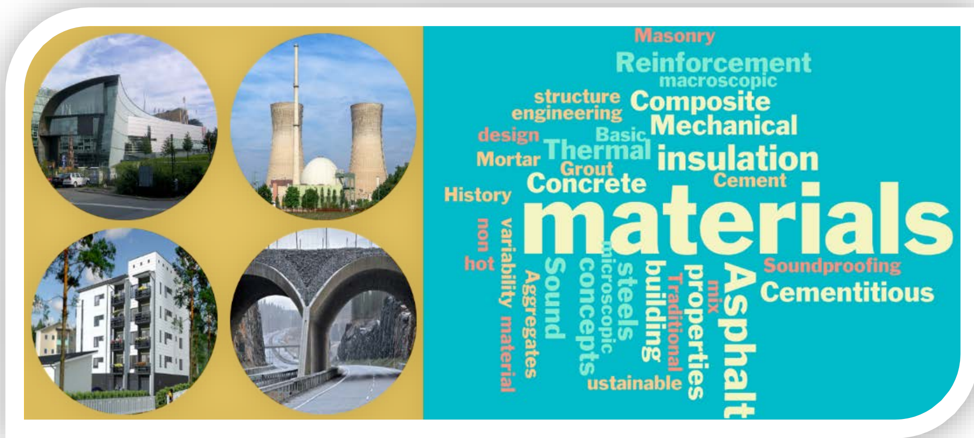


Lecture 4. Aggregates

Prepared by:
Fahim Al-Neshawy, D.Sc. (Tech.)
Aalto University School of Engineering
Department of Civil Engineering
A: P.O.Box 12100, FIN-00076 Aalto, Finland

Table of Contents

4.1 Classification of aggregates

Different types of rocks are classified into the following groups:

1. Classification according to aggregates' source
2. Classification according to unit weight
3. Classification according to aggregates' size

4.1.1 Aggregate sources classification

4.1.1.1 Natural aggregates

- Natural aggregates consists of rock fragments that are used in their natural state, or are used after mechanical processing such as crushing, washing, and sizing.
- Some natural aggregate deposits, called pit-run gravel, consist of gravel and sand that can be readily used in concrete after minimal processing.
- Natural gravel and sand are usually dug or dredged from a pit, river, lake, or seabed.

Figure 1. Natural aggregates & gravels

4.1.1.2 Crushed rock aggregates

- Crushed aggregate is quarried or excavated stone that has been crushed and screened to the desired standard particle size and distribution.
- The particles of crushed aggregate are completely crushed. This gives the products good compaction and load-bearing properties.
- Crushed stone aggregates are particularly suitable for use in the courses of streets, roads and other areas exposed to traffic.

Figure 2. Crushed rock aggregates (1)

4.1.1.3 Artificial aggregates [2]

- Artificial aggregates are made out of various waste materials.
- Artificial aggregates are sometimes produced for special purposes:
  - for making lightweight concrete: burned clays, artificial cinders, foamed slag, expanded shales and slate, sintered fly ash exfoliated vermiculite are used
  - for making heavy- weight concrete: steel rivet punchings and iron ore (Magentite) have been used.

Figure 3. Artificial aggregates example - Air-cooled blast furnace slag (3).

---

[1] Crushed rock aggregates. Available online at: http://www.lemminkainen.com/Infrastructure-construction/mineral-aggregates/Crushed-rock-aggregates/

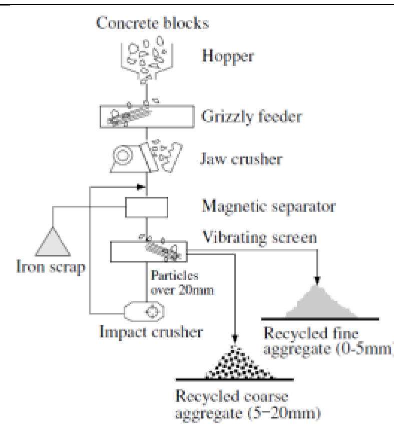
[2] P. Priyadharshini, G. Mohan Ganesh, A. S. Santhi (2012). A Review on Artificial Aggregates. International Journal of Earth Sciences and Engineering. ISSN 0974-5904, Volume 05, No. 03 (01)

[3] Blast furnace slag. Available online at: http://www.euroslag.com/products/absgbs/

4.1.1.4 Recycled aggregates [4]

- Recycled aggregate is derived from crushing inert construction and demolition waste. It may be classified as **recycled concrete aggregate (RCA)** when consisting primarily of crushed concrete or more general **recycled aggregate (RA)** when it contains substantial quantities of materials other than crushed concrete. Currently, only the use of coarse aggregate derived from construction or demolition waste is recommended for use in new concrete construction.
- The characteristic of recycled aggregates could be different by its parent concrete because the parent concrete was designed for its purposes such as permeable, durable and high strength concrete
- Recycling of concrete is a relatively simple process. It involves breaking, removing, and crushing existing concrete into a material with a specified size and quality. Reinforcing steel and other embedded items, if any, must be removed, and care must be taken to prevent contamination by other materials that can be troublesome, such as asphalt, soil and clay balls, chlorides, glass, gypsum board, sealants, paper, plaster, wood, and roofing materials.
- In general, applications of recycled aggregates without any processing include:
  - many types of general bulk fills
  - bank protection
  - base or fill for drainage structures
  - road construction
  - noise barriers and embankments
- applications of new concrete with recycled aggregates include:
  - pavements, shoulders, median barriers, sidewalks, curbs and gutters
  - bridge foundations
  - econocrete bases
  - bituminous concrete.

(a)



(b)

Figure 4. (a)Recycled aggregates, (b) Flow chart for recycled aggregate production.

[4]Portland Cement Association (PCA), Recycled Aggregates. Available online at: http://www.cement.org/for-concrete-books-learning/concrete-technology/concrete-design-production/recycled-aggregates

4.1.2 Unit weight classification

The variability in aggregates' density can be used to classify aggregates of widely different unit weights, shown in Table 1. The most common classification of aggregates on the basis of bulk specific gravity is lightweight, normal-weight, and heavyweight aggregates.

Table 1. Unit weight classification of aggregates

Category	Bulk specific gravity	Examples	Typical applications
ultra-lightweight		vermiculite, ceramic	Can be sawed or nailed, Also used for its insulating properties
Lightweight	$G_s < 2.4$	Expanded perlite, shale or slate Burned clay Crushed brick	Structural lightweight concrete 1350 to 1850 kg/m^3 Masonry units Also used for its insulating properties
Normal weight	$2.4 < G_s < 2.8$	Crushed limestone, Sand, River gravel, Crushed recycled concrete	Used for normal concrete projects Produce **normal-weight concrete** 2200 to 2400 kg/m^3
Heavyweight	$G_s > 2.8$	Steel or iron shot Steel or iron pellets	Produce high-density concrete up to 6400 kg/m^3 • Radiation shielding • counterweights • other applications where a high mass-to-volume ratio is desired

4.1.3 Aggregates' size classification

The largest particle size in aggregates may have a diameter as large as 150 mm, and the smallest particle can be as fine as 5 to 10 microns. Aggregates are classified according to their particle size into:

1. **Course aggregates**: aggregate particles that are retained on a 4.75 mm sieve (metric No.4). → particle size ≥ 5 mm
2. **Fine aggregates:** aggregate particles that pass a 4.75 mm sieve (No. 4). → particle size < 5 mm. Fine aggregates content usually 35% to 45% by mass or volume of total aggregate

(b)

(a)

Figure 5. Aggregates' size classification, (a) fine aggregates and (b) coarse aggregates.

