Period #8 Notes: Aggregates

A. A QUICK LOOK AT AGGREGATES

1. Overview

In civil engineering materials, the term *aggregate* denotes granular media. Aggregate can be used in material systems where the individual grains are cemented together with a binder, or they can be used without binder.

For example, aggregate is used as a filler in portland cement concrete (pcc) and typically occupies 60-80% of the total volume. In asphalt cement concrete (acc), aggregates typically occupy 80-95% of the gross volume.

Aggregates are inexpensive, literally costing just a few dollars per ton, and yet they add a good deal of strength and stiffness to both pcc and acc.

2. Classes of Aggregates

The two primary classifications of aggregates are *natural* and *manufactured*.

a. Natural aggregates:

1) can be mined from naturally occurring alluvial or colluvial sand and gravel deposits. Because the aggregate particles in such deposits have generally been subjected to abrasive processes, they tend to be somewhat <u>*smooth and rounded*</u>.

2) can also be mined from the earth as large rocks that are then crushed down to the desired size. Because they are created by fracturing of larger rocks, and because they have not been subjected to long-term abrasive processes, crushed aggregate particles tend to be rough, angular, and jagged.

3) The commonly used general purpose natural aggregates tend to have specific gravities in the range of 2.3-2.9. Occasionally when heavyweight aggregate is desired for the purposes described below, iron-ores such as magnetite (G_s=5.04) and hematite (G_s=5.21) are used. When lightweight pcc is needed, some of the natural aggregates that might be used are pumice (G_s=0.25 - 1.25), vermiculite (G_s=0.64 - 1.2), and scoria.

b. Manufactured aggregates tend to be used when either very heavyweight or very lightweight aggregate is desired, or when there is a need to re-use by-products of other industrial processes.

1) Heavyweight aggregate is sometimes desired when structures such as pcc walls and floors are constructed and radiation shielding is important. One common example is in hospitals where X-ray facilities might be enclosed in heavyweight pcc walls so that the radiation used therein does not escape and pose a threat to other building occupants. A few examples of heavyweight aggregates are iron slugs and steel ball bearings.

- Lightweight aggregates are used when lightweight pcc is needed or desired. Among the manufactured lightweight aggregates used to achieve lightweight pcc are: (1) hollow glass beads; (2) foamed polymer beads; (3) expanded vermiculite [G_s=.064 - 0.16]; (4) expanded blast slag; and (5) expanded clay and shale aggregates.

- Blast furnace slag is a by-product from steel-making can be used in crushed form as an aggregate in normal-weight pcc. As briefly noted above, it can also be used in expanded form as a lightweight aggregate.

B. DETERMINING SUITABILITY OF AGGREGATE

The suitability of a potential aggregate naturally depends on the application:

1. For aggregates used as base courses in roadways, the most vital properties tend to be the grain size distribution which in turn determines the drainage characteristics. Coarse aggregates have the best drainage characteristics and are preferred. Fine aggregates have lower permeability (lower drainage) and can thus trap moisture beneath roads. This makes the subgrade vulnerable to frost-heaves at sub-freezing temperatures.

2. For aggregates used in pcc, the aggregate characteristics of most common interest are:

   - Structural properties like strength and stiffness;
   - Its resistance to abrasion, if the pcc is to be used in a wearing surface such as a roadway or a floor.
   - Its vulnerability to freeze-thaw degradation;
   - Its chemistry. Will the aggregate react with the hydrated portland cement paste?
   - Its thermal properties. The thermal conductivity of the aggregate might be an issue in lightweight concrete used for thermal insulation, and the coefficient of thermal expansion of the aggregate might also be an issue of the pcc will be subject to a large range of service temperatures.
   - The roughness or smoothness of the aggregate plays a role in the workability of fresh pcc.
   - The gradation of the aggregate is also of some importance.

3. For aggregates used in acc, the aggregate characteristics of most common interest are:

- The texture, with crushed, angular particles generally preferred over smoothed, rounded particles;
- The grain-size distribution of aggregate, with well-graded preferred over uniform.
- Its vulnerability to freeze-thaw degradation;
- Its chemistry. Will asphalt cement adhere well to the aggregate?

