Chapter 2
Aggregates

Aggregates are intensively used in civil and transportation infrastructures. In specification ASTM C125-21 (2021), aggregates are defined as granular materials such as sand, gravel, and crushed stones or slag, used with a cementing medium to form hydraulic cement concrete or mortar. In specification JTG E42 2005 (2005), aggregates are defined as granular materials used in mixture as skeleton structure and filling, including gravel, crushed stones, crushed sand, stone chips and sand, etc.

Aggregates can be used either as underlying materials for foundations and pavements or as ingredients in Portland cement concrete and asphalt mixture. As underlying materials, aggregates can provide a stable base or a drainage layer. As ingredients, aggregates can provide strong inter-particle friction, which is the key to the strength and stability of concrete. Aggregates account for 75–85% by weight in Portland cement concrete, and 92–96% by weight in the asphalt mixtures.

2.1 Production of Aggregates

2.1.1 Aggregate Sources

According to the sources, aggregates can be classified as natural aggregates, manufactured aggregates, and recycled aggregates. Natural aggregates include gravel which is obtained from gravel pits and river deposits, and crushed stones which are obtained by processing rocks from quarries. It is noted that gravel also needs to be crushed to obtain the required size and shape. The manufactured aggregates include the by-product aggregates which are mostly the slag waste from iron and steel production and the expanded shale and clay which are produced by the drying and sintering of clay or shale raw material, forming a sintered porous structure. Recycled aggregates are obtained from the demolition of buildings, bridges, pavements, and other structures. Recycled concrete aggregates contain not only the original aggregates,

Q. Dong et al. (eds.), *Civil Engineering Materials for Transportation Infrastructure*,
https://doi.org/10.1007/978-981-99-1300-8_2

but also the cement paste or asphalt mortar, which may reduce the specific gravity and increases the porosity.

According to the density, aggregates can be classified into heavy-weight, normal-weight, and light-weight aggregates. The traditional concrete using natural aggregates is normal-weight concrete. Slag aggregates are heavy-weight aggregates and are usually used in the heavy-weight concrete for radiation shields. Expanded shale, clay, or slate materials that have been calcined in a rotary kiln to develop porous structures are light-weight aggregates and can be used in light-weight concrete for heat or sound insulation.

2.1.2 Types of Rocks

Rock has been an important civil engineering material since the beginning of civilization. Compared to other abundant natural materials such as timber, rock is much harder and more durable whereas very heavy. Rocks constitute the earth's crust and are mainly crystalline solids with definite physical and chemical properties which also determine the properties of aggregates. Rocks can be classified into three types based on how they are formed, including igneous, sedimentary, and metamorphic rocks.

1. Igneous rocks

Igneous rocks are hardened or crystallized volcanic molten materials. There are two types of igneous rocks: the extrusive or volcanic rocks formed by the rapid cooling of the magma at the earth's surface and the intrusive rocks formed by the slow cooling of the magma at depths within the earth's crust. The most frequently seen igneous rocks include granite, basalt, diabase, pozzolan, and pumice. Granite, basalt, and diabase have higher density and strength while pozzolan and pumice have much lower density and strength.

(1) Granite

The composition and texture of rocks can be characterized by petrographic analysis. Granite is an intrusive igneous rock showing a variety of tonalities (white, grey, blue, pink, or red) and a holocrystalline granular texture ranging from less than 0.1–10 cm. Granite is mainly composed of feldspar and quartz. It usually contains 20–60% quartz by volume and is hard and usually difficult to be mechanically processed. Based on the chemical composition, granite is typically described as the ultrabasic rock with silica oxides (SiO_2) content higher than 40% by weight. The common types of granite contain more than 60% silica oxides. Other compounds of granite include alumina (Al_2O_3), iron oxide III (Fe_2O_3), magnesium oxide (MgO), sodium oxide (Na_2O), and potassium oxide (K_2O). The apparent density of granite is between 2.65 and 2.75 g/cm^3 and the compressive strength usually lies above 200 MPa.

(2) Basalt and Diabase

Basalt is mostly formed as an extrusive rock with dark color and pyroxene and olivine crystals. Basalt usually includes 45–55% silica oxides and less than 10% feldspar. Its apparent density is around 3 g/cm^3 and the compressive strength is between 100 and 500 MPa. Diabase is similar to basalt and normally has finer crystals. Its apparent density is between 2.7 and 2.9 g/cm^3 and the compressive strength is between 160 and 180 MPa. It has good resistance to acid.

(3) Pozzolan and Pumice

Pozzolan is a powdery volcanic rock with a grain size of less than 5 mm. It has a pozzolanic activity that can react with calcium oxide and therefore can be used as raw materials for the supplementary materials of Portland cement. Pumice is a volcanic rock with a grain size of larger than 5 mm and a porous structure. Its apparent density is between 0.3 and 0.6 g/cm^3 which is less than the density of water.

2. Sedimentary rocks

Sedimentary rocks are deposits of disintegrated existing rocks, soils, or other inorganic materials. Natural cementing binds the particles together. Sedimentary rocks can be classified by the predominant mineral, including calcareous (limestone, chalk, etc.), siliceous (chert, sandstone, etc.), and argillaceous (shale, etc.).

(1) Limestone

Limestone is the most widely used sedimentary rock. Its major components are calcite and aragonite, which are different crystal forms of calcium carbonate. Limestone can be classified according to the mode of formation, and show many colors including white, grey, buff, and blue. Its apparent density is 2.6–2.8 g/cm^3. The compressive strength is 80–160 MPa. Its water absorption is between 2 and 10%.

(2) Sandstone

Sandstone is composed of sand-sized mineral particles or rock fragments. Depending on the original sand deposit, the sandstone has a texture ranging from 0.06 to 2 mm. Sandstone can have different colors including white, buff, grey, brown, and shades of red depending on the natural cement. Its apparent density is around 2.65 g/cm^3, the compressive strength ranges from 5 to 200 MPa and its water absorption is between 0.2 and 7%.

3. Metamorphic rocks

When igneous or sedimentary rocks are drawn back to the earth's crust and exposed to heat and pressure, then the grain structure is reformed and the metamorphic rocks are formed. Metamorphic rocks generally have a crystalline structure, with grain sizes ranging from fine to coarse. Metamorphic rocks frequently have anisotropic texture and typical examples are gneiss, and marble. Marble is a metamorphic stone with higher hardness, formed at a variable depth of the earth's surface. Marble forms from complete recrystallization from other rocks. It is mainly used for building decoration. The compressive strength is between 50 and 140 MPa.

2.1.3 *Physical Properties of Rocks*

Natural aggregates are produced from the breakdown of large rocks. The properties of aggregates are mostly determined by the rocks and the processing method. The technical properties of rocks include physical, mechanical, and chemical properties.

Physical properties of rocks generally include density, absorption, and permeability. They are directly related to the physical properties of aggregates and are often used as performance indices. To calculate the density of rocks, we first need to understand the two types of voids in a rock particle as shown in Fig. 2.1. The impermeable voids are the pores inside the rock particle, whereas the permeable voids or open pores are connected to the surface and could absorb moisture or be filled with water.

(1) Solid density: The solid density is obtained by grinding rocks into small particles to exclude impermeable voids and then measuring the density of the small particles in a similar way as fine aggregate.
(2) Bulk density: The bulk density is the ratio of the weight of rock over the bulk volume which includes the permeable voids.
(3) Apparent density: The apparent density is the ratio of the weight of rock over the apparent volume which excludes the permeable voids.
(4) Moisture content: Moisture content means the water content in an air dry state. It is the ratio of the weight of water to the dry weight of the rock particles.
(5) Absorption at saturation: The absorption at saturation means the maximum water content when all the permeable voids of rock particles are filled with water, which is also called the saturated surface dry (SSD) status.

1. Water damage resistance

Water damage resistance is evaluated by the softening coefficient, which is the ratio of the compressive strength of a water-saturated rock sample over that of a dry rock sample. A higher softening coefficient means higher resistance to water damage. The water damage resistance of rocks can be classified into four levels based on the softening coefficient.

- High: > 0.9
- Medium: 0.75–0.9
- Low: 0.6–0.75

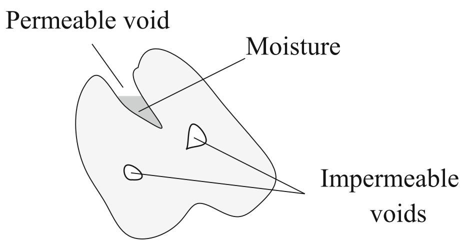


Fig. 2.1 Two types of voids in a rock particle, revised after Mamlouk and Zaniewski (2017)

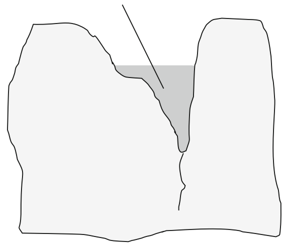


Fig. 2.2 Cracks caused by freezing

- Unstable: < 0.6.

2. Freeze-thaw resistance

Freeze-thaw resistance is evaluated by the reduction in strength or weight loss after specific freeze-thaw cycles. As shown in Fig. 2.2, when the absorbed water in the permeable voids freezes, its volume expands and causes cracks or forces cracks to widen. During thawing, more water may be absorbed into the cracks and the fracture action continues. A quality rock should have a strength reduction less than 25% and a weight loss less than 5%, and have no penetrating cracks.

3. Soundness

The soundness is tested by submerging the rock sample in a saturated solution of sodium sulfate and letting salt crystals form in permeable pores, thus simulating the formation of ice crystal. The damage caused by the expanded crystals is observed to evaluate the soundness.

2.1.4 Mechanical Properties of Rocks

Mechanical properties of rocks include compressive strength, impact toughness, and abrasion resistance and are used to evaluate the ability to withstand loads, wearing, or deformation.

(1) Compressive strength: The compressive strength of rocks is measured by the unconfined compressive test of the cores of rock samples. It measures the ability of rock samples to withstand compressive loads and resist deformation.
(2) Impact toughness: Impact toughness measures the rock fracture toughness under impacts. It measures the ability of rock samples to absorb energy and resist fracturing when force is applied.
(3) Abrasion resistance: Abrasion resistance is the behavior of rock samples under the shear stress and gouging action of abrasion. It indicates the wearing quality when the rock is exposed to traffic loading.

