

Chapter Three: Aggregates



3.1 Definition

Aggregates are defined as **inert**, **granular**, and **inorganic** materials that normally consist of stone or stone-like solids. Aggregates can be used alone (in road bases and various types of fill) or can be used with cementing materials (such as Portland cement or asphalt cement) to form composite materials or concrete.

The most popular use of aggregates is to form Portland cement concrete. Approximately 75% of the volume of Portland cement concrete is occupied by aggregate. It is inevitable that a constituent occupying such a large percentage of the mass should have an important effect on the properties of both the fresh and hardened products.

3.2 Classification of Aggregates

Aggregates can be divided into several categories according to different criteria.

A. In accordance with size:

Coarse aggregate: Aggregates predominately retained on the No. 4 (4.75 mm) sieve. For mass concrete, the maximum size can be as large as 150 mm.

Fine aggregate (sand): Aggregates passing No.4 (4.75 mm) sieve and predominately retained on the No. 200 (75 μ m) sieve.

B. In accordance with sources

Natural aggregates: This kind of aggregate is taken from natural deposits without changing their nature during the process of production such as crushing and grinding. Some examples in this category are sand, crushed limestone, and gravel.

By-Product Aggregates:

Comprise blast-furnace slags and cinders, fly ash, etc. Cinders are residue of coal or wood after burning.

Processed Aggregates:

These are heat treated, expanded materials with lightweight characteristics.

Example: Perlite, burnt clays, shales, processed fly ash.

Colored Aggregates:

Glass, ceramics, manufactured marble for decorative and architectural purposes.

Recycled Aggregates:

This type of aggregates comes from the demolished structural concrete elements (footings, columns, slabs, etc)

C. In accordance with unit weight

Light weight aggregate: The unit weight of aggregate is less than 1120kg/m^3 . The corresponding concrete has a bulk density less than 1800kg/m^3 (cinder, blast-furnace slag, volcanic pumice).

Normal weight aggregate: The aggregate has unit weight of $1520\text{-}1680\text{kg/m}^3$. The concrete made with this type of aggregate has a bulk density of $2300\text{-}2400\text{ kg/m}^3$.

Heavy weight aggregate: The unit weight is greater than 2100 kg/m^3 . The bulk density of the corresponding concrete is greater than 3200 kg/m^3 . A typical example is magnesite limonite, a heavy iron ore. Heavy weight concrete is used in special structures such as radiation shields.

D. In accordance with origin:

Igneous rock Aggregate:

Sedimentary rock Aggregates:

Metamorphic rock Aggregate:

3.3 Physical Properties of Aggregates

3.3.1 Specific Gravity

The specific gravity of an aggregate is a characteristic of the material, which needs to be determined in making calculations of mix design of concrete. There are several types of specific gravities:

(a) **The absolute specific gravity** refers to the volume of the solid material excluding all pores.

(b) The apparent specific gravity: If the volume of the solid is deemed to include the impermeable pores. The apparent specific gravity is then the ratio of the mass of the aggregate to the mass of water occupying a volume equal to that of the solid including the impermeable pores (Total Volume of Solid).

This is the specific gravity most frequently and easily determined, and it is used for calculations of yield of concrete or of the quantity of aggregate required for a given volume of concrete. The apparent specific gravity of aggregate depends on the specific gravity of the minerals of which the aggregate is composed and also on the amount of voids. The majority of natural aggregates have a specific gravity of between 2.6 and 2.7.

3.3.2 Bulk Density (Unit Weight)

The bulk density depends on how dense the aggregate is packed. For a coarse aggregate of given specific gravity, a higher bulk density means there are fewer voids to be filled by sand, and cement. The bulk density test has been used as a basis of proportioning of mixes.

Empty space between the aggregate particles are termed VOIDS. It is the difference between the gross volume of aggregate mass and volume occupied by the particles alone.

$$\text{Voids ratio} = 1 - \frac{\text{bulk density}}{\text{apparent specific gravity (SSD)} \times \text{Unit Weight of Water}}$$

Voids ratio indicates the volume of mortar required to fill the space between the coarse aggregate particles.