4.2 Aggregates - Manufacturing process [5]

4.2.1 Manufacturing process of normal aggregates

Manufacturing process of the normal aggregates include the following steps:

Step 1: supply:

Three major sources of aggregates can be identified:

- **Unconsolidated (loose) rock:** sand and alluvial materials (dry river beds). This is "rolled" sand because the grains are rounded.
- **Solid rock:** limestone and hard rock or crushed volcanic rock. This is "crushed" sand because the grains are pointed.
- **Recycled materials:** often of industrial origin, from demolition, recycled concrete, railway ballast, etc.

Step 2: extraction:

Extraction is a key phase during production from solid rock, particularly because strategic choices, such as the selection of a slab for color or hardness, can make a real difference.

Step 3: crushing, grinding, screening:

Once extracted, the materials are transported to the processing site for scalping. This process involves removing unwanted materials, such as blocks, clay, etc. The scalped product is crushed once to transform the block into broken stone. The process is repeated as many times as necessary to obtain the desired fragment size.

The resulting material is then screened to obtain aggregates of the desired grade. The larger pieces that are rejected are returned to the crusher and subsequently re-screened, with the process continuing until the desired size is obtained.

Some categories of aggregates, such as sand and gravel, undergo complementary processing including washing, cycloning (pyörrepuhdistus) and scrubbing (märkäpuhdistus), primarily to make them cleaner.

[5] All about Aggregates – Available online at: http://www.lafarge.in/wps/portal/in/3_B_2_A-All_about_Aggregates

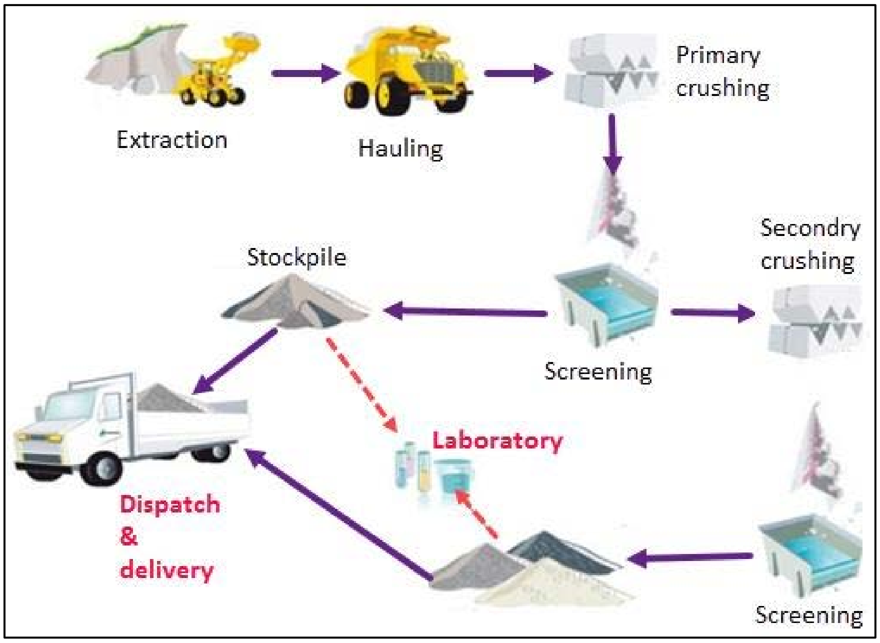


Figure 6. Phases of the aggregates' manufacturing process [5].

4.2.2 Manufacturing of lightweight aggregates [6]

Manufactured lightweight aggregates are produced by expanding some raw materials in a rotary kiln, on a sintering grate, or by mixing them with water. The most common lightweight aggregates are pumice, scoria, expanded shale, expanded clay, expanded slate, expanded perlite, expanded slag and vermiculite.

To produce lightweight aggregate, the raw material (excluding pumice) is expanded to about twice the original volume of the raw material. The expanded material has properties similar to natural aggregate, but is less dense and therefore yields a lighter concrete product.

The production of lightweight aggregate:

- Mining or quarrying the raw material.
- The material is crushed with cone crushers, jaw crushers, hammer mills, or pug mills and is screened for size. Oversized material is returned to the crushers, and the material that passes through the screens is transferred to the storage.
- From the storage, the material is fed to a rotary kiln, which is fired with coal, coke, natural gas, or fuel oil, to temperatures of about 1200°C.
- As the material is heated, it liquefies and carbonaceous compounds in the material form gas bubbles, which expand the material; in the process, volatile organic compounds (VOC) are released.

[6] Lightweight Aggregate Manufacturing – available online at: https://www3.epa.gov/ttnchie1/ap42/ch11/final/c11s20.pdf

- From the kiln, the expanded product (clinker) is transferred by conveyor into the clinker cooler where it is cooled by air, forming a porous material.
- After cooling, the lightweight aggregate is screened for size, crushed if necessary, stockpiled (storage), and shipped.
- Figure 7 illustrates the lightweight aggregate manufacturing process.

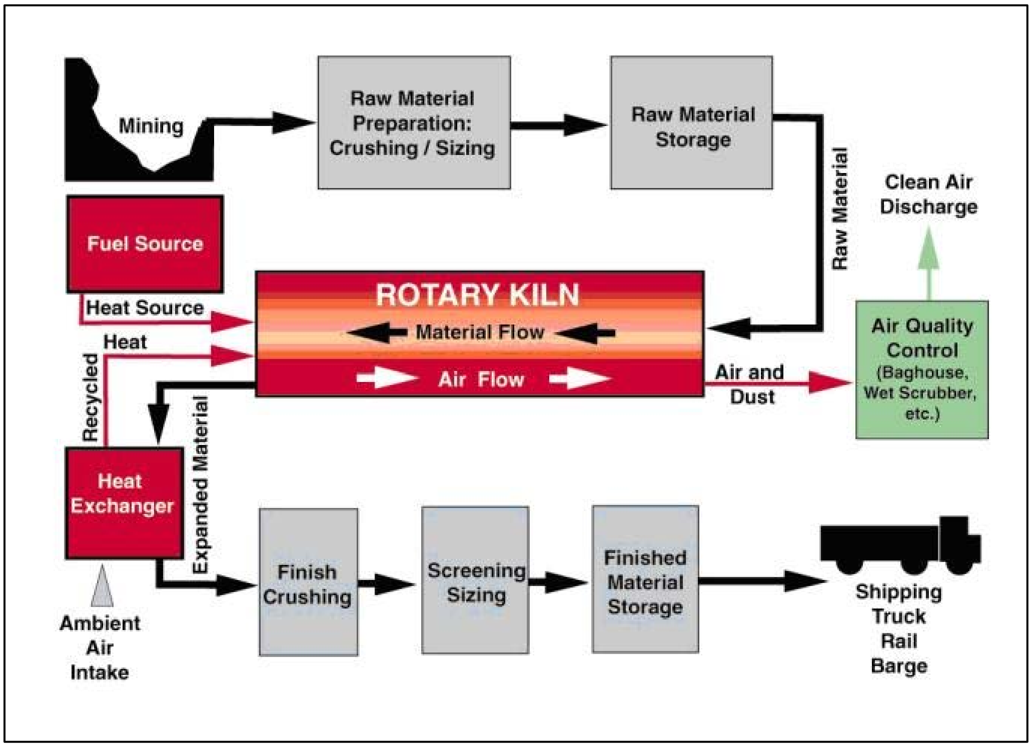


Figure 7. Manufacturing of expanded shale, clay and slate ([7]).