2.1.5 Chemical Properties of Rocks

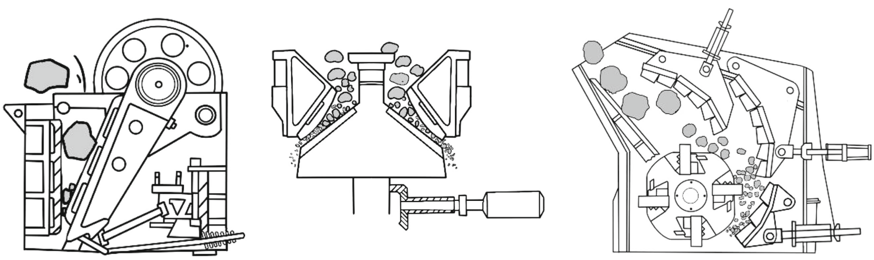
The chemical properties of rocks related to aggregates mainly include the alkali reaction and affinity with water or asphalt. The result of the alkali reaction test indicates whether the rock is inert or active, which is critical for the alkali reaction in cement concrete. The affinity with water or asphalt indicates the bonding between aggregates and asphalt. Usually, limestone has a better affinity with asphalt than granite.

2.1.6 Crusher

For aggregates using natural resources, rocks are usually obtained from quarries and crushed to obtain the needed size, shape, and texture. There are generally three types of crushers: the jaw crusher, the cone crusher, and the impact crusher. As shown in Fig. 2.3, the jaw or cone crusher uses a compressive force to crush aggregates, while the impact crusher uses an impact force to crush aggregates. In the impact crusher, aggregates are firstly crushed by the rotating bars and then thrown against the breaker plates for secondary crushing. The jaw or cone crusher tends to produce more aggregates with sharp angles due to the shear fracture of aggregates under the compressive or squeezing force. The impact crusher tends to produce more round shape aggregates. Usually, the jaw or cone crusher is used to crush larger rocks and the impact crusher is then used to crush aggregates into smaller sizes.

2.2 Physical Properties of Coarse Aggregates

The properties of aggregates are defined by the characteristics of both the individual particles and the combined materials. In specification JTG E42-2005 (2005), the pavement aggregate tests include 26 tests for coarse aggregates, 19 tests for fine



(a) The jaw crusher (b) The cone crusher (c) The impact crusher

Fig. 2.3 Three types of aggregate crushers

Table 2.1 Requirements for coarse aggregates in asphalt mixtures (JTG F40-2004, 2004)

Test items	Expressway and Class I road		Other roads	Test methods
	Surface	Other layers		
Max. crushing value (%)	26	28	30	T 0316
Max. LA abrasion value (%)	28	30	35	T 0317
Min. apparent specific gravity	2.60	2.50	2.45	T 0304
Max. absorption (%)	2.0	3.0	3.0	T 0304
Max. soundness (%)	12	12	–	T 0314
Max. flakiness content (%)	15	18	20	T 0312
Max. percentage of > 9.5 mm (%)	12	15	–	
Max. percentage of < 9.5 mm (%)	18	20	–	
Max. percentage of < 0.075 mm (%)	1	1	1	T 0310
Max. content of soft particles (%)	3	5	5	T 0320

aggregates, and 5 tests for mineral fillers, covering the physical, mechanical and chemical characterizations of aggregates. Table 2.1 summarize the quality requirements for coarse aggregates used in asphalt mixtures and corresponding test methods from JTG E42-2005 (2005), mainly including the physical and mechanical properties.

2.2.1 Sampling

The sample of aggregates being tested must represent the whole population of aggregates. For coarse aggregates, the sample size is determined by the nominal maximum size of aggregates. Larger-sized aggregates require larger samples to minimize errors. Usually, field samples are reduced using sample splitters or by quartering to obtain the samples needed for testing. The specification JTG E42-2005 T0301 (2005) recommends a quartering method to obtain coarse aggregate samples, which includes flattening and quartering the mixed field samples, and then retaining opposite quarters as the sample as shown in Fig. 2.4.

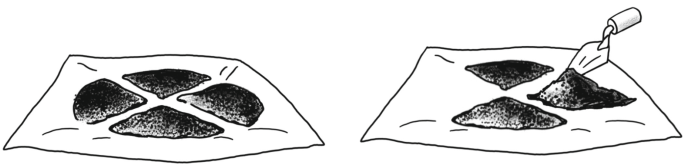


Fig. 2.4 Quartering and taking opposite quarters

2.2.2 Sieve Analysis and Gradation

Sieve analysis is to evaluate the size of aggregates by passing the aggregates through a series of sieves of progressively smaller mesh size (Fig. 2.5). As defined in specification JTG E42-2005 T0302 (2005) and T0327, the common sieve sizes range from 0.075 to 75 mm, including 75, 63, 53, 37.5, 31.5, 26.5, 19, 16, 13.2, 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15, and 0.075 mm. Gradation is the particle size distribution of aggregates and is one of the most important characteristics for aggregates, especially in pavement asphalt mixtures. The gradation results are usually described by the cumulative percentage of aggregates that either pass through or are retained by a specific sieve size.

As shown in Table 2.2, from sieve analysis, we could obtain the weight retained on each sieve and the pan, the total weight and the weight lost during sieve analysis, which can be calculated as below.

$$m_{\mathrm{s}} = m_{\mathrm{t}} - \sum m_i \tag{2.1}$$

where

m_s = weight lost during sieve analysis (g);

m_t = total weight (g);

m_i = weight retained on the ith sieve and the bottom (g).

Based on the weight retained on each sieve, we can calculate the percentage retained which is the weight retained on each sieve over $\sum m_i$, the cumulative

Fig. 2.5 Sieve analysis

Table 2.2 Results of sieve analysis

Sieve (mm)	Retained (g)	Retained (%)	Cumulative retained (%)	Passing (%)
$D_0 = D_{max}$	$m_0 = 0$	$a_0 = 0 \times 100$	$A_0 = 0$	$P_0 = 100$
D_1	m_1	$a_1 = m_1/\sum m_i \times 100$	$A_1 = a_1$	$P_1 = 100 - A_1$
D_2	m_2	$a_2 = m_2/\sum m_i \times 100$	$A_2 = a_1 + a_2$	$P_2 = 100 - A_2$
D_3	m_3	$a_3 = m_3/\sum m_i \times 100$	$A_3 = a_1 + a_2 + a_3$	$P_3 = 100 - A_3$
…	…	…	…	…
D_i	m_i	$a_i = m_i/\sum m_i \times 100$	$A_i = a_1 + a_2 + a_3 + \cdots + a_i$	$P_i = 100 - A_i$
…	…	…	…	…
D_n	m_n	$a_n = m_n/\sum m_i \times 100$	$A_n = a_1 + a_2 + a_3 + \cdots + a_n$	$P_n = 100 - A_n$

percentage retained which is the sum of the percentage retained above this sieve, and the passing percentage as below.

$$a_i = \frac{m_i}{\sum m_i} \times 100 \quad (2.2)$$

$$A_i = a_1 + a_2 + \cdots + a_i \quad (2.3)$$

$$P_i = 100 - A_i \quad (2.4)$$

where

$a_i =$ percentage retained (%);

$A_i =$ cumulative percentage retained (%);

$P_i =$ passing percentage (%).

For the example shown in Table 2.3, the weight retained on the 4.75 mm sieve is 1000 g and the total weight of the aggregate is 2000 g. The retained percentage on this sieve is 1000/2000 = 50%. The cumulative retained percentage can be calculated by adding the retained percentage of all the sieves above the 4.75 mm sieve, which equals 60%, indicating that 60% of the sample are larger than 4.75 mm. The passing percentage is one minus the cumulative retained percentage, which equals 40%, indicating 40% of the sample passes the 4.75 mm sieve.

2.2.3 Aggregate Size

Aggregates can be classified by size as coarse aggregates, fine aggregates, and fillers. As shown in Table 2.4, in the ASTM specification (2021), coarse aggregates are larger than 4.75 mm. Fine aggregates are between 4.75 and 0.075 mm. Fillers are smaller than 0.075 mm. In the Chinese specification JTG E42-2005 (2005), for

Table 2.3 The example of a sieve analysis

Sieve (mm)	Retained (g)	Retained (%)	Cumulative retained (%)	Passing (%)
13.2	0	0	0	100
9.5	200	10	10	90
4.75	1000	50	60	40
2.36	600	30	90	10
1.18	0	0	90	10
0.6	200	10	100	0
0.3	0	0	100	0
Bottom	0	0	100	0

asphalt mixtures, the threshold for classifying coarse and fine aggregates is 2.36 mm while for cement concrete, the threshold for classifying coarse and fine aggregates is 4.75 mm. Generally, large aggregates have a smaller specific surface area and require less binder, and are economical when using in mixes. However, large aggregate mixes tend to have poor workability and cause more voids.

There are two maximum sizes based on the results of the sieve analysis. The maximum aggregate size is the smallest sieve through which 100% of the aggregate sample particles pass. The maximum aggregate size cannot represent the aggregate size when the amount of large particles is very limited. Therefore, the nominal maximum aggregate size is defined, which is the largest sieve that retains some of the aggregate particles but generally not more than 10% by mass.

Table 2.5 shows the passing percentage of three groups of aggregates at different sieve sizes. For group 1, the passing percentages at 25 and 19 mm are 100% and 93%, respectively. According to the definition, its maximum size is 25 mm and its nominal maximum size is 19 mm. For group 2, it is easy to determine that its maximum size is 19 mm and its nominal maximum size is 16 mm. For group 3, its maximum size is 19 mm. But its passing percentage at 16 mm is 80%, indicating the retained percentage on 16 mm sieve is 20%, higher than 10%. Therefore its nominal maximum size should still be 19 mm.

Table 2.4 Aggregate size

Types	JTG E42-2005		ASTM (mm)
	Asphalt mixtures (mm)	Cement concrete (mm)	
Coarse	> 2.36	> 4.75	> 4.75
Fine	0.075–2.36	≤ 4.75	0.075–4.75
Filler	< 0.075	–	< 0.075

Table 2.5 The passing percentage of three groups of aggregates

Samples		Group 1	Group 2	Group 3
Sieve size	25 mm	100%	100%	100%
	19 mm	93%	100%	100%
	16 mm	80%	93%	80%
Maximum size (mm)		25	19	19
Nominal maximum size (mm)		19	16	19

2.2.4 Moisture Condition

Aggregates can absorb water and asphalt in surface or permeable voids. The amount of water absorbed by the aggregate is important in the design of Portland cement concrete. Although the absorbed water usually cannot react with the cement or improve the workability of the fresh concrete, the aggregate absorption must be considered to determine the amount of water mixed into the concrete. For asphalt concrete, absorbed asphalt can help improve the bonding between the asphalt and the aggregate, whereas too much absorption requires a great amount of asphalt, increasing the cost of the mix. Therefore, low-absorption aggregates are preferred for asphalt concrete.