C. COMMON PROPERTIES

1. Shape and Texture:

Bulky grains are generally preferred over plate-like or rod-like particles.

Surface roughness is generally of highest importance in acc, since it is desired that the aggregate will have a high degree of packing and internal friction contributing to the overall strength.

On the other hand, the higher the roughness of the aggregate particles, the more difficult it is to compact them into a very dense arrangement with a low void ratio.

In pcc, a high degree of roughness in the aggregate can make the fresh concrete have a low degree of fluidity or workability.

2. Soundness and Durability

In cold climates, freeze-thaw degradation of aggregates is a potential concern. Aggregates that absorb quite a bit of moisture tend to break and crumble when the water freezes and expands. This reduces the integrity of the pcc or acc of which the aggregate is a part.

Common test (ASTM C88) for measuring the soundness of aggregate involves cyclic soaking in sulfate solutions followed by drying. The crystallization of sulfates within the aggregates simulates the expansion of water upon freezing. If the grain-size distribution of an aggregate changes appreciably in such a test, then the aggregate is vulnerable to freeze-thaw degradation in service.

Other similar tests that measure the soundness of aggregates are ASTM C666, C682, D4792, and AASHTO T103.

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- The grain-size distribution of aggregate, with well-graded preferred over uniform.
- Its vulnerability to freeze-thaw degradation;
- Its chemistry. Will asphalt cement adhere well to the aggregate?

3. Toughness, Hardness, and Abrasion Resistance:

A high toughness, hardness, and abrasion resistance generally means that aggregate particles will not break and polish under normal handling conditions. These characteristics are typically measured indirectly and empirically in the Los Angeles abrasion test (ASTM C131, C535). In this test, a sample from the aggregate of interest is blended to a fixed grain size distribution and then placed in a steel drum with standardized steel balls. The drum is rotated for 500 rotations and the aggregate is then recovered. The recovered aggregate is then placed on a sieve that retained 100% of the initial sample. The percent weight of the recovered aggregate sample that passes through the sieve is termed the LA abrasion number. The higher this number, the lower the toughness, hardness, and abrasion resistance of the aggregate.

4. Absorption

The extent to which aggregate absorbs moisture is important to know for both pcc and acc applications. A high degree of absorption can be a cause for concern, since it indicates that the aggregate particles have a high degree of surface porosity. Consider the aggregate particle shown below in Fig. 8.1. There are a number of volumes associated with it:

- V_p denotes the volume of surface pores;
- V_i denotes the volume of interior voids;
- V_s denotes the solid volume of the aggregate excluding voids and surface pores.

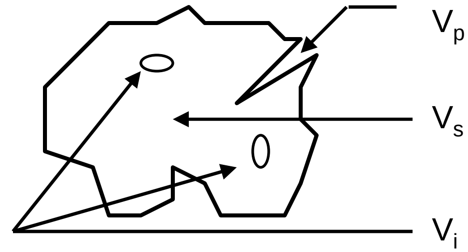
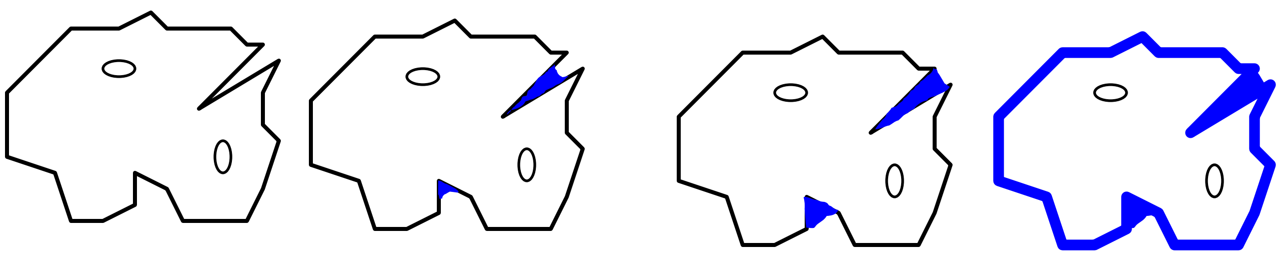


Fig. 8.1 Aggregate particle.