3.3.3 Particle shape (Rounded, Angular, Flaky, Elongated, Irregular)

a) **Rounded Aggregate:** Good workability, low water demand, poor bond



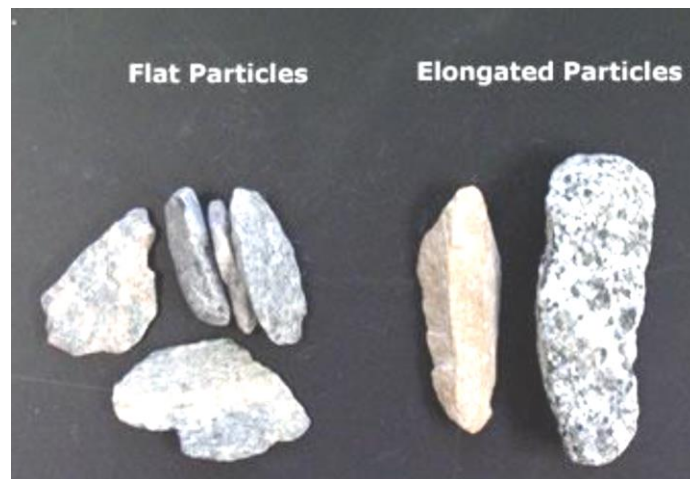
b) **Angular Aggregate:** Increased water demand, good bond



c) Flaky Aggregate: Aggregate stacks give workability problems



d) Elongated Aggregate: May lack cohesion and require increased fines



e) Irregular Aggregate: Fair workability, low water demand. Irregular shape with rounded edges.



Shape Classification of Particles

Classification	Description	Examples
Rounded	Fully water-worn or completely shaped by attrition	River or seashore gravel; desert, seashore and wind-blown sand
Irregular	Naturally irregular, or partly shaped by attrition and heaving rounded edges	Other gravel; land or dug flint
Flaky	Material of which the thickness is small relative to the other two dimensions	Laminated rocks
Angular	Possessing well defined edges formed at the intersection of roughly planar faces	Crushed rocks of all types
Elongated	Material, usually angular in which the length is considerably larger than the other two dimensions	
Flaky and Elongated	Material having the length considerably larger than the width and the width considerably larger than the thickness	

Angularity number

Angularity number gives a qualitative representation of shape of aggregate.

In angularity number test, a quantity of single sized aggregate is filled into metal cylinder of 3 liters capacity. Then the aggregate is compacted in a standard manner and the percentage of void found out.

$$\% \text{ of Voids} = \frac{\text{Bulk Density}}{\text{Specific gravity}} \times 100$$

- If the void content of the aggregate is 33% the angularity of such aggregate is considered 0.
- If the void is 44%, the angularity number of such aggregate is considered 11.

Importance of Angularity Number:

- The normal aggregate which are suitable for making concrete may have angularity number anything from 0 to 11.
- Angularity number 0 represents the most practicable rounded aggregate.
- Angularity number 11 indicates the most angular aggregate that could be used for making concrete.

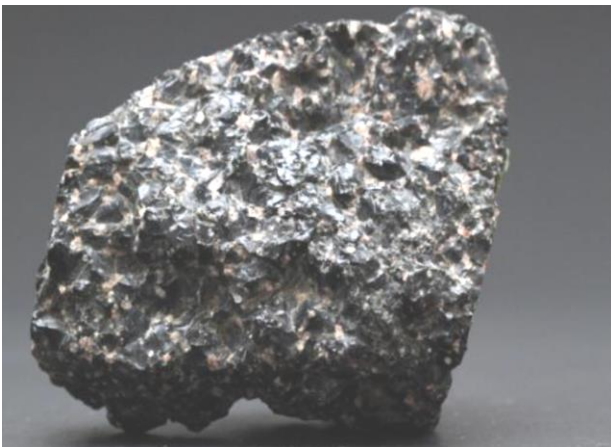
3.3.4 Surface Texture (smooth or rough):

It depends on hardness, grain size, pore structure, structure of the rock and degree to which forces acting on the particle surface have **smoothened** or **roughened** it.