Figure 2.6 shows the four moisture conditions for an aggregate particle. In a bone-dry condition, the aggregate particle contains no moisture, which usually requires drying the aggregate in an oven. In an air-dry condition, the aggregate particle contains some moisture but is not saturated. In a saturated surface-dry (SSD) condition, the aggregate's permeable voids are filled with water but the main surface area of the aggregate particle is dry. In a moist condition, the aggregate particle has water on the surface area in excess of the SSD condition. The fifth absorption condition only occurs in the asphalt mixture, in which only a portion of the water-permeable voids of the aggregate particle is filled with asphalt. The moisture content (MC) in the aggregate is calculated by Eq. (2.5). Absorption is defined as the moisture content in the SSD condition.

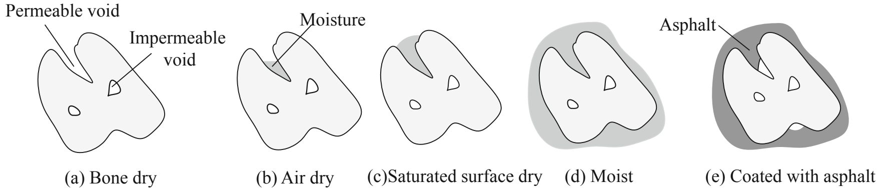


Fig. 2.6 Voids and absorption conditions of the aggregate, revised after Mamlouk and Zaniewski (2017)

$$MC = \frac{m_{\mathrm{m}} - m_{\mathrm{d}}}{m_{\mathrm{d}}} \times 100\% \tag{2.5}$$

where

$MC =$ moisture content (%);
$m_{\mathrm{m}} =$ weight of aggregates with moisture (g);
$m_{\mathrm{d}} =$ weight of dry aggregates (g).

2.2.5 Density

Aggregates have different types of density considering different volume and weight calculation methods. Density, the weight per unit volume, is important for mix design. However, specific gravity, which is the weight of a material divided by the weight of an equal volume of water, is more commonly used.

Figure 2.7 is an aggregate particle coated with asphalt (grey color), including the aggregate solid, impermeable voids, and permeable voids. The permeable voids can be further divided into the portion filled with absorbed asphalt and the portion not filled with asphalt. We have three types of volumes. The apparent volume includes the volume of aggregate solid and impermeable voids, excluding the permeable voids. The bulk volume which is the volume at SSD status includes the volume of aggregate solid, impermeable voids, and permeable voids. The effective volume for aggregate in asphalt mixture includes the volume of aggregate plus the volume in the water permeable voids that are not filled with asphalt. We have two types of weight. The dry weight is the weight of the solid while the SSD weight includes both the weight of the solid and the weight of absorbed water in the permeable voids at SSD condition.

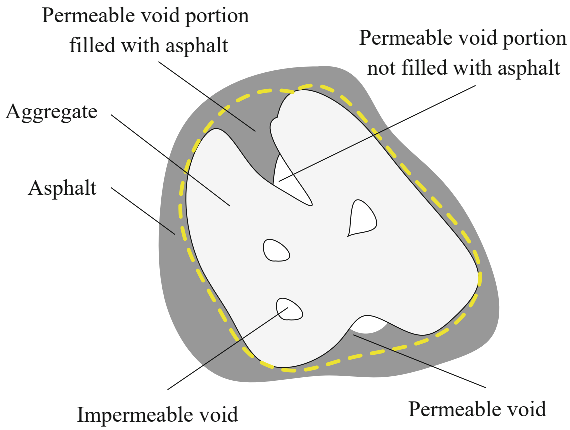


Fig. 2.7 An aggregate particle coated with asphalt

Four types of specific gravity are defined based on how voids in the aggregate particles are considered. Apparent specific gravity is the weight of the aggregate over the apparent volume. Bulk specific gravity is the weight of the aggregate to the bulk volume. SSD specific gravity is the weight of the aggregates and water in the water-permeable voids to the bulk volume. Effective specific gravity is the weight of the aggregate to the effective volume. In this chapter, we are going to discuss the calculation of the first three density. The calculation of the effective specific gravity will be discussed in the chapter on asphalt mixture.

The specification JTG E42-2005 T0304 (2005) provides a method to measure the density and absorption of coarse aggregates. We immerse the samples in water for 24 h, put them in the wire basket suspended in water, and measure the weight of aggregates underwater, denoted as m_w. It equals the weight of aggregates minus the weight of water with the same apparent volume. Then, we use a towel to remove the visible water film on the surface of aggregates and measure the SSD weight of aggregates, denoted as m_f, which equals the weight of aggregates plus the weight of water in the permeable voids. After that, we dry the aggregates in the oven to a constant weight and measure the dry weight of the aggregates, denoted as m_a.

1. Apparent density

The apparent specific gravity of coarse aggregates is calculated by Eq. (2.6). It is the dry weight of coarse aggregates over the apparent volume. The apparent density of coarse aggregates can be calculated by Eq. (2.7), which equals the density of water at testing temperature times the apparent specific gravity.

$$\gamma_a = \frac{m_a}{m_a - m_w} \tag{2.6}$$

$$\rho_a = \rho_w \gamma_a \tag{2.7}$$

where

$\gamma_a =$ apparent specific gravity of coarse aggregates;
$m_a =$ dry weight of coarse aggregates (g);
$m_w =$ weight of coarse aggregates underwater (g);
$\rho_a =$ apparent density of coarse aggregates (g/cm^3);
$\rho_w =$ density of water (g/cm^3).

2. Bulk density

The bulk specific gravity of coarse aggregates is calculated by Eq. (2.8). It is the dry weight of coarse aggregates over the bulk volume. The bulk density of coarse aggregates can be calculated by Eq. (2.9), which equals the density of water at testing temperature times the bulk specific gravity.

$$\gamma_b = \frac{m_a}{m_f - m_w} \tag{2.8}$$

$$\rho_{\mathrm{b}} = \rho_{\mathrm{w}} \gamma_{\mathrm{b}} \tag{2.9}$$

where
$\gamma_{\mathrm{b}} =$ bulk specific gravity of coarse aggregates;
$m_{\mathrm{f}} =$ SSD weight of coarse aggregates (g);
$\rho_{\mathrm{b}} =$ bulk density of coarse aggregates (g/cm^3).

3. SSD density

The SSD specific gravity of coarse aggregates is calculated by Eq. (2.10). It is the SSD weight of coarse aggregates over the bulk volume. The SSD density of coarse aggregates cabe calculated by Eq. (2.11), which equals the density of water at testing temperature times the SSD specific gravity of coarse aggregates.

$$\gamma_{\mathrm{s}} = \frac{m_{\mathrm{f}}}{m_{\mathrm{f}} - m_{\mathrm{w}}} \tag{2.10}$$

$$\rho_{\mathrm{s}} = \rho_{\mathrm{w}} \gamma_{\mathrm{s}} \tag{2.11}$$

where
$\gamma_{\mathrm{s}} =$ SSD specific gravity of coarse aggregate;
$\rho_{\mathrm{s}} =$ SSD density of coarse aggregate (g/cm^3).

4. Absorption

Absorption can be calculated by Eq. (2.12). It is the weight of water in the permeable voids over the dry weight of coarse aggregates.

$$w_{\mathrm{x}} = \frac{m_{\mathrm{f}} - m_{\mathrm{a}}}{m_{\mathrm{a}}} \times 100\% \tag{2.12}$$

where
$w_{\mathrm{x}} =$ absorption of coarse aggregates (%).

2.2.6 Unit Weight and Voids in Aggregates

Unit weight is used to estimate the weight of the aggregate by volume during purchase and transportation. According to specification JTG E42-2005 T0309 (2005), to measure the unit mass, we fill a rigid container of known volume with the aggregate and compact it by rodding, jigging, or shoveling, as shown in Fig. 2.8. The unit weight is calculated by Eq. (2.13). It is the weight of the aggregate over the volume of the container.

$$\rho_0 = \frac{m_0}{V_0} \tag{2.13}$$

(a) Unit weight test container (b) Aggregates packed in the container

Fig. 2.8 Tests for unit weight and percentage of voids

where

$\rho_0 =$ unit weight of coarse aggregates (g/cm^3);

$m_0 =$ weight of coarse aggregates (g);

$V_0 =$ volume of the container (cm^3).

The percentage of voids between aggregate particles can be calculated by Eq. (2.14). It equals one minus the volume of the aggregate over the volume of the container, or one minus the ratio of unit weight over the density of the aggregate. According to specification JTG E42-2005 (2005), the bulk density is used to calculate the percentage of voids of asphalt mixture; while the apparent density is used to calculate the percentage of voids of Portland cement concrete.

$$Void\% = \begin{cases} \left(1 - \frac{V_0}{V_b}\right) \times 100\% = \left(1 - \frac{\rho_0}{\rho_b}\right) \times 100\%, \text{ asphalt mixture} \\ \left(1 - \frac{V_0}{V_a}\right) \times 100\% = \left(1 - \frac{\rho_0}{\rho_a}\right) \times 100\%, \text{ cement concrete} \end{cases} \quad (2.14)$$

where

$Void\% =$ percentage of voids (%);

$V_b =$ bulk volume of coarse aggregates (cm^3);

$V_a =$ apparent volume of coarse aggregates (cm^3);

$\rho_b =$ bulk specific gravity of coarse aggregates (cm^3);

$\rho_a =$ apparent specific gravity of coarse aggregates (cm^3).

When two or more aggregates from different sources are mixed, some of the properties of the mixed aggregates can be calculated from the properties of the individual component. For example, if we mix aggregates A and B at a specific ratio. The mixed bulk specific gravity is calculated based on the principle of equal volume, which means the volume of the mixed aggregates equals the sum of the volumes of aggregates A and B. The absorption of the mixed aggregates equals the sum of absorbed water of aggregates A and B.

Question: Mix aggregates A and B at the ratio of 60:40, calculate (1) bulk specific gravity x and (2) absorption y of the mixed aggregates.