[7] ESCS Lightweight Aggregate – Online at: http://www.escsi.org/ContentPage.aspx?id=524

4.3 Gradation of aggregates

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.

4.3.1 Sieving method

In a sieve analysis, shown in Figure 8:

- A sample of dry aggregate of known weight is separated through a series of sieves with progressively smaller openings.
- Once separated, the weight of particles retained on each sieve is measured and compared to the total sample weight.
- Particle size distribution is then expressed as a percent retained by weight on each sieve size. Results are usually expressed in tabular or graphical format.

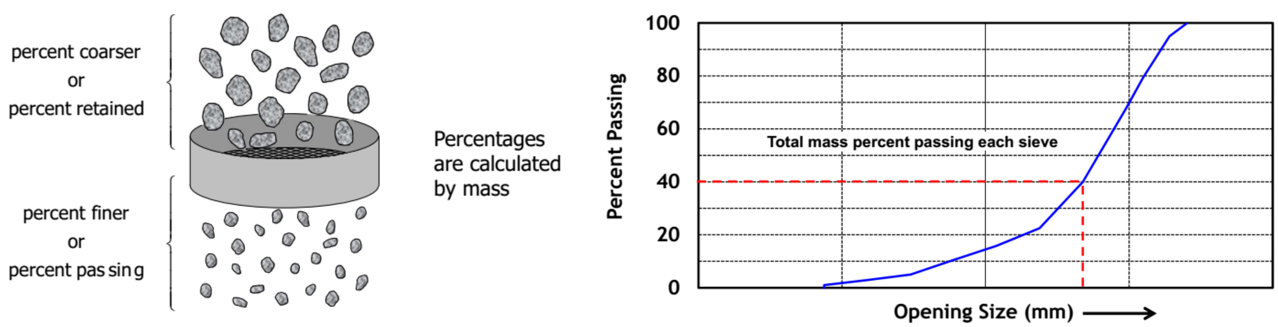


Figure 8. Principle of the sieve analysis method.

- The test consists of dividing up and separating, by means of series of sieves, a material into several particle size classification of decreasing sizes.
- The aperture sizes and the number of sieves are selected in accordance with the nature of the sample and the accuracy required.
- The mass of the particles retained on the various sieves is related to the initial mass of the material.
- The cumulative percentages passing each sieve are reported in numerical form or in graphical form.

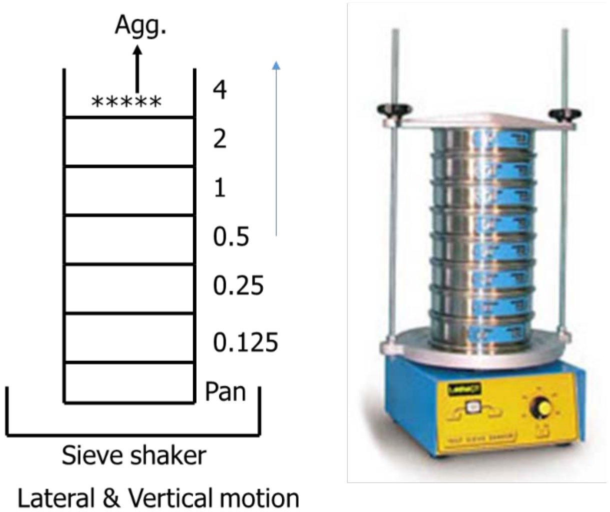


Figure 9. Grading of aggregates using sieving method.

The following terms are related to the sieving methods:

- **Individual retained** – the mass or percentage retained on one sieve after test
- **Cumulative retained** – sum of the mass or percentages retained on the sieve and on all coarser sieves.
- **Cumulative passing** – sum of the mass or percentage passing the sieve (e.g. sum of the retained on all finer sieves and pan)
- **Test sieves** – set of sieves with given aperture sizes and shape. The basic series of sieves (according EN 933-2) are: 0.063; 0.125; 0.250; 0.500; 1; 2; 4; 8; 16; 32; 63; 125 mm.

Table 2. Example of the particle size distribution calculation

Sieve aperture size [mm]	Mass of material retained [g]	Percentage of materials retained [%]	Cumulative percentages passing [%]
16	0,0	0,00	100,00
8	153,0 →	(153/2002)*100 7,64 →	(100 - 7,64) 92,36
4	240,0	(240/2002)*100 11,99	(92,36 - 11,99) 80,37
2	260,0	12,99	67,38
1	185,0	9,24	58,14
0.5	496,0	24,78	33,37
0,25	415,0	20,73	12,64
0,125	210,0	10,49	2,15
0,063	32,0	1,60	0,55
<0,063 (pan)	11,0	0,55	0,00
sum	2002,0	100,00	

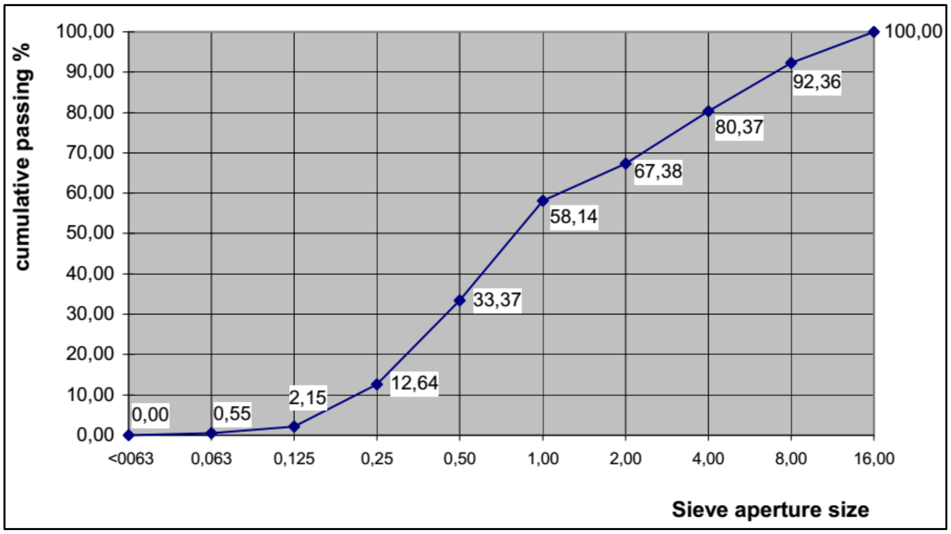


Figure 10. Example - Particle size distribution curve

4.3.2 Fineness modulus

Fineness Modulus (FM) is used in determining the degree of uniformity of the aggregate gradation. It is an empirical number relating to the fineness of the aggregate. The higher the FM is, the coarser the aggregate is. Fineness Modulus is defined as the sum of the cumulative percentages retained on specified sieves divided by 100.

