).

5.5.11 Affinity for Asphalt

Stripping, or moisture-induced damage, is a separation of the asphalt film from the aggregate through the action of water, reducing the durability of the asphalt concrete and resulting in pavement failure. The mechanisms causing stripping are complex and not fully understood. One important factor is the relative affinity of the aggregate for either water or asphalt. *Hydrophilic* (water-loving) aggregates, such as silicates, have a greater affinity for water than for asphalt. They are usually acidic in nature and have a negative surface charge. Conversely, *hydrophobic* (water-repelling) aggregates have a greater affinity for asphalt than for water. These aggregates, such as limestone, are basic in nature and have a positive surface charge. Hydrophilic aggregates are more susceptible to stripping than hydrophobic aggregates. Other stripping factors include porosity, absorption, and the existence of coatings and other deleterious substances.

Since stripping is the result of a compatibility problem between the asphalt and the aggregate, tests for stripping potential are performed on the asphalt concrete mix. Early compatibility tests submerged the sample in either room-temperature water (ASTM D1664) or boiling water (ASTM D3625); after a period of time, the technician observed the percentage of particles stripped from the asphalt. More recent procedures subject asphalt concrete to cycles of freeze–thaw conditioning. The strength or modulus of the specimens is measured and compared with the values of unconditioned specimens (ASTM D1075).

5.6 Handling Aggregates

Aggregates must be handled and stockpiled in such a way as to minimize segregation, degradation, and contamination. If aggregates roll down the slope of the stockpile, the different sizes will segregate, with large stones at the bottom and small ones at the top. Building stockpiles in thin layers circumvents this problem. The drop height should be limited to avoid breakage, especially for large aggregates. Vibration and jiggling on a conveyor belt tends to work fine material downward while coarse particles rise. Segregation can be minimized by moving the material on the belt frequently (up and down, side to side, in and out) or by installing a baffle plate, rubber sleeve, or paddle wheel at the end of the belt to remix coarse and fine particles. Rounded aggregates segregate more than crushed aggregates. Also, large aggregates segregate more readily than smaller aggregates. Therefore, different sizes should be stockpiled and batched separately. Stockpiles should be separated by dividers or placed in bins to avoid mixing and contamination (Figure 5.16) (Meininger and Nichols 1990).

5.6.1 Sampling Aggregates

In order for any of the tests described in this chapter to be valid, the sample of material being tested must represent the whole population of materials that is being quantified with the test. This is a particularly difficult problem with aggregates due to potential segregation problems. Samples of aggregates can be collected from any location in the production process, that is, from the stockpile, conveyor belts, or from bins within the mixing machinery (ASTM D75). Usually, the best location for sampling the aggregate is on the conveyor belt that feeds the mixing plant. However, since the aggregate segregates on the belt, the entire width of the belt should be sampled at several locations or times throughout the production process. The samples would then be mixed to represent the entire lot of material.

FIGURE 5.16 Aggregate bins used to stockpile aggregates with different sizes.

Sampling from stockpiles must be performed carefully to minimize segregation. Typically, aggregate samples are taken from the top, middle, and bottom of the stockpile and then combined. Before taking the samples, discard the 75mm to 150mm (3 in. to 6 in.) material at the surface. A board shoved vertically into the pile just above the sampling point aids in preventing rolling of coarse aggregates during sampling. Samples are collected using a square shovel and are placed in sample bags or containers and labeled.

Sampling tubes 1.8 m (6 ft) long and 30 mm (1.25 in.) in diameter are used to sample fine aggregate stockpiles. At least five samples should be collected from random locations in the stockpile. These samples are then combined before laboratory testing.

Field sample sizes are governed by the nominal maximum size of aggregate particles (ASTM D75). Larger-sized aggregates require larger samples to minimize segregation errors. Field samples are typically larger than the samples needed for testing. Therefore, field samples must be reduced using sample splitters (Figure 5.17) or by quartering (Figure 5.18) (ASTM C702).

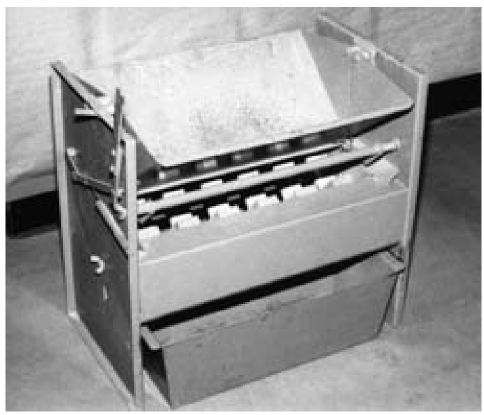


FIGURE 5.17 Aggregate sample splitter.