A: Bulk specific gravity = 2.952, absorption = 0.4%
B: Bulk specific gravity = 2.476, absorption = 5.2%

Answer:

(1) Calculate mixed bulk specific gravity x

$$\begin{aligned}\text{Mixed volume} &= \text{Volume of A} + \text{Volume of B}\\ 100/x &= 60/2.952 + 40/2.476\\ x &= 2.741\end{aligned}$$

(2) Calculate mixed absorption y

$$\begin{aligned}\text{Mixed water content} &= \text{Water content of A} + \text{Water content of B}\\ 100y &= 60 \times 0.4 + 40 \times 5.2\\ y &= 2.32\end{aligned}$$

2.2.7 Angularity and Flakiness

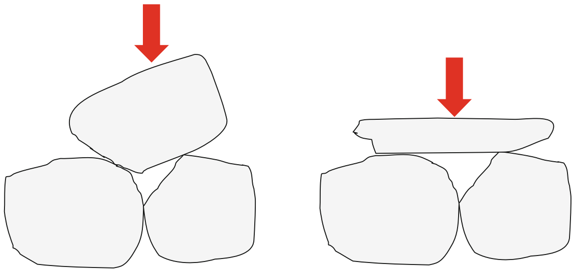
The shape and surface texture of the individual aggregate particle determines the packing density and the mobility of the aggregate in a mixture. There are two characterizations of the shape of the aggregate particle: angularity and flakiness. As shown in Fig. 2.9, coarse aggregates can be classified into angular and rounded based on their angularity. Angular and rough-textured aggregates produce bulk materials with higher stability than rounded and smooth-textured aggregates. However, the angular aggregates are more difficult to work into place than rounded aggregates, since their shapes make it difficult for them to slide across each other. Based on the flakiness, coarse aggregates can be classified as flaky, elongated, and flaky and elongated. The content of flaky and elongated particles should be limited in a good quality aggregate since they tend to break under loads and prevent the development of a strong aggregate skeleton (Fig. 2.10).

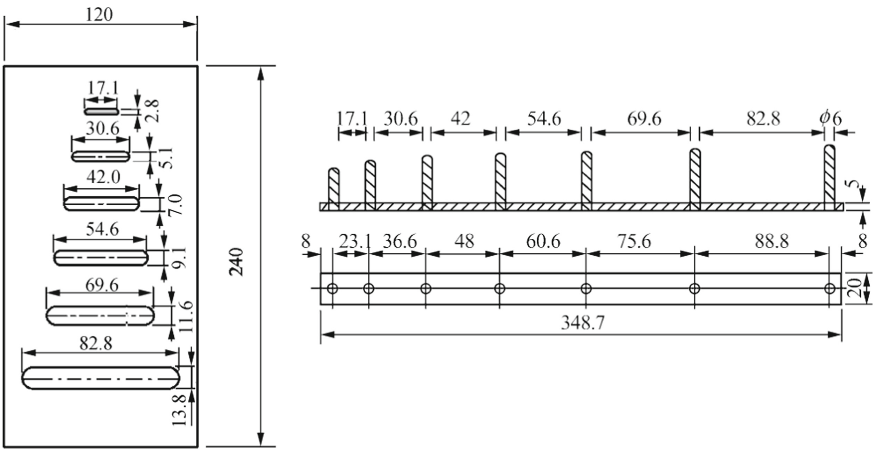
In specification ASTM D4791-19-2019 (2019), a particle is defined as “flat” if the ratio of the middle dimension to the smallest dimension exceeds 3–1. A particle is defined as “elongated” if the ratio of the longest dimension to the middle dimension exceeds 3–1. In the Superpave criteria, particles are classified as “flat and elongated” if the ratio of the largest dimension to the smallest dimension exceeds 5–1. The specification JTG E42-2005 T0311 (2005) provides a method to determine the flaky and elongated particles in coarse aggregates using two apparatus shown in Fig. 2.11, redrafted after JTG E42-2005 (2005).

(a) Angular (b) Rounded (c) Flaky (d) Elongated (e) Flaky and elongated

Fig. 2.9 Angularity and flakiness of coarse aggregates

Fig. 2.10 Flaky and elongated particles tending to break under loads





(a) Flaky gauge meter (b) Elongated gauge meter

Fig. 2.11 Flaky and elongated particle gauge meter (unit: mm), redrafted after JTG E42-2005 (2005)

Table 2.6 shows a specific amount of samples required for the test, depending on the nominal maximum size. The specification JTG E42-2005 T0312 (2005) introduces a method by measuring each aggregate particle with a caliper. A particle is defined as flaky or elongated if the ratio of the longest dimension to the smallest dimension exceeds 3–1. The weight percentage of flaky and elongated particles is usually calculated to evaluate the quality of the aggregate.

Table 2.6 The weight of samples required for the flaky and elongated particle test (JTG E42-2005, 2005)

Nominal maximum size (mm)	9.5	16	19	26.5	31.5	37.5	53		63
Minimum weight of samples (kg)	0.3	1	2	3	5	10	10		10

$$Q_e = \frac{m_1}{m_0} \times 100\% \tag{2.15}$$

where

$Q_e =$ content of flaky and elongated particles (%);
$m_1 =$ weight of flaky and elongated particles (g);
$m_0 =$ weight of the sample (g).

2.2.8 *Fractured Faces and Crushed Particle*

Fractured faces are angular, rough, or broken surfaces of an aggregate particle created by crushing, by other artificial means, or by nature. As shown in Fig. 2.12, a fractured face should be no less than 25% of the maximum cross-sectional area of the crushed particle. The number of fractured faces is directly related to the shape and surface texture of coarse aggregates. A crushed particle is defined as a particle of the aggregate having at least one fractured face. The specification JTG E42-2005 T0346 (2005) introduces a method to test the percentage of crushed particles of coarse aggregates. For a specific amount of samples, the fractured faces of each particle need to be checked, as shown in Table 2.7. Then the percentage of crushed particles can be calculated by Eq. (2.16). It is noted that Q should be less than 15%.

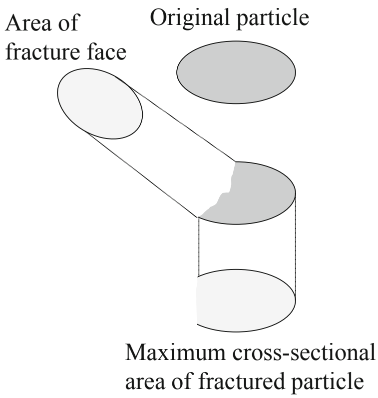


Fig. 2.12 Aggregates with a fractured face, redrafted after JTG E42-2000 (2000)

Table 2.7 The weight of samples required for the fractured faces test (JTG E42-2005, 2005)

Nominal maximum size (mm)	9.5	13.2	16	19	26.5	31.5	37.5	50
Minimum weight of samples (kg)	0.2	0.5	1	1.5	3	5	7.5	15

$$P = \frac{F + Q/2}{F + Q + N} \times 100\% \tag{2.16}$$

where

$P =$ percentage of crushed particles (%);

$F =$ weight of the particles with at least one fractured face (g);

$Q =$ weight of the particles that are difficult to determine if they include fractured faces (g);

$N =$ weight of the particles without a fractured face (g).

2.3 Mechanical Properties of Coarse Aggregates

The mechanical properties of coarse aggregates include crushing value, impact value, polished stone value, abrasion value, and soundness.

2.3.1 Crushing Value

The crushing value measures the strength of the aggregates under gradually applied compressive loads when they are used in pavements. It is the weight percentage of the crushed materials obtained when the test aggregates are subjected to a specified load. According to specification JTG E42-2005 T0316 (2005), 3 kg of coarse aggregates with sizes between 9.5 and 13.2 mm are air- or oven-dried and then put in the container for the test. A compressive load is applied at a uniform rate till 400 kN in 10 min and then held for 5 s (Fig. 2.13). The passing percentage at the 2.36 mm sieve of the crushed aggregates is calculated. Generally, aggregates with a crushing value less than 10% are strong aggregates while those with a crush value higher than 35% are weak aggregates.

2.3.2 Impact Value

Impact value measures the resistance of aggregates to sudden shock or impact especially when they are used in pavements. In specification JTG E42-2005 T0322 (2005), coarse aggregates with sizes between 9.5 and 13.2 mm are placed in the cup in three layers and each layer is compacted by 25 strokes of the tamping rod, as shown in

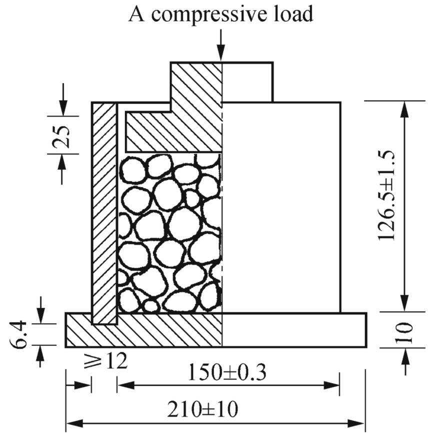


Fig. 2.13 Crushing value tester (unit: mm), reprinted after JTG E42-2005 (2005)

Fig. 2.14. Then, the hammer is raised 380 mm above the upper surface of the aggregates in the cup and falls freely onto the aggregates. The passing percentage at the 2.36 mm sieve of the crushed aggregate is calculated as the impact value.

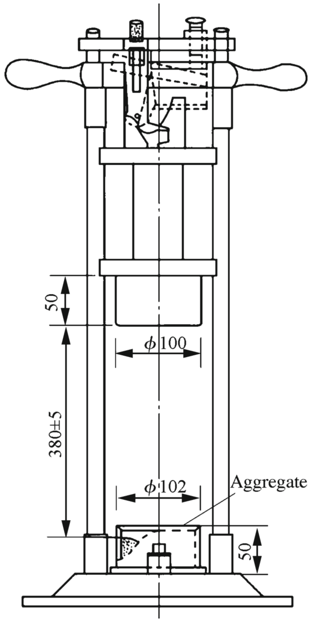


Fig. 2.14 Impact value tester (unit: mm), reprinted after JTG E42-2005 (2005)

2.3.3 Polished Stone Value

Polished stone value (PSV) measures the resistance of coarse aggregates to the polishing of vehicle tires for pavement surface course. High PSV indicates good resistance to the polishing of vehicle tires. In specification JTG E42-2005 T0321 (2005), the PSV test involves two tests: the polishing test and the skid resistance test. The coarse aggregates are firstly polished by an accelerated polishing machine as shown in Fig. 2.15. This machine polishes samples of aggregates, simulating actual road conditions. After polishing, the PSV is tested by the pendulum skid tester. During the test, the pendulum arm is raised and latched onto a rigid arm on the tester and then released. The pendulum swings down and drags the spring-loaded rubber block over the convex face of the sample. The needle indicator stops and remains at the highest point of the swing, which is recorded as the PSV. Table 2.8 presents the requirements for the PSV of aggregates used in the pavement surface course. The aggregate should have higher PSV when they are used in high-class roads and humid areas. Table 2.9 shows the typical PSV of rocks, mostly meeting the requirements in Table 2.8. In China, basalt is more widely used in the surface course of expressways.