$$FM = \frac{\sum(Cumulative\ percentage\ retained\ on\ specified\ sieves)}{100} \quad (1)$$

According EN 12620 - Aggregates for concrete, the FM is calculated on the following sieves: 4mm; 2 mm; 1 mm; 0.5 mm; 0.25 mm; and 0,125 mm. An example of sample calculation of Fineness Modulus is shown in XX

Table 3. Sample calculation of Fineness Modulus

Sieve Size	Percentage of individual fraction retained, by weight (%)	Cumulative percentage retained by weight (%)	Percentage passing by weight (%)
4	2	2	98
2	13	15	85
1	25	40	60
0.5	15	55	45
0.25	22	77	23
0.125	20	97	3
Pan	3	~~100~~	0
Total	100	Σ = 286	
		FM = 286/100 = 2.86	

4.4 Engineering properties of aggregates

Aggregates' properties are defined by the characteristics of both the individual particles and the characteristics of the combined material. As shown in Table 4, aggregates' properties can be further described by their (i) Physical characteristics, (ii) Chemical characteristics and (iii) Mechanical characteristics

Table 4. Basic Aggregate Properties (8)

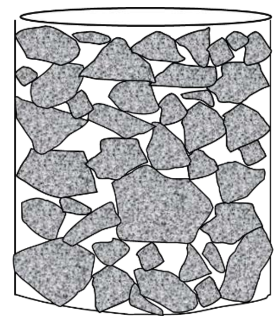
	Property	Relative Importance for End Use*		
		concrete	Asphalt	Base
Physical characteristics	Particle shape (angularity)	MI	VI	VI
	Particle shape (flakiness, elongation)	MI	MI	MI
	Particle size—maximum	MI	MI	MI
	Particle size—distribution	MI	MI	MI
	Particle surface texture	MI	VI	VI
	Pore structure, porosity	VI	MI	UI
	Specific gravity, absorption	VI	MI	MI
	Soundness—weatherability	VI	MI	MI
	Unit weight, voids—loose, compacted	VI	MI	MI
	Volumetric stability—thermal	MI	UI	UI
	Volumetric stability—wet/dry	MI	UI	MI
	Volumetric stability—freeze/thaw	VI	MI	MI
	Integrity during heating	UI	MI	UI
	Deleterious constituents	VI	MI	MI
Chemical characteristics	Solubility	MI	UI	UI
	Surface charge	UI	VI	UI
	Asphalt affinity	UI	VI	MI
	Reactivity to chemicals	VI	UI	UI
	Volume stability—chemical	VI	MI	MI
	Coatings	MI	MI	UI
Mechanical characteristics	Compressive strength	MI	UI	UI
	Toughness (impact resistance)	MI	MI	UI
	Abrasion resistance	MI	MI	MI
	Character of products of abrasion	MI	MI	UI
	Mass stability (stiffness, resilience)	UI	VI	VI
	Polishability	MI	MI	UI
*VI = Very important; MI = Moderately important; UI = unimportant or importance unknown				

[8] Meininger, R. C. and F. P. Nichols. (1990) Highway Materials Engineering, Aggregates and Unbound Bases. Publication no. FHWA-HI-90-007, NHI Course No. 13123. Washington, DC: Federal Highway Administration, 1990.

4.4.1 Physical properties

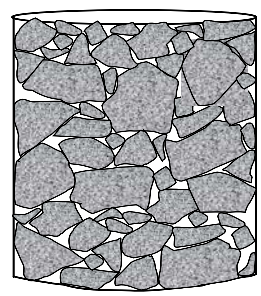
4.4.1.1 Bulk unit weight and voids in aggregate

Bulk unit weight is the weight of aggregate required to fill a "unit" volume. Typical unit volume is cubic meters. The procedure for measuring the aggregate bulk unit weight is:



<u>For loose aggregates:</u>

- Shovel dry aggregate into container
- Limit drop < 5 cm above rim of container
- Strike off aggregate level with top of container
- Determine weight of aggregate in container, W_S
- Compute unit weight



<u>For Compacted aggregates:</u>

- Shovel dry aggregate into container
  - Fill to 1/3 of volume
  - Rod 25 times
  - Repeat 3 times to fill container
  - Strike off aggregate level with top of container
- Determine weight of aggregate in container, W_S
- Compute unit weight

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 is (γ_b) determined as:

$$\gamma_b = \frac{W_s}{V} \tag{2}$$

where is W_s the weight of (stone) aggregate [kg], and V is the volume of the container [m^3].

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

$$\%V_s = \frac{V_s}{V} \times 100 = \frac{\left(\frac{W}{\gamma_s}\right)}{\left(\frac{W}{\gamma_b}\right)} \times 100 = \frac{\gamma_b}{\gamma_s} \times 100 = \frac{\gamma_b}{G_{sb} \cdot \gamma_w} \times 100 \tag{3}$$

$$\%\,Voids = 100 - \%V_s$$

Where Vs = the volume of aggregates (solid)

γ_s = the unit weight of aggregates

γ_b = the bulk unit weight of aggregates

γ_w = the unit weight of water

4.4.1.2 *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 **(G_s)**, the mass of a material divided by the mass of an equal volume of distilled water, is more commonly used.

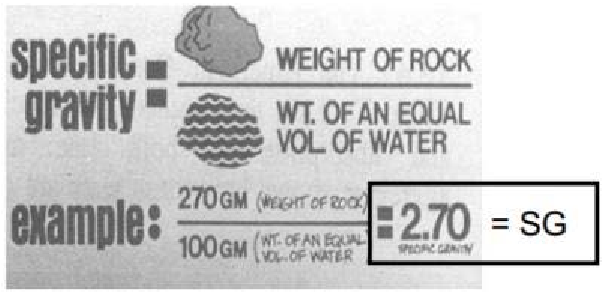


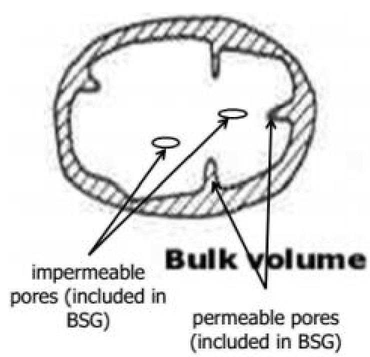
Figure 11. Specific gravity of rock.