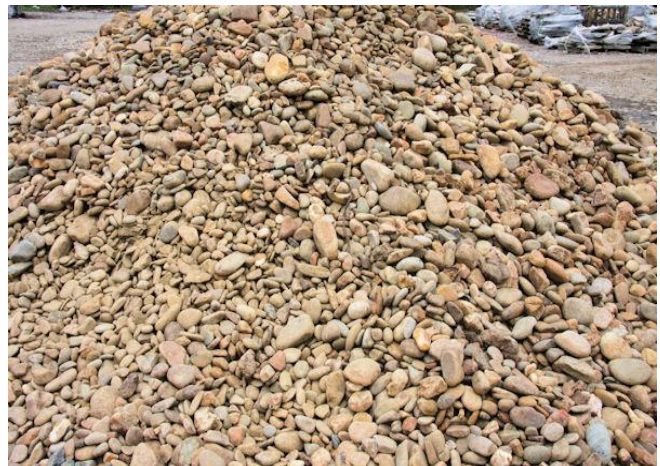
Smooth-textured aggregates are generally hard, dense and fine-grained aggregates. As surface smoothness increases, the surface area (contact area) decreases due to lesser irregularities, therefore these particles require quantity of cement paste for lubrication and hence less requirement of water and more compressive strength.

However, as surface smoothness increases, the bonding area with the concrete matrix reduces. Therefore, the flexural strength decreases due to poor bonding and interlocking.

The opposite behavior can be obtained with **rough-textured** aggregates.



Glassy textured aggregate



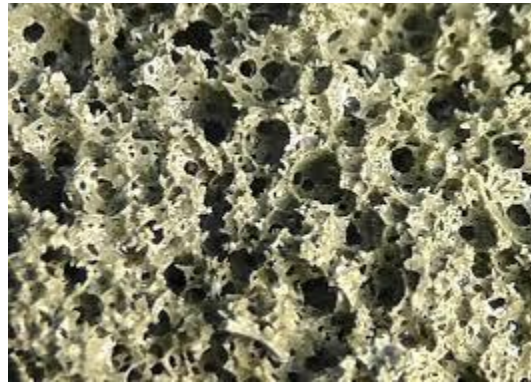
Smooth textured aggregate



Granular textured aggregate



Crystalline textured aggregate



Porous textured aggregate

Surface Texture of Aggregates

Surface	Texture Characteristics	Example
Glassy	Irregular break with curved face	Black flint (chalk), vitreous slag
Smooth	Water-worn, or smooth due to fracture of laminated or fine-grained rock	Gravels, marble, slate
Granular	Fracture showing more or less uniform rounded grains	Sandstone
Rough	Rough fracture of fine or medium grained rock containing no easily visible crystalline constituents	Limestone
Crystalline	Crystalline constituents. Containing easily visible crystalline	Granite
Honeycombed	Constituents with visible pores and cavities	Brick, slag