The typical aggregate particle has varying degrees of wetness that depend on which of the void volumes are filled with moisture. Four specific states of wetness are shown in Fig. 8.2 below:



a) bone dry b) air dry c) saturated surface dry (SSD) d) moist

Fig. 8.2. Aggregate particle in varying states of wetness. a) bone dry state contains no moisture at all; b) in the air-dry state, the surface pores are partially saturated; c) in the SSD state, the surface pores are just saturated; d) in the moist state there is additional moisture adhering to the particle surface.

The absorption of an aggregate is its moisture content in the SSD state. Specifically, it is:

$$Absorption = \frac{(W_s + W_p) - W_s}{W_s} = \frac{W_p}{W_s}$$

where: W_p is the weight of water in the aggregate under the SSD condition, and W_s is the weight of the aggregate in the bone-dry state.

5. Specific Gravity

Since the aggregate is often mixed in very precise proportions to make pcc or acc, it is important to know the specific gravity characteristics of the aggregate. There are at least four specific definitions:

$$\text{Bulk dry specific gravity} = \frac{\text{Dry mass}}{(\text{total particle volume})\gamma_w} = \frac{W_s}{(V_s + V_i + V_p)\gamma_w}$$

$$\text{Bulk SSD specific gravity} = \frac{\text{SSD weight}}{(\text{total particle volume})\gamma_w} = \frac{W_s + W_p}{(V_s + V_i + V_p)\gamma_w}$$

$$\text{Apparent specific gravity} = \frac{\text{Dry weight}}{(\text{particle volume not accessible to water})\gamma_w} = \frac{W_s}{(V_s + V_i)\gamma_w}$$

$$\text{Effective specific gravity} = \frac{\text{Dry weight}}{(\text{particle volume not accessible to a.c.})\gamma_w} = \frac{W_s}{(V_s + V_i + \alpha V_p)\gamma_w}$$

In the definition of effective specific gravity, a.c. denotes an asphalt cement, which cannot flow into all of the surface pores. α denotes the fraction of the surface pores unavailable to the a.c.

Two separate procedures exist for measuring the specific gravity and absorption characteristics of coarse and fine aggregates:

- ASTM C127 for coarse aggregate;
- ASCM 128 for fine aggregate.

a. Essentials of ASTM C127 for **coarse aggregate**

This test requires three key measurements:

- The dry weight of the aggregate, $A=W_s$;
- The SSD weight of the aggregate, $B=W_s+W_p$;
- The weight of the aggregate when submerged in water, $C=W_s-(V_s+V_i)*\gamma_w$;

From these three weights, the specific gravities and absorption of the aggregate can be quantified as follows:

$$\text{Bulk dry specific gravity} = \frac{\text{Dry weight}}{(\text{total particle volume})\gamma_w} = \frac{W_s}{(V_s+V_i+V_p)\gamma_w} = \frac{A}{B-C}$$

$$\text{Bulk SSD specific gravity} = \frac{\text{SSD weight}}{(\text{total particle volume})\gamma_w} = \frac{W_s+W_p}{(V_s+V_i+V_p)\gamma_w} = \frac{B}{B-C}$$

$$\text{Apparent specific gravity} = \frac{\text{Dry weight}}{(\text{particle volume not accessible to water})\gamma_w} = \frac{W_s}{(V_s+V_i)\gamma_w} = \frac{A}{A-C}$$

$$\text{Absorption} = \frac{\text{Weight of Moisture in SSD state}}{\text{Dry weight of aggregate}} = \frac{W_p}{W_s} = \frac{B-A}{A}$$

b. Essentials of ASTM 128 for **<u>fine aggregate</u>**

This test requires four key measurements:

- $A=W_s$, the dry weight of the aggregate;
- $B=V*\gamma_w+X$, the weight of a pyncometer filled with water, in which V is the container volume of the pyncometer, and X is the weight of the empty pyncometer.
- $C=W_s+(V-V_s-V_i)*\gamma_w+X$ which is the weight of a pyncometer filled with water and the fine aggregate;
- $D=W_s+W_p$, the SSD weight of the aggregate;
- The weight of the aggregate when submerged in water, $C=W_s-(V_s+V_i)*\gamma_w$;

From these four weights, the specific gravities and absorption of the fine aggregate can be quantified as follows:

$$\text{Bulk dry specific gravity} = \frac{\text{Dry weight}}{(\text{total particle volume})\gamma_w} = \frac{W_s}{(V_s + V_i + V_p)\gamma_w} = \frac{A}{B+D-C}$$

$$\text{Bulk SSD specific gravity} = \frac{\text{SSD weight}}{(\text{total particle volume})\gamma_w} = \frac{W_s + W_p}{(V_s + V_i + V_p)\gamma_w} = \frac{D}{B+D-C}$$

$$\text{Apparent specific gravity} = \frac{\text{Dry weight}}{(\text{particle volume not accessible to water})\gamma_w} = \frac{W_s}{(V_s + V_i)\gamma_w} = \frac{A}{A+B-C}$$

$$\text{Absorption} = \frac{\text{Weight of Moisture in SSD state}}{\text{Dry weight of aggregate}} = \frac{W_p}{W_s} = \frac{D-A}{A}$$

6. Strength of aggregate

For regular strength pcc, <u>it is generally desired that the aggregate particles will be stiffer and stronger than the binder phase</u> (hydrated cement paste). Nevertheless, it is very difficult to directly measure the strength characteristics of aggregate particles, due to their irregular shape and size characteristics.

The best way to determine if a given aggregate is too weak, or not sufficiently strong for a given application, is to use it in a trial pcc mix. When cylinders of the trial mix are compression tested to failure at 28-days, the failure surface within the concrete cylinders should be examined closely. If on the failure surface, a significant number of broken or sheared aggregate particles are observed, then it is likely that the aggregate is not much stronger than the hydrated cement paste (hcp). In this case, the overall strength of the pcc can probably be increased by using a different source of aggregate having stronger particles.

7. Gradation

The gradation of aggregates, which is determined by sieving analysis, can have significant impact on the performance characteristics of a material system:

<u>**For aggregates in sub-bases**</u>, coarseness, and well-gradedness are both important characteristics. A coarse aggregate will have high permeability, and thus excellent drainage. An aggregate that is well-graded will have many different grain sizes, so that small grains fit into the voids between larger grains, all the way down to very small grain sizes (See Fig. 8.3). Well-graded aggregates tend to be less prone to changes in volume (densification) due to re-arranging of the particles than uniform aggregates.

For portland cement concrete, the maximum aggregate size is limited by the size of the member, and the minimum space between reinforcing bars.

When the aggregate for a pcc is relatively fine, it has a higher specific surface area and thus will require more hcp to coat all of the individual particles. Conversely, when a relatively coarse aggregate is used in a pcc mix, less hcp is needed to coat the particles.

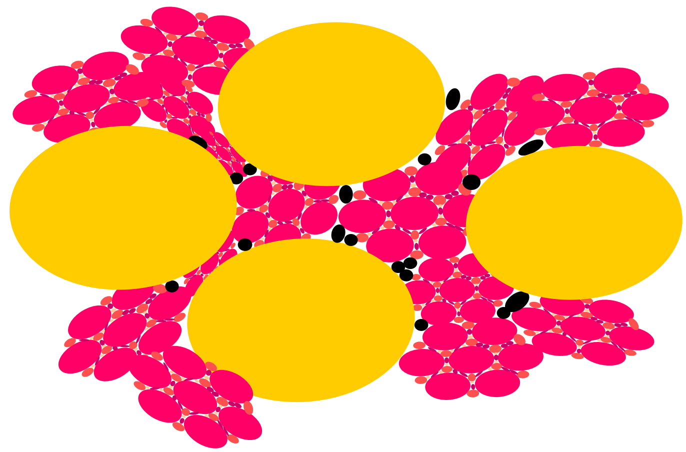


Fig. 8.3. A well-graded aggregate with particles of many different sizes.