Four types of specific gravity are defined based on how voids in the aggregate particles are considered:

1. bulk-dry specific gravity → Concrete
2. bulk-saturated surface–dry (SSD) specific gravity
3. apparent specific gravity
4. effective specific gravity

<u>Bulk Dry Specific Gravity (BSG):</u>

- Aggregate has tiny pores:
  - permeable or
  - impermeable to water.
- Bulk dry specific gravity includes the volume of both permeable and impermeable pores.
- The BSG is the 'Real' specific gravity

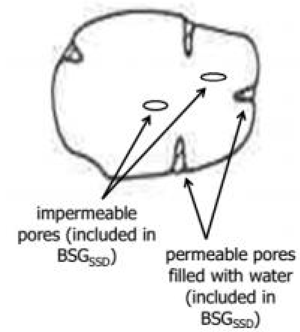


W_s = the weight of solids
V_s = the volume of solids
V_i = the volume of water impermeable voids
V_p = the volume of water permeable voids
γ_w = the unit weight of water

$$Bulk\ dry\ G_{sb} = \frac{Dry\ Weight}{(Total\ Particle\ Volume).\gamma_w} = \frac{W_s}{(V_s + V_i + V_p).\gamma_w} \quad (4)$$

<u>Bulk-saturated surface–dry (SSD) specific gravity</u> (BSG_{SSD})

- Saturated surface dry (SSD) is defined as the condition of an aggregate in which the surfaces of the particles are "dry" (i.e., surface adsorption would no longer take place), but the inter-particle voids are saturated with water.
- Assumes all permeable pores filled with water (saturated)
- Particles appear moist but not shiny (surface dry)

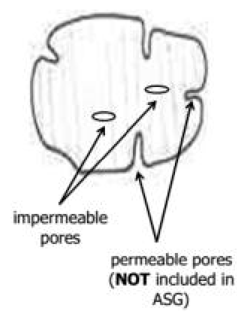


W_s = the weight of solids
W_p = the of water in the permeable voids
V_s = the volume of solids
V_i = the volume of water impermeable voids
V_p = the volume of water permeable voids
γ_w = the unit weight of water

$$Bulk\ SSD\ G_{s,b_{ssd}} = \frac{SSD\ Weight}{(Total\ Particle\ Volume).\gamma_w} = \frac{W_s + W_p}{(V_s + V_i + V_p).\gamma_w} \quad (5)$$

<u>Apparent specific gravity:</u> (ASG)

- The apparent specific gravity is defined as the ratio of the mass of the particles to the mass of a volume of water equal to the net volume of the particles
- Apparent specific gravity includes only the volume of impermeable pores.

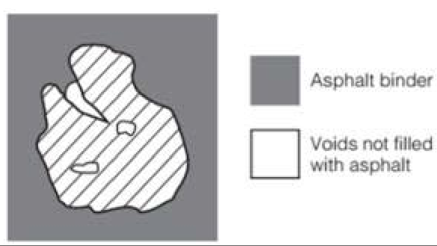


W_s = the weight of solids
V_s = the volume of solids
V_i = the volume of water impermeable voids
γ_w = the unit weight of water

$$Apparent\ G_{sa} = \frac{Dry\ Weight}{(Volume\ not\ Accessible\ to\ water).\gamma_w} = \frac{W_s}{(V_s + V_i).\gamma_w} \quad (6)$$

<u>Effective specific gravity</u>

- Only a portion of the water-permeable pores are filled with asphalt cement.
- Effective specific gravity includes the pores not accessible to asphalt.



W_s = the weight of solids
V_s = the volume of solids
V_c = the volume of voids not filled with asphalt cement
γ_w = the unit weight of water

$$Effective\ G_{se} = \frac{Dry\ Weight}{(Volume\ not\ accessible\ to\ asphalt).\gamma_w} = \frac{W_s}{(V_s + V_c).\gamma_w} \quad (7)$$

The specific gravity and absorption of coarse aggregates are determined in accordance with ASTM C127 (Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate). 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 saturated surface–dry (SSD) condition and weighed.
- Finally, the sample is dried to a constant weight and weighed.

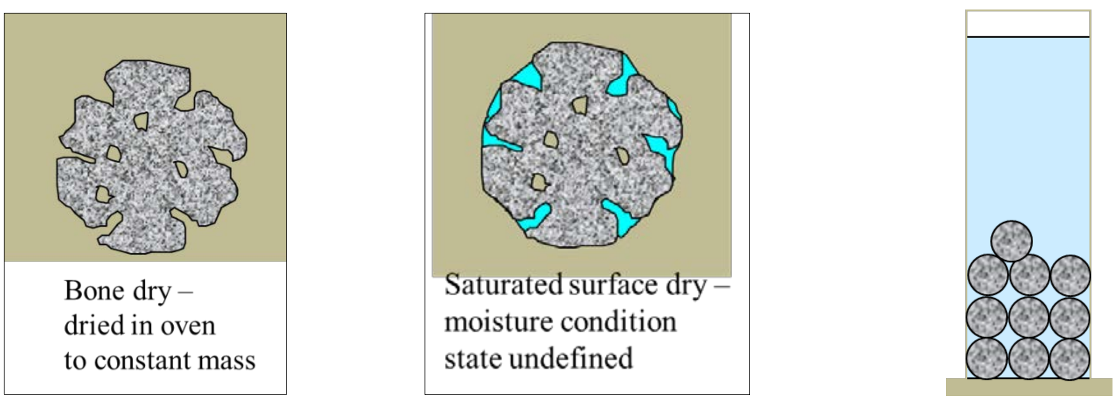
The specific gravity and absorption are determined by:

$$Bulk\ dry\ G_s = \frac{A}{B - C} \tag{8}$$

$$Bulk\ SSD\ G_s = \frac{B}{B - C} \tag{9}$$

$$Apparent\ G_s = \frac{A}{A - C} \tag{10}$$

$$Absorption\ (\%) = \frac{B - A}{A} \times 100 \tag{11}$$



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

Figure 12. The weight values as part of ASTM C127.

4.4.1.3 Particle shape and surface texture

- The shape and surface texture of the individual aggregate particles determine 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
- The shape of aggregate particles can be classified as either angular, subangular, subrounded or rounded.
- Angular and rough-textured aggregates
  - Crushing rocks produces angular particles with sharp corners and rough texture.
  - Due to weathering, the corners of the aggregates break down, creating subangular particles and smooth texture.
  - Generally, angular and rough-textured aggregates produce bulk materials with higher stability than rounded, smooth-textured aggregates.
- Rounded aggregates

- When the aggregates tumble while being transported in water, the corners can become completely rounded.
- Rounded aggregates will be easier to work into place than angular aggregates, since their shapes make it easy for them to slide across each other.

- Each shape has advantages and disadvantages depending on the desired properties of the finished product.

Particle shape of coarse aggregates

Figure 13 shows the different shapes of coarse aggregates: angular, rounded, flaky, elongated, and flaky and elongated. Flakiness, also referred to as flat and elongated, describes the relationship between the dimensions of the aggregate.