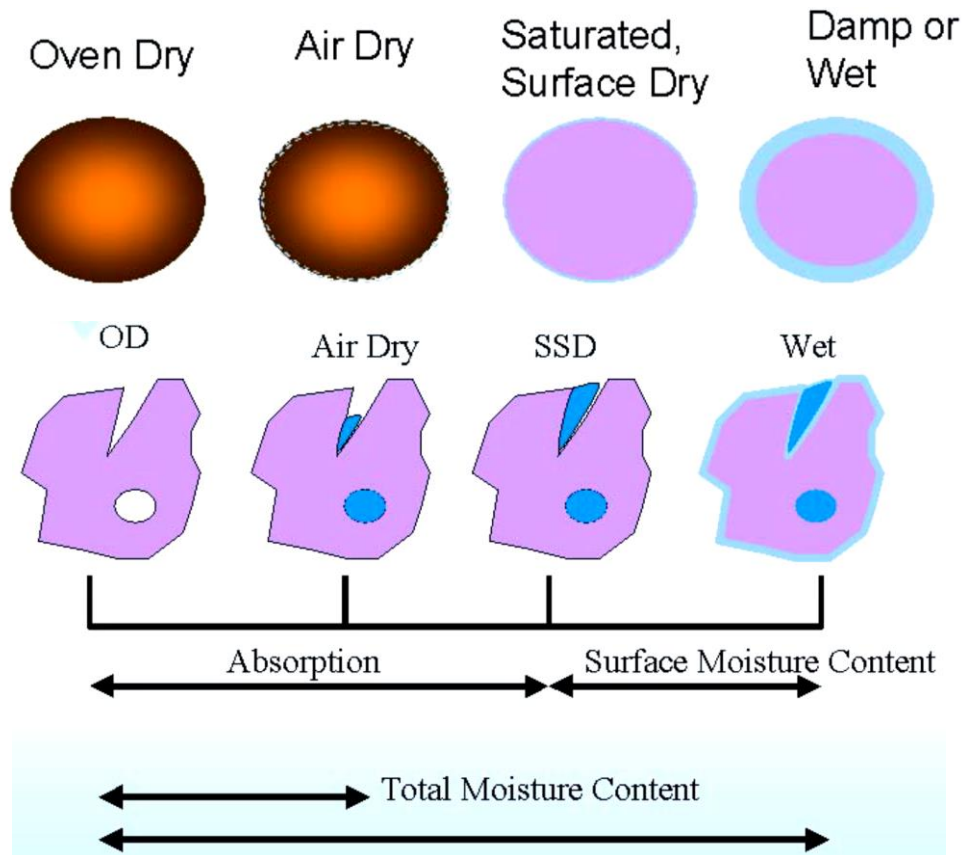
3.3.5 Absorption and Moisture Content of Aggregates

The **porosity of aggregate**, its **permeability**, and **absorption** influence the bonding between aggregate and cement paste, and also influence the resistance of concrete to freezing and thawing and resistance to abrasion.

The **water absorption** of aggregate is determined by measuring the increase in weight of an oven-dried sample when immersed in water; the surface water being removed. The ratio of the increase in weight to the weight of dry sample, expressed as a percentage is termed **absorption**.

The aggregates can be found in several moisture (water) contents as follows:

- **Oven dry condition.**
- **Air-dry condition.**
- **Saturated and surface dry (SSD) condition.**
- **Wet (moist or damp) condition.**



- Oven-dry condition:** All free moisture, whether external surface moisture or internal moisture, driven off by heat.
- Air dry condition:** No surface moisture, but some internal moisture remains.
- Saturated-surface dry condition (SSD):** Aggregates are said to be SSD when their moisture states are such that during mixing, they will neither absorb any of the mixing water added; nor will they contribute any of their contained water to the mix.
- Damp or Wet condition:** Aggregate containing moisture in excess of the SSD condition. It is called "free water". The free water, which will become part of the mixing water, is in excess of the SSD condition of the aggregate.

Notes:

- ❖ If Total moisture content is greater than absorption, surface water presents (wet condition).
- ❖ If Total moisture content is less than absorption, aggregate is air dry (air-dry condition).
- ❖ In mix-design calculations, it is assumed that aggregate to be saturated surface dry (SSD).
- ❖ If aggregate is drier than SSD, it will absorb water from concrete and reduce the workability. On the other hand, if it is moist, it will contribute water in the concrete reducing the strength. The **effective absorption (EA)** represents the amount of water required to bring an aggregate from the AD state to the SSD, expressed as a fraction of the SSD weight:

$$EA = (W_{SSD} - W_{AD}) / W_{SSD} \times 100\%$$

3.3.6 Aggregate Size

Larger size of aggregate is preferred in concrete because of the following reasons:

- It reduces the cement requirement.
- It reduces the water requirement.
- It reduces the shrinkage of concrete.

But practically, there are a number of factors which limit the use of higher size of aggregates in the concrete, such as spacing between reinforcing bars, thickness of section and concrete covers.

3.4 Sieve Analysis of Aggregates

Sieve analysis is the name of the operation of dividing a sample of aggregate into fractions, each consisting of particles of the same size. In practice each fraction contains particles between specific limits, these being the openings of standard test sieves. Sieves are used to be described by the **size of opening for larger openings** and by the **number of openings for smaller sizes**.