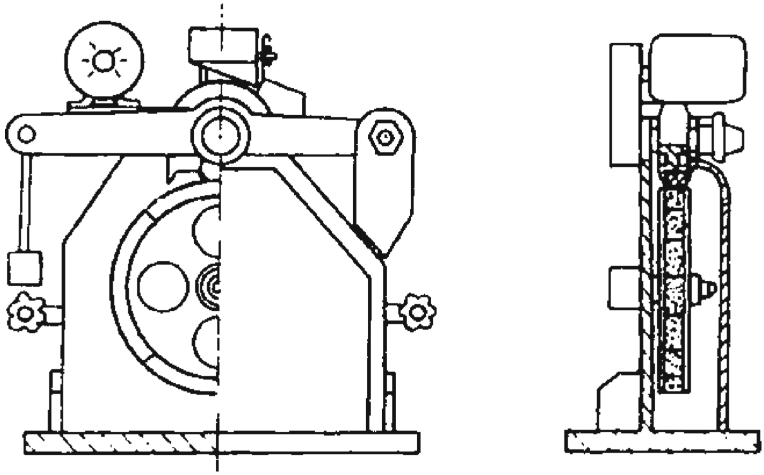


Fig. 2.15 Polished stone value tester, reprinted after Huang et al. (2020)

Table 2.8 Requirements of the PSV for aggregates used in pavements (JTG E42-2005, 2005)

Annual rainfall (mm)	Expressway and Class I road	Other roads
> 1000	> 42	> 40
500–1000	> 40	> 38
250–500	> 38	> 36
< 250	> 36	…

Table 2.9 Typical PSV of rocks

PSV	Limestone	Hornfels	Porphyry	Quartzite	Granite	Basalt
Average	43	45	56	58	59	62
Range	30–70	40–50	43–71	45–67	45–70	45–81

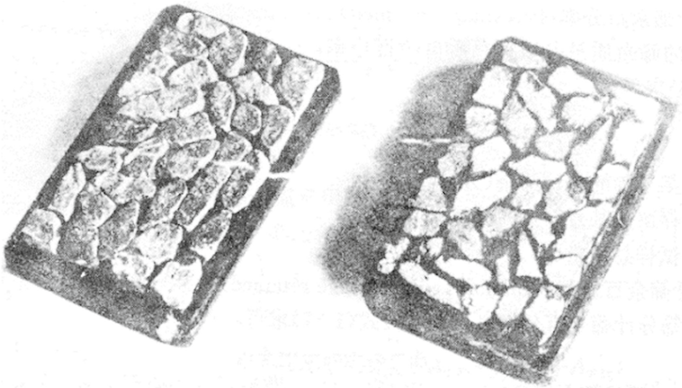


Fig. 2.16 Samples of the Dorry abrasion test, reprinted after Huang et al. (2020)

2.3.4 Abrasion Value

Abrasion value measures the resistance of aggregates to surface wear by abrasion. There are two types of abrasion tests. In specification JTG E42-2005 T0323 (2005), the Dorry abrasion tester is used to measure a cylindrical specimen with a height of 25 cm and a diameter of 25 cm subjected to the abrasion against a rotating metal disk sprinkled with quartz sand, as shown in Fig. 2.16. The weight loss of the cylinder after 1000 revolutions of the table is determined as the Dorry abrasion. In specification JTG E42 T0317 (2005), the Los Angeles (LA) abrasion tester is used to measure a coarse aggregate sample subjected to abrasion, impact, and grinding in a rotating steel drum containing a specified number of steel spheres (Fig. 2.17). Different sizes and weights of samples are tested depending on the maximum aggregate size. The passing percentage at 1.7 mm sieve of the crushed aggregate is calculated as the LA abrasion value. The LA abrasion test is more widely used.

2.3.5 Soundness

Soundness is the ability of aggregates to withstand weathering. The soundness test simulates weathering by soaking aggregates in a saturated sodium sulfate solution. During the soaking process, the Na_2SO_4 solution infiltrates into permeable voids.

Fig. 2.17 LA abrasion tester

Then, during the drying process, the Na_2SO_4 solution forms crystals, causing expansion. These sulfates form crystals which grow in the aggregates when dried, simulating the effect of freezing. Figure 2.18 shows the cracking caused by the expansion of sodium sulfate crystals. According to specification JTG E42-2005 T0314 (2005), a specific number of aggregate samples is firstly obtained, depending on the nominal maximum size of the aggregate as shown in Table 2.10. The test involves subjecting aggregates to 5 cycles of soaking in the sulfate for 16 h, followed by drying. Then, the average weight loss is calculated to evaluate the soundness.

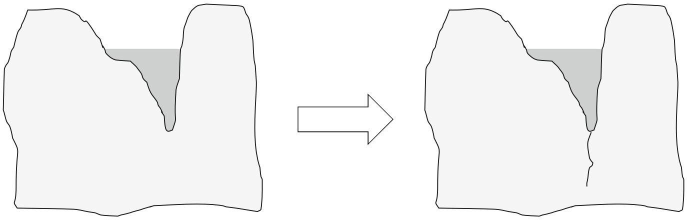


Fig. 2.18 Soundness test of aggregates

Table 2.10 The weight of each samples size required for the soundness test (JTG E42-2005, 2005)

Nominal maximum size (mm)	2.36–4.75	4.75–9.5	9.5–19	19–37.5	37.5–63	63–75
Sample weight (kg)	0.5	0.5	1	1.5	3	5

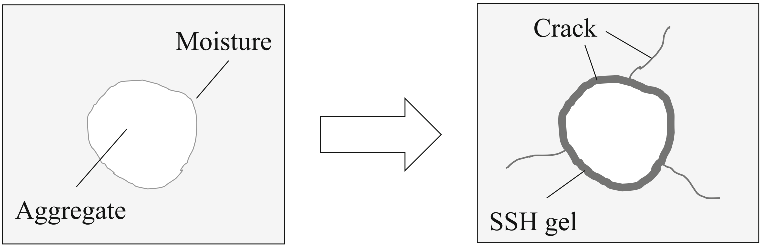


Fig. 2.19 Alkali reaction

2.4 Alkali Reaction

Alkali reaction is a swelling reaction in concrete between the highly alkaline cement paste and the reactive silica in aggregates in a moist environment. The soluble and viscous sodium silicate hydrate (SSH) gel formed during the reaction can absorb water and increase in volume, causing cracking of the concrete, as shown in Fig. 2.19. The reactivity of alkali-reactive aggregates can be minimized by limiting the alkali content of the cement. The reaction 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 reduce the alkali reaction.

The specification JTG E42-2005 T0347 (2005) introduces a method to calculate the relative content of hydrogen ions in aggregates to evaluate the alkali-reaction of aggregates. The specification JTG E42-2005 T0325 (2005) introduces a method to test the expansion of a 25.4 × 25.4 × 285 mm cement mortar beam at different curing times to evaluate the alkali-reactive potential of the aggregate.

2.5 Properties of Fine Aggregates

Fine aggregates have some common properties as coarse aggregates including density, angularity, and unit weight, although the test methods are different. In addition, fine aggregates have some specific properties such as fineness modulus, sand equivalency, and deleterious materials test.

2.5.1 *Density*

Same as coarse aggregates, the apparent, bulk, SSD, and effective specific gravity or density are also very important for fine aggregates. The mass-volume characteristics of coarse aggregates also apply to fine aggregates.

Fig. 2.20 Determination of SSD condition of fine aggregates, reprinted after Huang et al. (2020)

To test the density and absorption of fine aggregates, according to JTG E42-2005 T0328 (2005), we first measure the weight of the pycnometer filled with water to the calibration mark and record it as m_1. It includes the weight of the pycnometer, water of the same apparent volume of fine aggregates, and water of the rest volume in the pycnometer. We soak a representative sample of fine aggregates in water for 24 h, dry it back to the SSD condition, weigh around 500 g sample, and record it as m_3, which includes the weight of aggregates and water in the permeable voids. Then, we place the SSD sample in a pycnometer and add water to the constant volume mark on the pycnometer and the weight is determined again as m_2, which includes the weight of the pycnometer, fine aggregates, and water of rest volume in the pycnometer. After that, the sample is dried in an oven, and the weight is determined and recorded as m_0.

For coarse aggregates, we use a towel to dry the aggregates to a saturated surface dry condition. For fine aggregates, we can use the hair drier instead. As shown in Fig. 2.20, to determine if the sample is at the SSD condition, we put the partially dried fine aggregates into the mold and tamp them. Then we lift the mold vertically, if the surface moisture still exists, the fine aggregate will retain the molded shape. If this is the case, allow the sand to dry and repeat checking until the fine aggregates slump slightly, indicating that it has reached a surface-dry condition.

1. Apparent density

The apparent specific gravity of fine aggregates is calculated by Eq. (2.17). $(m_0 + m_1 - m_2)$ is the weight of the water of the same apparent volume of fine aggregates which equals the apparent volume of fine aggregates. The apparent density of fine aggregates can be calculated by Eq. (2.18), which equals the density of water at testing temperature times the apparent specific gravity of fine aggregates.

$$\gamma_a = \frac{m_0}{m_0 + m_1 - m_2} \tag{2.17}$$

$$\rho_a = \rho_w \gamma_a \tag{2.18}$$

where

γ_a = apparent specific gravity of fine aggregates;
m_0 = dry weight (g/cm^3);
m_1 = weight of pycnometer filled with water (g);

$m_2 =$ weight of the pycnometer filled with aggregates and water (g);
ρ_a= apparent density of fine aggregates (g/cm^3);
ρ_w = density of water (g/cm^3).