A quantity used in pcc mix design for measuring the coarseness of the aggregate is the so-called *fineness modulus*. When sieving is performed on the coarse aggregate, the fineness modulus is the cumulative mass fraction of the aggregate retained on the following sieve sizes: 0.15mm, 0.30mm, 0.60mm, 1.18mm, 2.36mm, 4.75mm, 9.5mm, 19.0mm, 37.5mm, and 75mm. The larger the fineness modulus is for an aggregate, the coarser that aggregate generally is. Generally the range of acceptable fineness modulus values is [2.3, 3.1].

For aggregates used in asphalt cement concrete (acc) it is typically desired that the aggregate be very well-graded with a full spectrum of grain sizes. By having a full-spectrum of grain sizes, the aggregate of acc does not have an excessively large specific surface area, and thus does not require high asphalt cement contents to coat all of the aggregate particles. Also, a well-graded aggregate yields greater volumetric stability, as noted before.

To achieve a very well-graded aggregate that will pack to a high density, Fuller's curve generally provides a good target to shoot for. Fuller's curve is given by the following formula:

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

where: D represents the maximum aggregate grain size; d_i represents a given particle size, and P_i denotes the percent of the aggregate that is finer than d_i. A typical value for the exponent *n* is 0.45 or 0.50.

<u>Example 8.1</u>: For the aggregate whose grain-size distribution is provided in Table 8.1, calculate the fineness modulus

Solution:

$$\text{fineness modulus} = \frac{97+77+55+40+15+2}{100}$$
$$= 2.86$$

Table 8.1. Grain-size distribution data for an aggregate sample.

Size (mm)	% retained	Cumulative % retained	Cumulative % passing
9.5	0	0	100
4.75	2	2	98
2.36	13	15	85
1.18	25	40	60
0.60	15	55	45
0.30	22	77	23
0.15	20	97	3
pan	3	100	0

Example 8.2. For the data in Example 8.1 plot the grain-size distribution and compare to the Fuller curve with n=0.5.

Solution: The maximum grain size in the aggregate sample is 4.75mm. So the Fuller curve plotted in Fig. 8.4 is: $P=[d(mm)/4.75mm]^{.5}$. Since the data plots close to the Fuller curve, the aggregate is very well-graded.

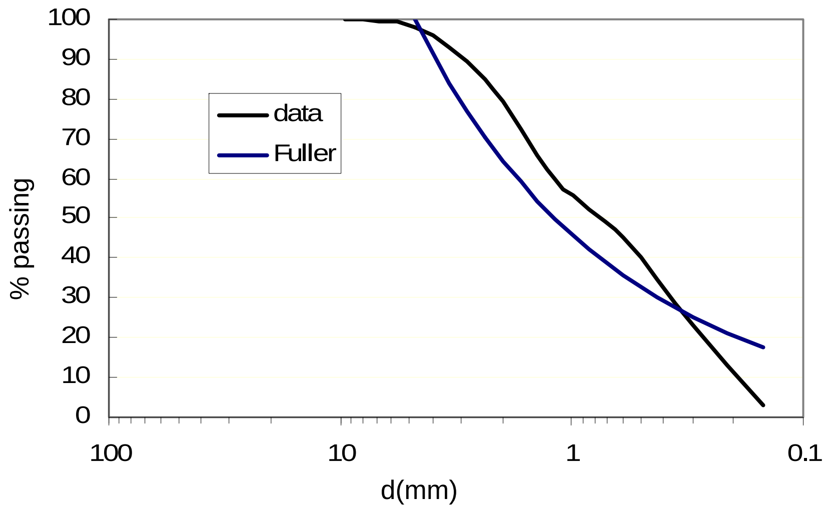


Fig. 8.4. Grain-size distribution for aggregate together with the Fuller curve with D=4.75mm and n=0.5