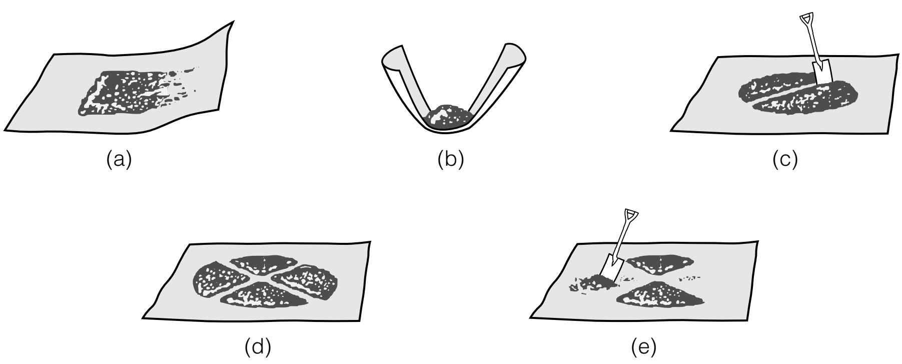


FIGURE 5.18 Steps for reducing the sample size by quartering: (a) mixing by rolling on blanket, (b) forming a cone after mixing, (c) flattening the cone and quartering, (d) finishing quartering, (e) retaining opposite quarters (the other two quarters are rejected). (ASTM C702). Copyright ASTM. Reprinted with permission.

SUMMARY

Aggregates are widely used as a base material for foundations and as an ingredient in portland cement concrete and asphalt concrete. While the geological classification of aggregates gives insight into the properties of the material, the suitability of a specific source of aggregates for a particular application requires testing and evaluation. The most significant attributes of aggregates include the gradation, specific gravity, shape and texture, and soundness. When used in concrete, the compatibility of the aggregate and the binder must be evaluated.

QUESTIONS AND PROBLEMS

5.1 What are the three mineralogical or geological classifications of rocks and how are they formed?

5.2 Discuss five different desirable characteristics of aggregate used in portland cement concrete.

5.3 Discuss five different desirable characteristics of aggregate used in asphalt concrete.

5.4 The shape and surface texture of aggregate particles are important for both portland cement concrete and hot mix asphalt.

a. For preparing PCC, would you prefer round and smooth aggregate or rough and angular aggregate? Briefly explain why (no more than two lines).

b. For preparing HMA, would you prefer round and smooth aggregate or rough and angular aggregate? Briefly explain why (no more than two lines).

5.5 A sample of fine aggregate has the following properties:

Wet mass = 521.0 g
Dry mass = 491.6 g
Absorption = 2.5%

Determine: (a) total moisture content, and (b) free moisture content

5.6 Use the following information to determine the total and free moisture contents in percent:

Mass of wet sand = 627.3 g
Mass of dry sand = 590.1 g
Absorption = 1.5%

5.7 A sample of wet aggregate weighed 19.682 N. After drying this sample in an oven it weighed 18.365 N. The absorption of this aggregate is 4.8%. Calculate the percent of free water in the original wet sample.

5.8 Samples of coarse aggregate from a stockpile are brought to the laboratory for determination of specific gravities. The following weights are found:

Mass of moist aggregate sample as brought to the laboratory: 5298 grams
Mass of oven dried aggregate: 5216 g
Mass of aggregates submerged in water: 3295 g
Mass of SSD (Saturated Surface Dry) Aggregate: 5227 g

Find
a. The aggregate bulk specific gravity
b. The aggregate apparent specific gravity
c. The moisture content of stockpile aggregate (report as a percent)
d. Absorption (report as percent)

5.9 Base course aggregate has a target dry density of 124.9 lb/cu ft in place. It will be laid down and compacted in a rectangular street repair area of 1000 ft $\times$ 52 ft $\times$ 6 in. The aggregate in the stockpile contains 2.7 percent moisture. If the required compaction is 95 percent of the target, how many tons of aggregate will be needed?

5.10. Calculate the percent voids between aggregate particles, which have been compacted by rodding, if the dry-rodded unit weight is 88.0 lb/cu ft and the bulk dry specific gravity is 2.701.