Sieve designations

British standards (millimeters)	American standards	Nominal openings (inches)
75	3 in	3
37.5	1 ½	1.5
20	¾	0.75
12.5	½	0.5
6.3	¼	0.25
4.75	No 4	0.187
2.36	No 8	0.0937
1.18	No 16	0.0469
0.600	No 30	0.0234
0.300	No 50	0.0117
0.150	No 100	0.0059
0.075	No 200	0.0029

All sieves are mounted in frames, which can rest. It is thus possible to place the sieves one above the other in order the size with the largest sieve at the top, and the material retained on each sieve after shaking represents the fraction of aggregate coarser than the sieve in question but finer than the sieve above.

3.4.1 Grading Curves

Grading is the particle-size distribution of an aggregate as determined by a sieve analysis. The results of a sieve analysis can be graded much more easily if represented graphically, and for this reason grading charts are very extensively used. By using a chart, it is possible to see at a glance whether the grading of a given sample conforms to that specified or is too coarse or too fine.

In the grading chart commonly used, the ordinates represent the cumulative percentage passing and the abscissa the sieve opening plotted to a logarithmic scale.

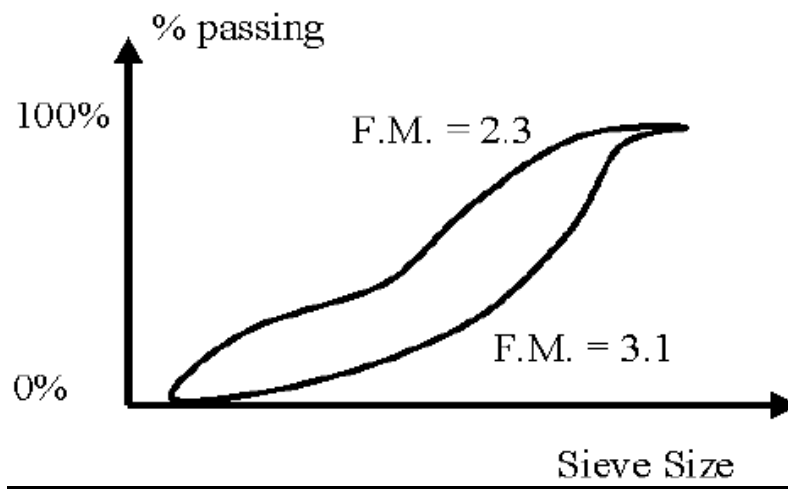
3.4.2 Fineness Modulus (FM)

Fineness modulus is the sum of the cumulative percentage retained on the sieves of the standard series. It is an index of fineness of an aggregate. The value of the fineness modulus is higher for the coarser aggregates.

FM of fine aggregates is required for mix design since sand gradation has the largest effect on workability. A fine sand (low FM) has much higher effect on paste requirements for good workability. Therefore, it is used in concrete mix design such as in ACI 211. FM of the coarse aggregate is not required for mix design

Standard test sieves are as follows:

Fine aggregate: 4.75mm, 2.36mm, 1.18mm, 0.600mm, 0.300mm, 0.150mm



Limits for FM

Sand	FM
Fine Sand	2.2 – 2.6
Medium Sand	2.6 – 2.9
Coarse Sand	2.9 – 3.2

3.4.3 Maximum Aggregate Size (MSA)

- It is the smallest sieve opening through which the entire sample passes (or in practice only 5% retained on this sieve).
- The largest size particle presents significantly to affect concrete properties. It affects the paste requirements. The higher MSA, the lower the paste requirements for the mix. Aggregate size affects the following concrete properties: water demand, cement content, micro-cracking (strength).

3.5 Grading Requirements

The purpose of sieve analysis is to determine whether or not a particular grading is suitable. The related problem of grading is the combining of fine and coarse aggregates so as to produce desired grading.

The main factors governing the desired aggregate grading are:

- Surface area of the aggregate, which determines the amount of water necessary to wet all the solids.
- Relative volume occupied by the aggregate.
- Workability of the mix.
- Tendency to segregation.