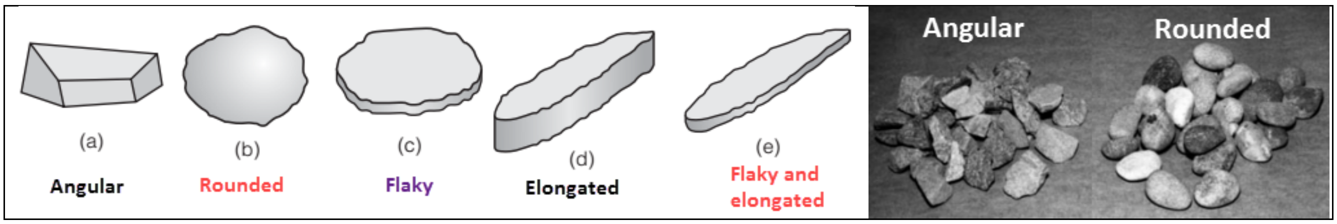


Figure 13. Aggregates' particle shapes.

Figure 14 shows the concept of the flakiness test. This is an evaluation of the coarse portion of the aggregates, but only aggregates retained on the 9.5 mm (3/8 inch) sieve are evaluated.

- **A flat particle** is defined as one where the ratio of the "middle" dimension to the **smallest dimension** of the particle exceeds the 3 to 1.
- **An elongated particle** is defined as one where the ratio of the **longest dimension** to the middle dimension of the particle exceeds the 3 to 1.
- Under the Superpave criteria, particles are classified as "**flat and elongated**" if the ratio of the largest dimension to the smallest dimension exceeds 5 to 1.

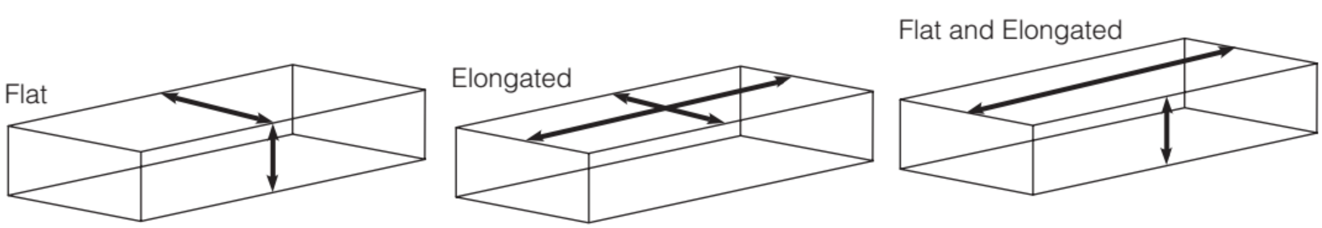


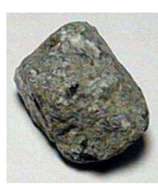
Figure 14. Concept of flakiness test.

Texture of coarse aggregates

The roughness of the aggregate surface plays an important role in the way the aggregate compacts and bonds with the binder material.

- Surface texture is a measure of the smoothness and roughness of aggregate.
- The grouping of aggregate is broad and is based on visual examination of the specimen.
- the aggregates are classified into five groups, namely, Glassy, Smooth, Granular, Crystalline, Honeycombed and Porous

Table 5. Classification of aggregates based on shape and surface texture.

	Classification	Example		Application
Aggregate shape	Rounded	River or seashore gravels		Rounded aggregates are suitable to use in concrete because flaky & elongated particles reduce workability, increase water demand & reduce strength.
	Partly rounded	Pit sands & Gravels		
	Angular	Crushed Rocks		To meet the needs of angular aggregates with high texture, many specifications for coarse aggregates used in asphalt concrete require a minimum percentage of aggregates with crushed faces as a surrogate angularity and texture requirement.
	Flaky	Laminated rocks		Flaky and elongated aggregates are undesirable for asphalt concrete, since they are difficult to compact during construction and are easy to break
Surface texture	Glassy	Natural flint		This natural coloured flint is perfect for driveways, footpaths, borders and general landscaping, plus for 'spray tar' and chip treatment for driveways.
	Smooth	Gravel, Marble		The stability of Portland cement concrete is mostly developed by the cementing action of the Portland cement and by the aggregate interlock, it is desirable to use rounded and smooth aggregate particles to improve the workability of fresh concrete during mixing.
	Granular	Sandstone		Sandstone is used in cement manufacturing, construction aggregate, and for road aggregate, Sandstone is used also for production of glass and ceramics, and as a raw material for the manufacture of mortar
	Rough	Basalt		Rough texture generally improves bonding and increases interparticle friction The stability of asphalt concrete and base courses is mostly developed by the aggregate interlock. Therefore, 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
	Crystalline	Granite		Granite is the best aggregate for high-grade concrete. Granite is also used as a decorative stone. It can be grey, red, or pink and has a lot of shades.

<u>Particle shape and texture of fine aggregates</u>

The angularity and texture of fine aggregates have a very strong influence on the stability of asphalt concrete mixes.

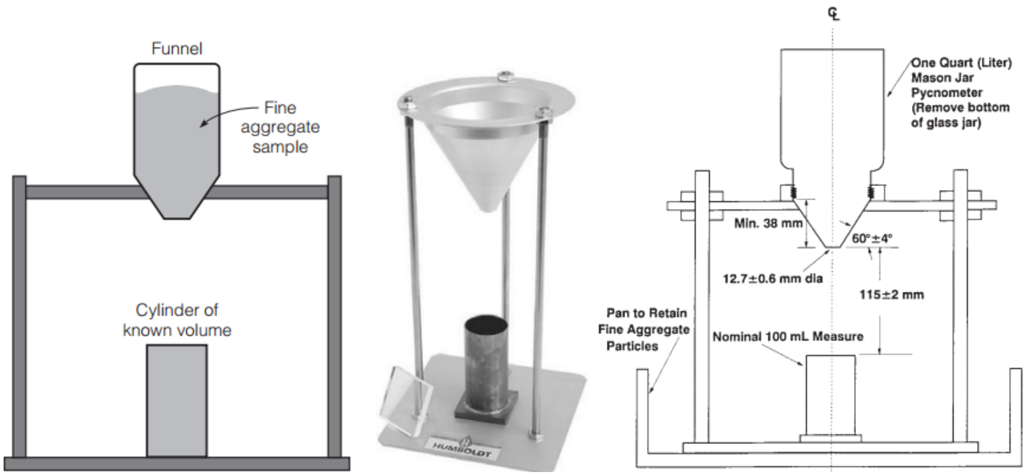


Figure 15. Apparatus used to measure angularity and surface texture of fine aggregate.

Uncompacted Void Content test [ASTM C-1252] is an indirect method for measuring fine aggregate angularity:

- The test determines percent air voids present in loosely compacted fine aggregate when a sample of fine aggregate is allowed to flow into a small calibrated cylinder through a standard funnel.
- The diameter of the funnel orifice is approximately 12.5 mm, and its tip is located 114 mm above the top of the cylinder, as shown in Figure 15.
- This test relates uncompacted void content to the number of fractured faces in an aggregate
- Air voids present in loosely compacted or uncompacted aggregates are calculated as the difference between the volume of the calibrated cylinder and the absolute volume of the fine aggregate collected in the cylinder.
- The volume of the cylinder is calibrated and is approximately 100 ml.
- Absolute volume of the collected fine aggregate is calculated using the dry bulk specific gravity of the fine aggregate.
- The uncompacted void content of fine aggregate is calculated from the following formula:

$$U = \frac{V - \left(\frac{F}{G_b}\right)}{V} \times 100 \qquad (12)$$

Where:

U = uncompacted void content in fine aggregate, %;
V = volume of a calibrated cylinder, ml;
F = mass of fine aggregate in the cylinder; and
G_b = dry bulk specific gravity of fine aggregate.