5.11. Coarse aggregate is placed in a rigid bucket and rodded with a tamping rod to determine its unit weight. The following data are obtained:

Volume of bucket = $\frac{1}{2}$ ft^3
Weight of empty bucket = 20.3 lb
Weight of bucket filled with dry rodded coarse aggregate = 69.6 lb

a. Calculate the dry-rodded unit weight
b. If the bulk dry specific gravity of the aggregate is 2.620, calculate the percent voids between aggregate particles.

5.12 The following laboratory tests are performed on aggregate samples:
a. Specific gravity and absorption
b. Soundness
c. Sieve analysis test

What are the significance and use of each of these tests?

5.13 The specific gravity and absorption test (ASTM C128) was performed on fine aggregate and the following data were obtained:

Mass of SSD sand = 500.0 g
Mass of pycnometer with water only = 623.0 g
Mass of pycnometer with sand and water = 938.2 g
Mass of dry sand = 495.5 g

Calculate the specific gravity values (dry bulk, SSD, and apparent) and the absorption of the fine aggregate.

5.14 Referring to ASTM specification C33, what is the maximum sieve size and the nominal maximum sieve size for each of the standard sizes Numbers 4, 57, and 7.

5.15 Calculate the sieve analysis of the following aggregate and plot on a semilog gradation paper:

Sieve size	Amount Retained, g	Cumulative Amount Retained, g	Cumulative Percent Retained	Percent Passing
25 mm (1 in.)	0			
9.5 mm (3/8 in.)	35.2			
4.75 mm (No. 4)	299.6			
2.00 mm (No. 10)	149.7			
0.425 mm (No. 40)	125.8			
0.075 mm (No.200)	60.4			
Pan	7.3			

5.16 Calculate the sieve analysis of the following aggregate, and plot on a 0.45 power gradation chart:

Sieve size	Amount, g	Cumulative Amount Retained, g	Cumulative Percent Retained	Percent Passing
Plus 37.5 mm	0			
37.5 mm to 25 mm	206			
25 mm to 19 mm	603			
19 mm to 9.5 mm	1413			
9.5 mm to 4.75 mm	508			
4.75 mm to 0.60 mm	963			
0.60 mm to 0.075 mm	1425			
Pan	32			

5.17 A sieve analysis test was performed on a sample of aggregate and produced the following results:

Sieve Size, mm	Amount Retained, g	Sieve Size, mm	Amount Retained, g
25	0	1.18	891.5
19	376.7	0.60	712.6
12.5	888.4	0.30	625.2
9.5	506.2	0.15	581.5
4.75	1038.4	0.075	242.9
2.36	900.1	Pan	44.9

Calculate the percent passing through each sieve. Plot the percent passing versus sieve size on

a. a semilog gradation chart, and
b. a 0.45 gradation chart (Figure A.22).

5.18 A sieve analysis test was performed on a sample of coarse aggregate and produced the following results:

Sieve Size	Amount Retained, lb
3 in.	0
2 in.	0
1-1/2 in.	5.2
1 in.	18.1
3/4 in.	14.8
1/2 in.	16.3
3/8 in.	25.0
No. 4	8.5
Pan	1.6

a. Calculate the percent passing through each sieve.
b. What is the maximum size?
c. What is the nominal maximum size?
d. Plot the percent passing versus sieve size on a semilog gradation chart.
e. Plot the percent passing versus sieve size on a 0.45 gradation chart (Figure A.22).
f. Referring to ASTM C33, what is the closest size number and does it meet the gradation for that standard size?

5.19 Draw a graph to show the cumulative percent passing through the sieve versus sieve size for well-graded, gap-graded, open-graded, and one-sized aggregates.

5.20 Table P5.20 shows the grain size distributions of aggregates A, B, and C. The three aggregates must be blended at a ratio of 15:25:60 by weight, respectively. Using a spreadsheet program, determine the grain size distribution of the blend.