2. Bulk density

The bulk specific gravity of fine aggregates is calculated by Eq. (2.19). ($m_3+m_1-m_2$) is the weight of the water of apparent volume of fine aggregates and the weight of the water in permeable voids, which equal the bulk volume of fine aggregates. The bulk density of fine aggregates can be calculated by Eq. (2.20), which equals the density of water at testing temperature times the bulk specific gravity of fine aggregates.

$$\gamma_b = \frac{m_0}{m_3 + m_1 - m_2} \tag{2.19}$$

$$\rho_b = \rho_w \gamma_b \tag{2.20}$$

where
γ_b = bulk specific gravity of fine aggregates;
$m_3 =$ SSD weight of fine aggregates (g);
$\rho_b =$ bulk density of fine aggregates (g/cm^3).

3. SSD density

The SSD specific gravity of fine aggregates is calculated by Eq. (2.21). The SSD density of fine aggregates can be calculated by Eq. (2.22), which equals the density of water at testing temperature times the SSD specific gravity of fine aggregates.

$$\gamma_s = \frac{m_3}{m_3 + m_1 - m_2} \tag{2.21}$$

$$\rho_s = \rho_w \gamma_s \tag{2.22}$$

where
$\gamma_s =$ SSD specific gravity of fine aggregates (g);
ρ_s = SSD density of fine aggregates (g/cm^3).

4. Absorption

Absorption can be calculated by Eq. (2.23). It is the weight of water in the permeable voids over the dry weight of fine aggregates.

$$w_x = \frac{m_3 - m_0}{m_0} \times 100\% \tag{2.23}$$

where
w_x = absorption of fine aggregates (%).

2.5.2 Unit Weight and Void Ratio

According to specification JTG E42-2005 T0331 (2005), the unit weight of fine aggregates can be tested with a standard funnel and container (as shown in Fig. 2.21) and calculated by Eq. (2.24)

$$\rho_0 = \frac{m_0}{V_0} \tag{2.24}$$

where

ρ_0 = unit weight of the fine aggregates (g/cm^3);
m_0 = weight of fine aggregates (g);
V_0 = volume of the container (cm^3);

The percentage of voids between aggregate particles, $Void\%$, can be calculated by one minus the volume of aggregate over the volume of the container, which equals one minus the ratio of unit weight over the apparent density.

$$Void\% = \left(1 - \frac{\rho_0}{\rho_a}\right) \times 100\% \tag{2.25}$$

where

ρ_a = apparent density of the fine aggregates (g/cm^3).

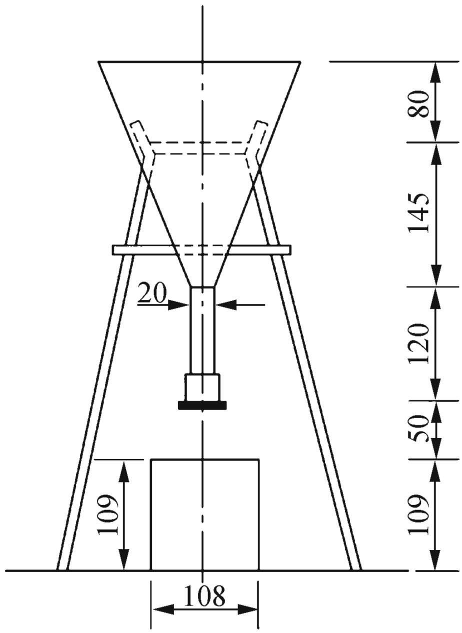


Fig. 2.21 Unit weight tester for fine aggregates (unit: mm), reprinted after JTG E42-2005 (2005)

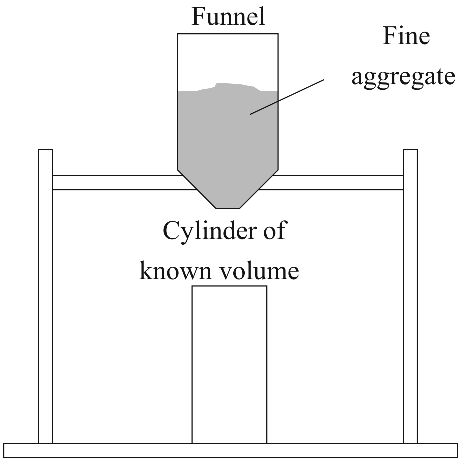


Fig. 2.22 Angularity test of fineness, reprinted after JTG E42-2005 (2005)

2.5.3 Angularity

Fine aggregates angularity is important because an excess of rounded fine aggregates may cause asphalt pavement rutting. According to specification JTG E42-2005 T0344 (2005), the test estimates angularity by measuring the loose uncompacted void content of a fine aggregate sample using a funnel as shown in Fig. 2.22. The loose uncompacted void content is indicative of the relative angularity and surface texture of the sample. The higher the void content, the higher the assumed angularity and rougher the surface.

2.5.4 Fineness Modulus

The fineness modulus is a measure of the fine aggregates' gradation and is a critical factor for the mix design of Portland cement concrete. The fineness modulus for fine aggregates used in cement concrete is calculated by Eq. (2.26). Fine aggregates with a fineness modulus between 3.1 and 3.7 are regarded as coarse sands, fine aggregates with a fineness modulus between 2.3 and 3.0 are regarded as medium sand, while fine aggregates with a fineness modulus between 1.6 and 2.2 are regarded as fine sand.

$$M_X = \frac{A_{0.15} + A_{0.3} + A_{0.6} + A_{1.18} + A_{2.36} - 5A_{4.75}}{100 - A_{4.75}} \tag{2.26}$$

where

M_X = fineness modulus;

$A_{0.15}$, $A_{0.3}$, $A_{0.6}$, $A_{1.18}$, $A_{2.36}$, $A_{4.75}$= cumulative percentage retained on sieve with size of 0.15, 0.3, 0.6, 1.18, 2.36, and 4.75 mm.

As shown in Eq. (2.27), the fineness modulus for asphalt mixtures and pavement base is an empirical figure obtained by adding the cumulative percentage retained on each of a specified series of sieves, and dividing the sum by 100. Therefore, a high fineness modulus means more aggregates are retained on those sieves and therefore the size of aggregates is larger. Fine aggregates with a fineness modulus between 2.9 and 3.2 are regarded as coarse sand, a fineness modulus between 2.6 and 2.8 are regarded as medium sand, while a fineness modulus between 2.2 and 2.5 are regarded as fine sand.

$$M_X = \frac{A_{0.15} + A_{0.3} + A_{0.6} + A_{1.18} + A_{2.36} + A_{4.75}}{100} \quad (2.27)$$

2.5.5 Sand Equivalency

Sand equivalency (SE) is the relative volume ratio of sand over all particles in fine aggregates. It indicates the relative volume of sand in fine aggregates. According to specification JTG E42-2005 T0334 (2005), a small amount of flocculating solution is poured into a graduated cylinder and is agitated to loosen the clay-like coatings from the sand particles. The sample is then irrigated with additional flocculating solution forcing the clay-like material into suspension above the sand. As shown in Fig. 2.23, the sand equivalency is expressed as a ratio of the height of sand over the height of the clay top.

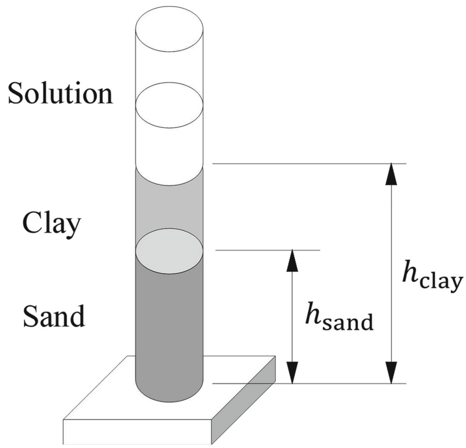


Fig. 2.23 Sand equivalency test, redrafted after Huang et al. (2020)

$$SE = \frac{h_{\text{sand}}}{h_{\text{clay}}} \times 100 \tag{2.28}$$

where
h_{clay} = height of the clay (mm);
h_{sand} = height of the sand (mm).

2.5.6 Methylene Blue Test

The methylene blue test of fine aggregates is a measure of the amount of potentially harmful fine materials such as clay and organic materials. According to specification JTG E42-2005 T0349 (2005), the methylene blue value is a function of the amount and characteristics of clay minerals. High methylene blue values indicate increased potential for diminished fine aggregates or mineral filler performance in a cementitious mixture due to the presence of clay.

2.6 Filler

Fillers are defined as aggregate particles smaller than 0.075 mm sieve. In asphalt mixtures, fillers are mixed with asphalt binder to form asphalt mortar, which could improve the bond between aggregates and asphalt, and increase the stability or rutting resistance of asphalt mixtures. It can also fill the voids in the asphalt mixtures and thus reduce the required asphalt. Table 2.11 summarizes the requirements of mineral fillers used in asphalt mixtures and the corresponding test methods.

Table 2.11 Requirements for mineral fillers for asphalt mixtures (JTG E42-2005, 2005)

Properties	Expressway and first-class road	Other roads	Test methods
Min. apparent specific gravity	2.50	2.45	T 0352
Max. absorption (%)	1	1	T 0103
Proportion < 0.6 mm (%)	100	100	T 0351
Proportion < 0.15 mm (%)	90–100	90–100	
Proportion < 0.075 mm (%)	75–100	70–100	
Appearance	No agglomeration	–	–
Max. hydrophilic coefficient	1	–	T 0353
Max. plastic index (%)	4	–	T 0354
Thermal stability	Normal	–	T 0355

2.7 Gradation Design

Gradation describes the particle size distribution which is an important attribute of aggregates. Gradation design is to determine the optimal particle size distribution of aggregates when used in Portland cement concrete and asphalt mixtures, or as an unbound material.

2.7.1 Gradation Curves

A typical gradation curve shows the passing percentage of aggregates at different sieve sizes. In a gradation curve chart, the horizontal axis is the sieve size usually in a logarithm scale or 0.45 power scale. The log or 0.45 power transform can spread out the small values and bring large values closer together. The vertical axis is the passing percentage. Figure 2.24 uses a logarithm horizontal axis to expand the small numbers so that the small size sieves can be differentiated in the horizontal axis.

Figure 2.25 shows different aggregates or gradations identified in the gradation chart. The coarse aggregates are on the right side of the chart while the fine aggregates are on the left side of the chart. Fine gradations lie above the diagonal line because they have higher passing percentages at most sieves. Coarse gradations lie below the diagonal line because they have lower passing percentages at most sieves.