4.4.1.4 Absorption and surface moisture

Although aggregates are inert, they can capture water and asphalt binder in surface voids.

For using in concrete:

- 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 react with the cement or to improve the workability of the plastic concrete.
- 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.

For using in asphalt:

- 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.
- 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.

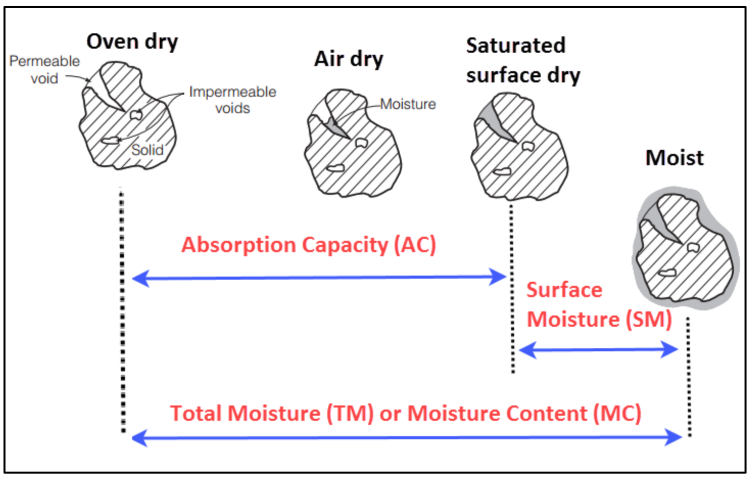


Figure 16. Voids and moisture absorption of aggregates.

Figure 16 demonstrates the four moisture condition states for an aggregate particle:

1. **Bone dry** means the aggregate contains no moisture; this requires drying the aggregate in an oven to a constant mass.
2. **Air dry condition**, the aggregate may have some moisture but the saturation state is not quantified.
3. **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.
4. **Moist aggregates** have 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.

The percent **Absorption Capacity (AC)**, which is the maximum amount of water aggregate can absorb, can be calculated as:

$$AC = \frac{W_{SSD} - W_{O.dry}}{W_{O.dry}} \times 100 \tag{13}$$

The percent **Surface Moisture (SM)**, which is the amount of water on the surface of aggregate particles, can be calculated as:

$$SM = \frac{W_{moist} - W_{SSD}}{W_{SSD}} \times 100 \tag{14}$$

The percent **Moisture Content (MC)** in the aggregate in any state, can be calculated as:

$$MC = \frac{W_{moist} - W_{O.dry}}{W_{O.dry}} \times 100 \tag{15}$$

Where:

W_{moist} = weight of moist aggregate;
$W_{o.dry}$ = weight of oven dry aggregate
W_{SSD} = weight of saturated surface dry aggregate

4.4.2 Chemical Properties [9]

The chemical properties of aggregates have to do with the molecular structure of the minerals in the aggregate particles. These properties are:

- Chemical composition
- Reactions with asphalt
- Reactions with cement

4.4.2.1 Chemical Composition

- Aggregates consisting of materials that can **react with alkalies** in cement and cause excessive expansion, cracking and deterioration of concrete mix should never be used. Therefore it is required to test aggregates to know whether there is presence of any such constituents in aggregate or not.
- Some aggregates have minerals that are subject to oxidation, hydration, and carbonation. These properties are not particularly harmful, except when the aggregates are used in Portland cement concrete. As might be expected, iron sulfides, ferric and ferrous oxides, free lime, and free magnesia in industrial products and wastes are some of the common substances. Any of these substances may cause distress in the Portland cement concrete and give the concrete an unsightly appearance.

4.4.2.2 Asphalt affinity

Stripping, or **moisture-induced** damage, is a:

[9] http://www.in.gov/indot/files/chapter_03.pdf

- Separation of the asphalt film from the aggregate through the action of water,
- Reducing the durability of the asphalt
- Resulting in pavement failure.

The mechanisms causing stripping are complex. 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 mix:

- Early compatibility tests submerged the sample in either **room temperature water** (*ASTM D1664 - Test Method for Coating and Stripping of Bitumen-Aggregate Mixtures*) → observation of the percentage of particles stripped from the asphalt vs time
- **Boiling water** (*ASTM D3625 - Standard Practice for Effect of Water on Bituminous-Coated Aggregate Using Boiling Water*) → observation of the percentage of particles stripped from the asphalt vs time.
- More recent procedures subject asphalt 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 - Standard Test Method for Effect of Water on Compressive Strength of Compacted Bituminous Mixtures*).

4.4.2.3 Alkali–aggregate reactivity

- Silica, SiO_2, is a component of many rocks; however, not all forms of silica react significantly with the pore solution of concrete and, thus, not all siliceous aggregates produce damaging ASR. For example, the mineral quartz is stable whereas the mineral opal is highly reactive, although both are silica minerals with similar chemical composition, being primarily composed of SiO_2.
- Opal has a highly disordered (amorphous) structure which renders it unstable at high pH and, as such, aggregates containing significant quantities of the mineral opal may be expected to react and result in expansion when used in concrete, provided there is sufficient alkali present. On the other hand, quartz will not react deleteriously regardless of the alkali content of the concrete.

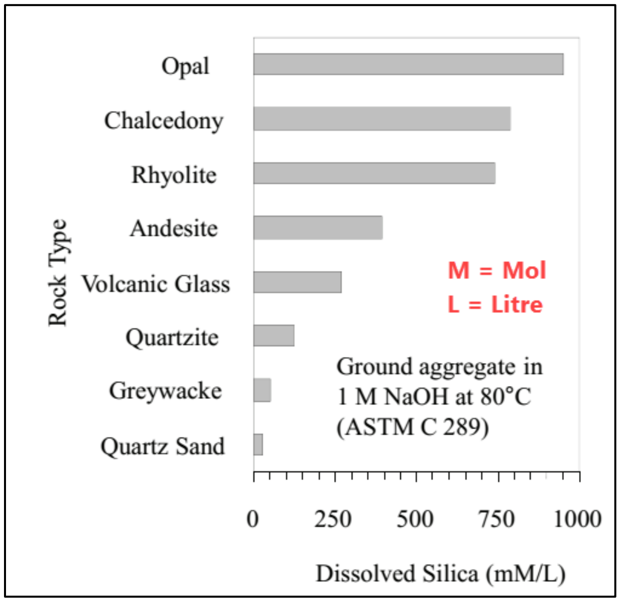
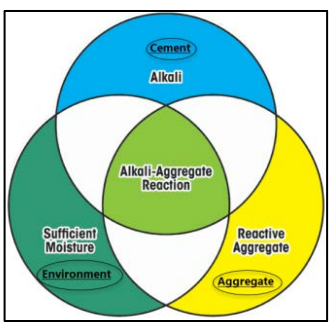


Figure 17. Solubility of the silica of different types of aggregates.