Table P5.20

	Percent Passing								
	Size								
	25 mm	19 mm	12.5 mm	9.5 mm	4.75 mm	1.18 mm	0.60 mm	0.30 mm	0.15 mm
Aggregate A	100	100	100	83	67	49	37	25	18
Aggregate B	100	100	74	51	32	24	19	13	7
Aggregate C	100	82	66	42	27	14	5	0	0

5.21 Table P5.21 shows the grain size distributions of two aggregates A and B.

Table P5.21

Sieve Size, mm	25	19	12.5	9.5	4.750	2.36	1.18	0.600	0.300	0.150	0.075
% Passing Agg. A	100	92	76	71	53	38	32	17	10	5	3.0
% Passing Agg. B	100	100	92	65	37	31	30	29	28	21	15.4

Answer the following questions and show all calculations:

a. What are the maximum sizes of aggregates A and B?
b. Is aggregate A well graded? Why?
c. Is aggregate B well graded? Why?

5.22 Three aggregates are to be mixed together in the following ratio:

Aggregate A 20%
Aggregate B 45%
Aggregate C 35%

For each aggregate, the percent passing a set of five sieves is shown in the following table:

Sieve Size (mm)	% Passing Agg. A	% Passing Agg. B	% Passing Agg. C
9.5	85	50	40
4.75	70	35	30
0.6	35	20	5
0.3	25	13	1
0.15	17	7	0

Determine the percent passing each sieve for the blended aggregate.

5.23 Table P5.23 shows the grain size distribution for two aggregates and the specification limits for an asphalt concrete. Determine the blend proportion required to meet the specification and the gradations of the blend. On a semilog gradation graph, plot the gradations of aggregate A, aggregate B, the selected blend, and the specification limits.

Table P5.23

	Percent Passing								
	Size								
	19 mm (3/4 in.)	12.5 mm (1/2 in.)	9.5 mm (3/8 in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	0.60 mm (No. 30)	0.30 mm (No. 50)	0.15 mm (No. 100)	0.075 mm (No. 200)
Spec. limits	100	80–100	70–90	50–70	35–50	18–29	13–23	8–16	4–10
Aggregate A	100	85	55	20	2	0	0	0	0
Aggregate B	100	100	100	85	67	45	32	19	11

5.24 Laboratory specific gravity and absorption tests are run on two coarse aggregate sizes, which have to be blended. The results are as follows:

Aggregate A: Buck specific gravity = 2.814; absorption = 0.4%
Aggregate B: Buck specific gravity = 2.441; absorption = 5.2%

a. What is the specific gravity of a mixture of 50% aggregate A and 50% aggregate B by weight?
b. What is the absorption of the mixture?

5.25 The mix design for an asphalt concrete mixture requires 2 to 6 percent minus No. 200. The following three aggregates are available:

	Minus No. 200
Coarse	0.5%
Intermediate	1.5%
Fine Aggregate	11.5%

Considering that approximately equal amounts of coarse and intermediate aggregate will be used in the mix, what is the percentage of fine aggregate that will give a resulting minus No. 200 in the mixture in the middle of the range, about 4 percent?

5.26 Define the fineness modulus of aggregate. What is it used for?

5.27 Calculate the fineness modulus of aggregate B in problem 5.21. (Note that the percent passing the 1.18-mm (No. 16) sieve is not given and must be estimated.)

5.28 A portland cement concrete mix requires mixing sand having a gradation following the midpoint of the ASTM gradation band (Table 5.4) and gravel having a gradation following the midpoint of size number 467 of the ASTM gradation band (Table 5.5) at a ratio of 2:3 by weight. On a 0.45 power gradation chart, plot the gradations of the sand, gravel, and the blend. Is the gradation of the blend well graded? If not, what would you call it?

5.29 Discuss the effect of the amount of material passing the 0.075-mm (No. 200) sieve on the stability, drainage, and frost susceptibility of aggregate base courses.

5.30 Aggregates from three sources having the properties shown in Table P5.30 were blended at a ratio of 60:30:10 by weight. Determine the properties of the aggregate blend.

Table P5.30

Property	Aggregate 1	Aggregate 2	Sand
Coarse aggregate angularity, percent crushed faces	100	87	N/A
Bulk specific gravity	2.631	2.711	2.614
Apparent specific gravity	2.732	2.765	2.712

5.31 Three aggregates are blended by weight in the following percentages:

50% Crushed limestone	Bulk dry Sp. Gr. = 2.702
30% Blast furnace slag	Bulk dry Sp. Gr. = 2.331
20% Natural sand	Bulk dry Sp. Gr. = 2.609

What is the bulk specific gravity of the blended aggregates?

5.32 What is alkali–silica reactivity? What kind of problems are caused by ASR? Mention two ways to minimize ASR.

5.33 What are the typical deleterious substances in aggregates that affect portland cement concrete? Discuss these effects.

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