Figure 2.26 shows the typical gradation curves of aggregates and Fig. 2.27 shows the cross-sectional view of the mixes. In addition to the traditional dense gradation curve, aggregates can have other distributions. Open-graded aggregates are missing small size aggregates, leaving a lot of voids, and the material is highly permeable. Gap-graded aggregates are missing one or more middle size aggregates. Their gradation curve has a near horizontal section indicating that nearly the same portions of the aggregates pass two sieves of different sizes.

Figure 2.28c shows the dense and open gradation asphalt mixtures on rainy days. The left-side pavement uses dense gradation; the right-side pavement uses open

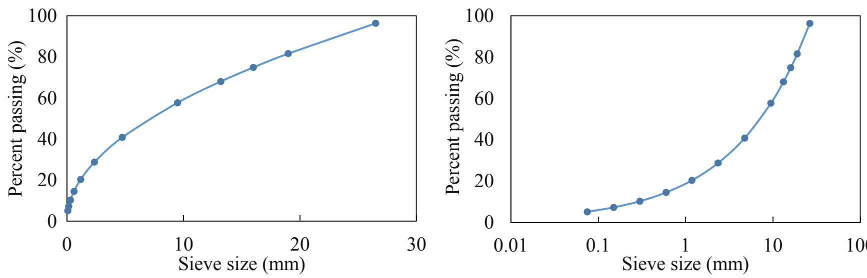


Fig. 2.24 The normal horizontal axis (left) and the logarithm horizontal axis (right), redrafted after Huang et al. (2020)

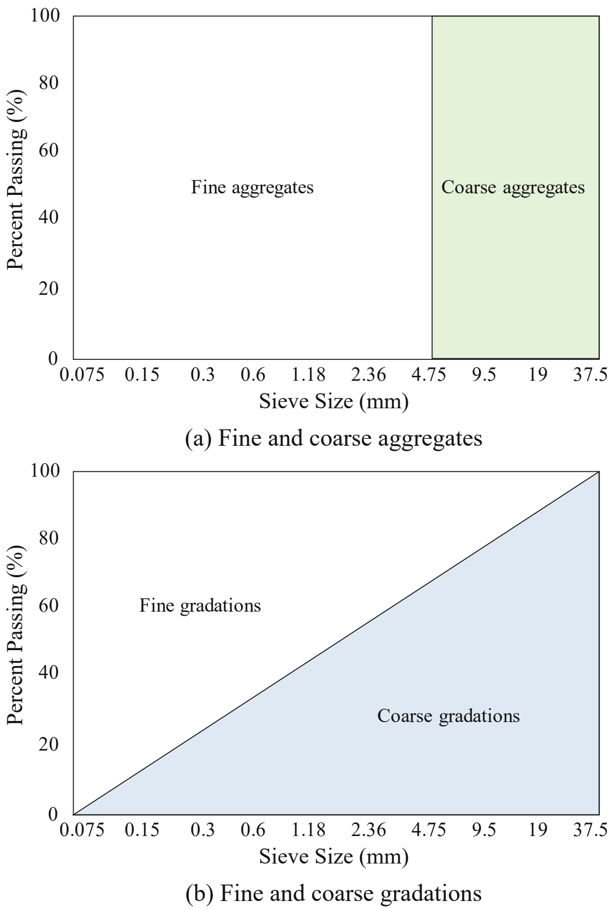


Fig. 2.25 Different aggregates and gradations in the gradation charts

gradation. The open gradation asphalt mix has much less water film and splashing, and therefore the riding safety on rainy days is greatly improved. Some research found that the open gradation asphalt mix can significantly reduce the traffic accident rate in a long term.

2.7.2 Gradation Theory

There have been several theories to help design aggregate gradation including maximum density theory, the Barley method, and the particle intervention theory. The maximum density theory is the most widely used, in which the density of an aggregate mix is a function of the size distribution of the aggregates. In 1907, Fuller

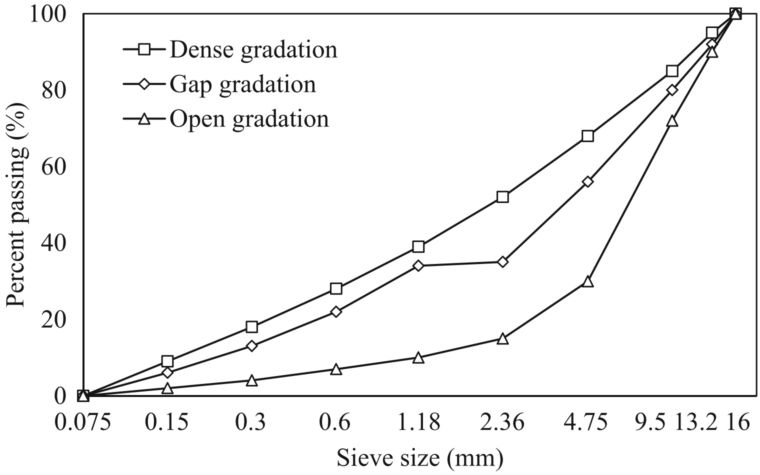


Fig. 2.26 Three gradation curves, redrafted after Huang et al. (2020)

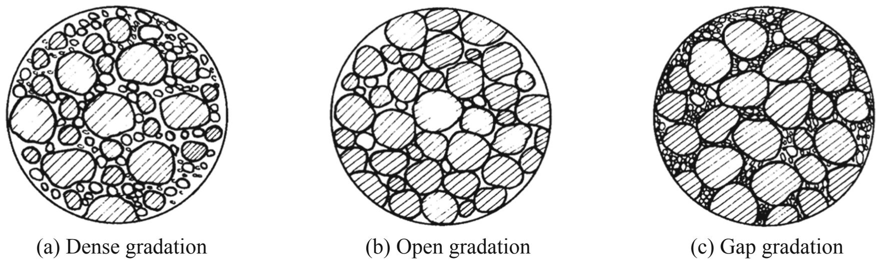
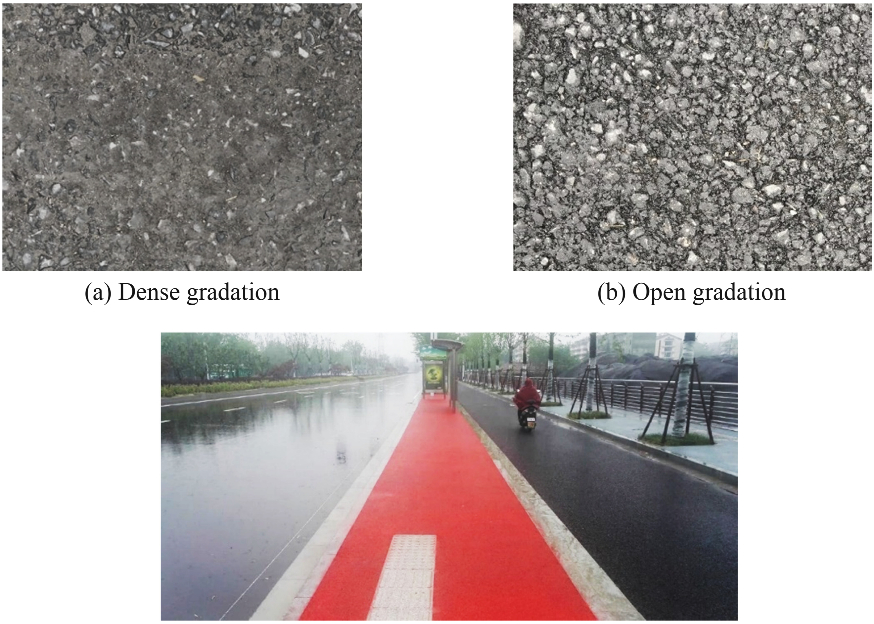


Fig. 2.27 Aggregates of different gradations, reprinted after Huang et al. (2020)

and Thompson established the relationship to determine the distribution of aggregates that provides the maximum density or minimum amount of voids.



(a) Dense gradation

(b) Open gradation

(c) The dense (left) and open (right) gradation asphalt mixtures

Fig. 2.28 Pavement surface with dense and open gradation asphalt mixtures

$$p^2 = kd \tag{2.29}$$

where

$p =$ passing percentage (%);
$k =$ coefficient;
$d =$ sieve size (mm).

Later, Fuller improved the maximum density curve with the power function as shown in Eq. (2.30). The value of the exponent n recommended by Fuller is 0.5. In the 1960s, the US Federal Highway Administration (FHWA) recommended a value of 0.45 for n and introduced the "0.45 power" gradation chart in the Strategic Highway Research Program (SHRP) for asphalt mixture design. Portland cement concrete usually uses a value of 0.35 for n, as shown in Fig. 2.29.

$$p = 100\left(\frac{d}{D}\right)^n \tag{2.30}$$

where

$n =$ power number;
$D =$ maximum size of the aggregate (mm).

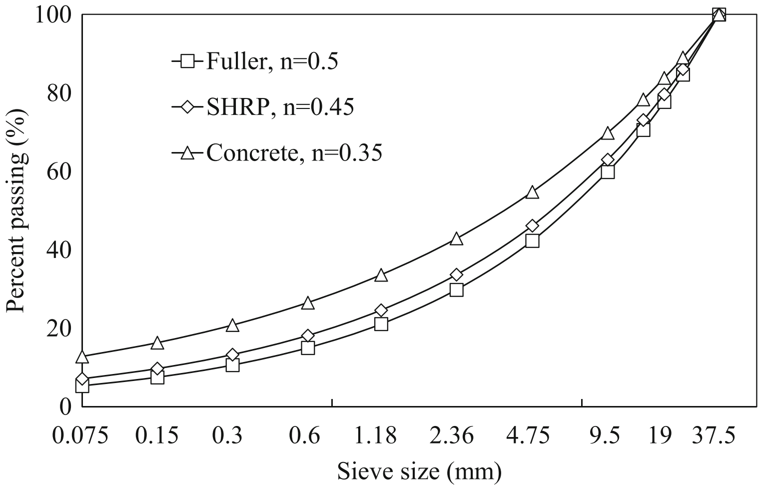


Fig. 2.29 The maximum density curves

2.7.3 Gradation Design

A single aggregate source is unlikely to meet the gradation requirements. One way for gradation design is to prepare the aggregates at each single sieve size and mix them at the designed proportion. This means that for *n* sieves, *n* groups of aggregates of the sieve sizes need to be prepared, which is costly. Therefore, the blending of aggregates from two to five sources is commonly used. As shown in Table 2.12, the objective of gradation design is to determine the optimum proportions of the four aggregates to let the mixed gradation fall within the required range and as close as possible to the designed gradation which is the mid-value of the lower and upper limits. The proportion can be determined by the graphical method and the numerical method.