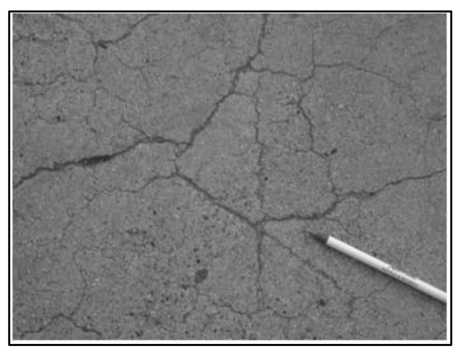
The most common reaction, particularly in **humid and warm climates**, is between the:

- 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 pop-outs in concrete, as shown in Figure 18b.



(a)



(b)

Figure 18. ASR: (a) The three necessary components for ASR-induced damage in concrete, (b) Example of cracking in concrete due to alkali-silica reactivity

Other constituents in the aggregate, such as carbonates, can also react with the alkali in the cement (**alkali–carbonate reactivity**); 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 - Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)) test can be used to determine the potentially expansive alkali–silica 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 - Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)) can be used to identify potentially reactive siliceous aggregates.
- ASTM C586 - Standard Test Method for Potential Alkali Reactivity of Carbonate Rocks as Concrete Aggregates (Rock-Cylinder Method) is used to determine potentially expansive carbonate rock aggregates (alkali–carbonate reactivity).

4.5 Aggregate uses [10]

Aggregate can be used in a number of ways in construction. In roads and railway ballast the aggregates are used to resist the overall (static as well as dynamic) load, to distribute the load properly to the supporting ground and to drain the water off the surface. In concrete the aggregate is used for economy, reduce shrinkage and crakes and to strengthen the structure. They are also used in water filtration and sewage treatment processes. The uses of aggregates can be summarized in to the following three categories:

- As a Load Bearing Material
- As a Filling Material
- As an Infiltrating Material

4.5.1 Constructional in general

Aggregates are used in construction to provide drainage, protect pipes, and to provide hard surfaces.

- They are also used in water filtration and sewage treatment processes. Water will percolate through a trench filled with aggregate more quickly than it will through the surrounding soil, thus enabling an area to be drained of surface water. → This is frequently used alongside roads in order to disperse water collected from the asphalt surfacing.
- Voids created around the foundations of buildings during construction are filled with aggregate because it is easier to compact than the original soil that was removed, resulting in a more solid finish that will support the structure. Aggregates generally are not affected by the weather as much as soils, particularly clay soils, and will not suffer from shrinkage cracking during dry spells.

[10] Uses of Aggregates – online at: http://www.sustainableaggregates.com/overview/uses.htm

- Pipes laid to convey treated water, or as conduits for cables, need to be protected from sharp objects in the ground and are therefore laid on, and surrounded by fine aggregate before trenches are backfilled.
- Unpaved roads and parking areas are covered in a surface layer of aggregate to provide a more solid surface for vehicles. → This prevents the vehicles from sinking into the soil, particularly during wet weather.
- Groundwater is filtered naturally through aquifers, often layers of sand and gravel, and only needs to be disinfected with chlorine before it is safe to use. This natural process can be replicated in treatment works to remove suspended solids from surface or stored water, before disinfection. In addition sand beds are used during the last stages of sewage treatment works as a final filter and cleaning process before the water is released into watercourses. In some cases reed beds are used at this stage, where the reeds will be grown on gravel.

4.5.2 Concrete and mortars

- Concrete is a mixture of aggregates, cement and water. The purpose of the aggregates within this mixture is to provide a rigid skeletal structure and to reduce the space occupied by the cement paste. Both coarse aggregates (particle sizes of 20 mm to 4 mm) and fine aggregates (particle sizes less than 4 mm) are required but the proportions of different sizes of coarse aggregate will vary depending on the particular mix required for each individual end use.
- The smaller the aggregate size, the greater the surface area and the more cement will be required to bind it all together, resulting in a higher cost. However, in general terms, the greater the quantity of cement used the stronger the concrete will be.
- Mortar consists of sand, cement and water. In some circumstances lime may also be added, together with admixtures (chemicals to control setting and workability) and/or pigments if required. They are used to bond bricks or concrete blocks together in walls and to provide weather protection (known as rendering).

4.5.3 Asphalt and road stone

- This category includes not just roads, but also pavements, airport runways, school playgrounds, car parks, most footpaths or cycle ways, and other similar structures. Although each type of structure will require some variation in the material, it is useful to look at the **basic structure of roads** because they represent the bulk of the aggregate use in this category.

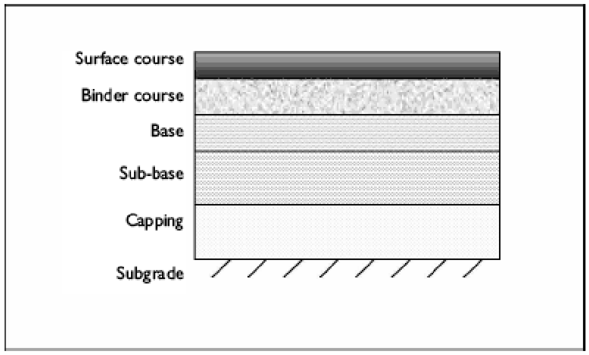


Figure 19. Cross-section of a typical road construction

- The **subgrade** represents the natural soil, which will be compacted before the road construction starts.
- The **capping layer** is an optional layer, used when the local soils require extra strength, and it is not coated with bitumen.
- The **sub-base** is the main uncoated road stone layer and its role is to give strength and act as a solid platform for the layers above.
- The **binder course** (previously two layers known as the base course and road base) and surface course (previously known as wearing course) are commonly called 'asphalt'. They consist of coarse aggregates, with particle sizes typically between 2 mm to 28 mm, and fine aggregates, with particle sizes of less than 2 mm, mixed with a bitumen binder and occasionally some additional filler if required. The exact sizes required for the coarse aggregates will depend on the particular use and the asphalt recipe specified.
- The binder course is the main load-bearing layer and provides an even plane for the surface course.
- The **surface course** provides the road with protection from the weather because water ingress would be very destructive, but also gives the final running surface that must be resistant to abrasion and skidding.

4.5.4 Railway ballast

- A fully loaded train weighs a considerable amount (> 2 000 tonnes), added to this is the weight of the track itself and the sleepers it rests on. It soon becomes obvious that a very **tough aggregate** is needed to support this weight and distribute the load of a passing train to avoid serious damage to the ground, or other structures, underneath. Similarly the railway track and sleepers must be held in place firmly and not move as a train passes along them.

Figure 20. Example of a railway ballast.

- Railway ballast generally consists of a tough igneous rock, such as granite, with large (40-50 mm size) angular pieces that lock together. Because of the way igneous rock is formed it is highly resistant to pressure and does not break easily.