1. Graphical method

As shown in Fig. 2.30a, we have four aggregates with different sizes and their gradation curves have neither overlappings nor spaces. The diagonal line is the objective gradation. In the mixed aggregates, those larger than size *A* are all from aggregate *A*. We can draw a vertical line at sieve size *A* and a horizontal line starting from the crossover point of the vertical line and the objective gradation curve. We can determine that the proportion of aggregate *A* is *X*. Then, those larger than size *B* in the mixed aggregates are all from aggregates *A* and *B* and the proportion of aggregate *A* is already known, therefore the rest is the proportion of aggregate *B*. Similarly, we can find that the proportion of aggregate *B* is *Y*, and the proportion of aggregate *C* is *Z*. The rest proportion *W* is for aggregate *D*. Usually, there are overlappings or

Table 2.12 Gradation design template

Sieve size (mm)	4#	3#	2#	1#	Blended	Designed	Lower limit	Upper limit
37.5	100	100	100	100	100	100	100	100
25	100	100	100	100	100	100	100	100
19	96	100	100	100	99.2	98	96	100
12.5	88	100	100	100	97.6	97.5	95	100
9.5	49	87	100	100	87.85	86	82	90
4.75	9	56	100	100	75.2	75	70	80
2.36	2	13	90	98	64.05	65	60	70
1.18	2	6	57	46	33.95	35	30	40
0.6	2	3	36	31	22.25	23	20	26
0.3	2	2	24	22	15.5	15	10	20
0.15	2	2	12	13	8.9	9	6	12
0.075	2	1	6	5	4.05	4	2	6
Proportion (%)	20	15	25	4	–	–	–	–

spaces between the gradation curves of aggregates. As shown in Fig. 2.30b, we can use the mid-point between the two curves to estimate the corresponding proportions.

2. Numerical method

The numerical method uses the trial and error procedure to determine the proportions. For k types of aggregates, at sieve No. 1, the sum of the passing percentage of the k aggregates, $p_{1(1)} \cdot x_1 + p_{2(1)} \cdot x_2 + \cdots + p_{k(1)} \cdot x_k$ should be equal to the designed passing percentage $p_{(1)}$ at sieve 1. Similarly, at sieve No. n, the sum of the passing percentage of the k aggregates, $p_{1(n)} \cdot x_1 + p_{2(n)} \cdot x_2 + \cdots + p_{k(n)} \cdot x_k$ should be equal to the designed passing percentage $p_{(n)}$. For a total of n sieves, we have a total of n Eqs. (2.31). The trial and error procedure or the programming optimization method can be adopted to find the optimal ratio of x_1, x_2 and x_k to determine the gradation.

$$\begin{aligned} p_{1(1)} \cdot x_1 + p_{2(1)} \cdot x_2 + \cdots + p_{k(1)} \cdot x_k &= p_{(1)} \\ p_{1(2)} \cdot x_1 + p_{2(2)} \cdot x_2 + \cdots + p_{k(2)} \cdot x_k &= p_{(2)} \\ \cdots \\ p_{1(n)} \cdot x_1 + p_{2(n)} \cdot x_2 + \cdots + p_{k(n)} \cdot x_k &= p_{(n)} \end{aligned} \tag{2.31}$$

Questions

1. Discuss the three main types of crushers to produce aggregates and which one is preferred when producing small-size aggregates.
2. Define the fineness modulus of aggregates and how to classify the sand based on its fineness modulus?
3. Discuss how to measure the angularity of coarse and fine aggregates?

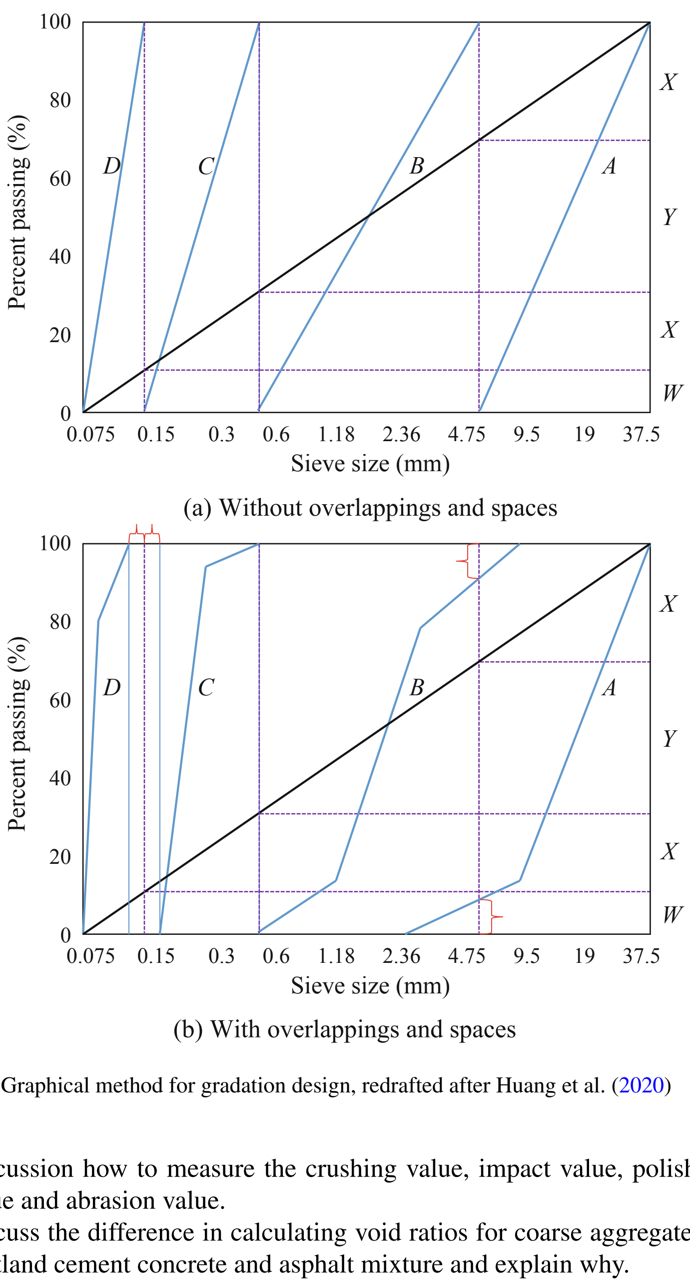


Fig. 2.30 Graphical method for gradation design, redrafted after Huang et al. (2020)

4. Discussion how to measure the crushing value, impact value, polished stone value and abrasion value.
5. Discuss the difference in calculating void ratios for coarse aggregates used in Portland cement concrete and asphalt mixture and explain why.
6. For the two samples of fine aggregates shown in Table 2.13, calculate the moisture content for each sample, and the moisture content of the mix if they are mixed at a ratio of 1:2.
7. For a sample of coarse aggregates from a stockpile, the following weights are found:

Weight of moist aggregate sample as brought to the laboratory: 5289 g
Weight of oven-dried aggregates: 5205 g
Weight of aggregates submerged in water: 3288 g
Weight of SSD aggregates: 5216 g
Calculate

(1) The bulk specific gravity
(2) The apparent specific gravity
(3) The moisture content of stockpile aggregate
(4) Absorption.

8. For a sample of fine aggregates from a stockpile, the following weights are found:
Weight of SSD sand = 500.0 g
Weight of pycnometer with water only = 621.7 g
Weight of pycnometer with sand and water = 935.2 g
Weight of dry sand = 496.1 g
Calculate

(1) The bulk specific gravity
(2) The apparent specific gravity
(3) The SSD specific gravity
(4) Absorption.

9. For two coarse aggregates which have to be blended. The results are as follows:
Aggregate A: Bulk specific gravity = 2.796; absorption = 0.5%
Aggregate B: Bulk specific gravity = 2.468; absorption = 5.1%
Calculate

(1) What is the specific gravity of a mixture of 50% aggregate A and 50% aggregate B by weight?
(2) What is the absorption of the mixture?

10. Make a spreadsheet blend template in the Excel to perform a gradation analysis with the five aggregates including fillers for the following lower and upper limits (Table 2.14).

Table 2.13 Measured weights of two samples of fine aggregates

Measures	Sample	
	A	B
Wet weight (g)	520.1	521.6
Dry weight (g)	490.5	491.3
Absorption (%)	2.6	2.7

Table 2.14 Gradations of the five aggregates and design limits

Sieve size (mm)	Passing (%)							
	4#	3#	2#	1#	Filler	Mix	Lower limit	Upper limit
26.5	83.5	100	100	100	100	–	95	100
19	30.4	100	100	100	100	–	75	90
16	15.1	99.3	100	100	100	–	62	80
13.2	1.6	70	100	100	100	–	53	73
9.5	0	53.3	100	100	100	–	43	63
4.75	0	15	80	100	100	–	32	52
2.36	0	0	30	98.3	100	–	25	42
1.18	0	0	5	60	100	–	18	32
0.6	0	0	0	40	100	–	13	25
0.3	0	0	0	15	98.6	–	8	18
0.15	0	0	0	10	93.3	–	5	13
0.075	0	0	0	0.1	81.9	–	3	7

References

ASTM C125-21. (2021). Standard terminology relating to concrete and concrete aggregates. West Conshohocken, PA: American Society for Testing and Materials International.

ASTM D4791-19. (2019). Standard test method for flat particles, elongated particles, or flat and elongated particles in coarse aggregate. West Conshohocken, PA: American Society for Testing and Materials International.

Huang, X., Gao, Y., & Zhou, Y. (2020). *Civil engineering materials* (4th ed.). Southeast University Press.

JTG E42-2005. (2005). Test methods of aggregate for highway engineering. Ministry of Transport of the People's Republic of China. Beijing: China Communications Press.

JTG F40-2004. (2004). Technical specification for construction of highway asphalt pavements. Ministry of Transport of the People's Republic of China. Beijing: China Communications Press.

Mamlouk, M. S., & Zaniewski, J. P. (2017). *Materials for civil and construction engineers* (3rd ed.). Pearson Prentice Hall.