The grading of aggregate is a major factor in the workability of a concrete mix. Workability, affects the water and cement requirements, controls segregation, has some effect on bleeding, and influence the placing and finishing of the concrete. These factors represent the important characteristics of fresh concrete and affect also the properties in the hardened state: strength, shrinkage and durability.

It also must be remembered that far more important than devising a good grading is ensuring that the grading is kept constant; otherwise variable workability results and variable strength is obtained.

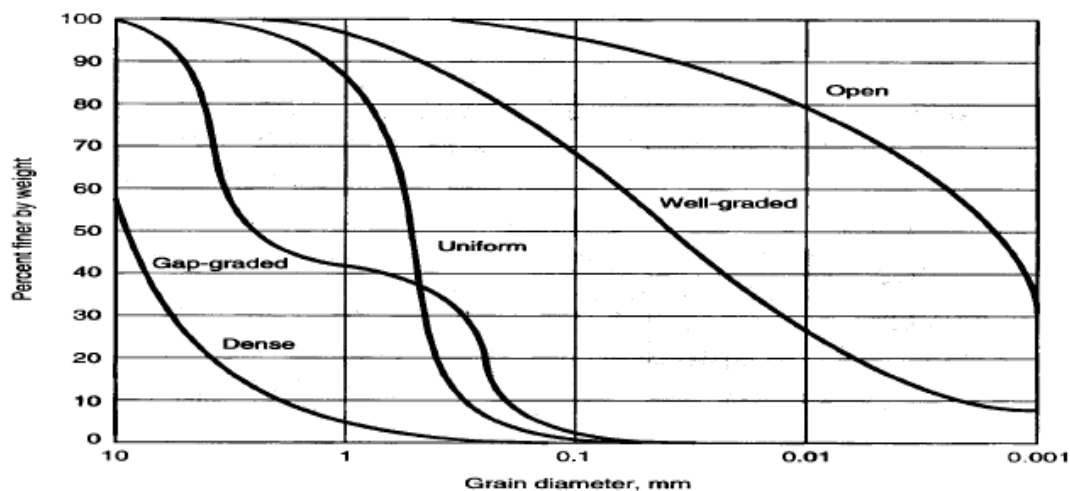
3.5.1 Types of Aggregate Gradation

Gap grading is a grading in which one or more intermediate size fractions are omitted.

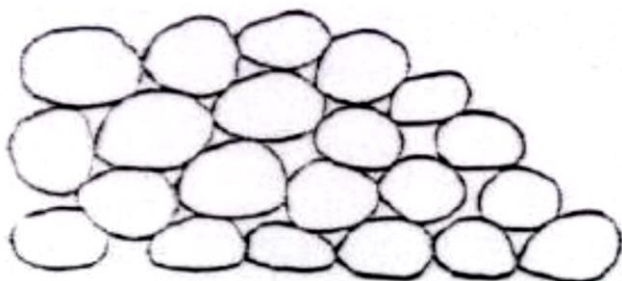
Well Graded means sizes within the entire range are in approximately equal amounts (friction at many points, excellent interlocking, very few voids).

Uniform gradation means a large percentage of the particles are of approximately the same size (poor interlocking, high percentage of voids, friction at few points of contact).

Combined gradation means fine and coarse aggregates are combined (friction at many points, good interlocking, few voids, economical).

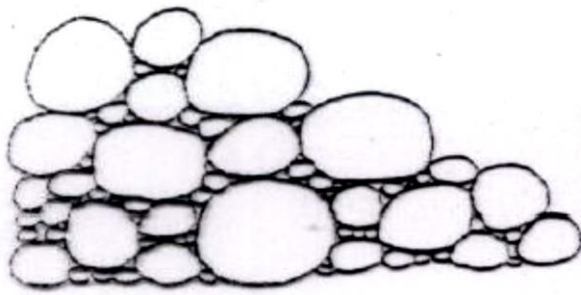


Types of gradation



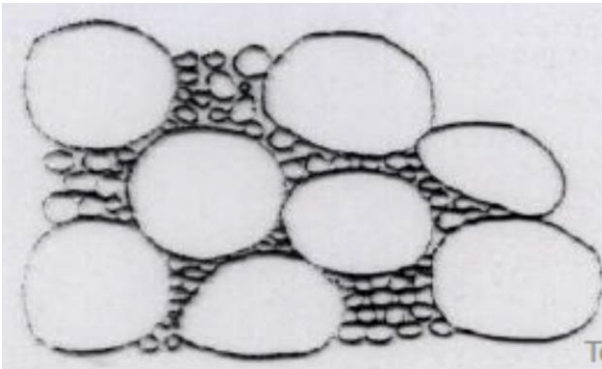
Uniform gradation:

1. Friction at few points of contact
2. Poor interlocking.
3. High percentage of voids



Well-graded gradation:

1. Friction at many points of contact
2. Excellent interlocking.
3. Very few voids



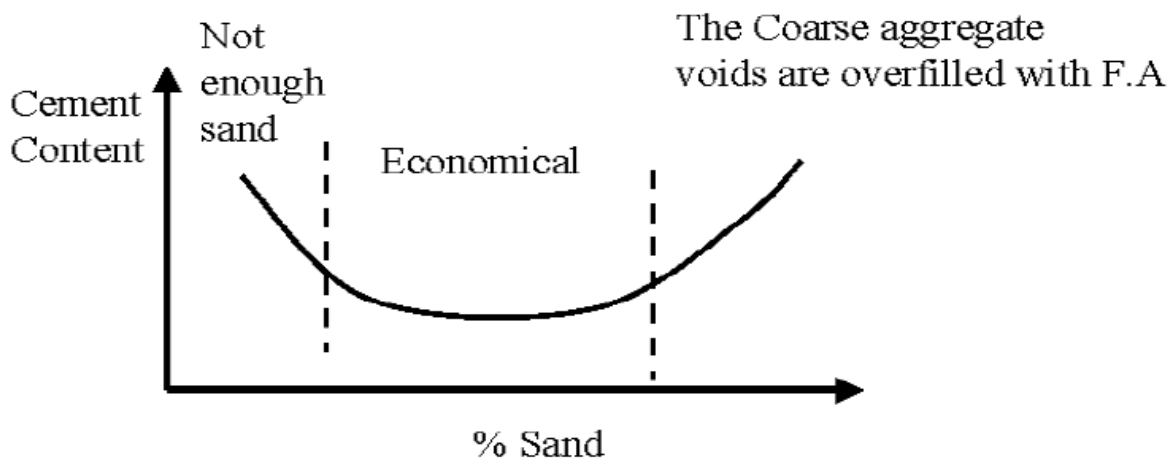
Combined gradation

1. Friction at many points of contact
2. good interlocking.
3. few voids

3.5.2 Significance of Gradation

Gradation of aggregate affects the following concrete properties

- Economy
- Consistency
- Strength
- Shrinkage
- Finish ability



3.5.3 ASTM Grading Requirements for Fine and Coarse Aggregates

ASTM C33/C 33M Grading Requirements for Fine Aggregates

Sieve	Percent passing
9.5 mm	100
4.75 mm	95-100
2.36 mm	80-100
1.18 mm	50-85
600 μm	25-60
300 μm	5-30
150 μm	0-10

ASTM C33/C 33M Grading Requirements for Coarse Aggregates

Size mm	Amounts finer than each laboratory sieve, mass percent													
	100	90	75	63	50	37.5	25	19	12.5	9.5	4.75	2.36	1.18	0.300
90-37.5	100	90-100	...	25-60	...	0-15	...	0-5	...	...	...	...	...	...
63-37.5	...	...	100	90-100	35-70	0-15	...	0-5	...	...	...	...	...	...
50-25	...	...	...	100	90-100	35-70	0-15	...	0-5	...	...	...	...	...
50-4.75	...	...	...	100	95-100	...	35-70	...	10-30	...	0-5	...	...	...
37.5-19	...	...	...	...	100	90-100	20-55	0-15	...	0-5	...	...	...	...
37.5-4.75	...	...	...	...	100	95-100	...	35-70	...	10-30	0-5	...	...	...
25-12.5	...	...	...	...	...	100	90-100	20-55	0-10	0-5	...	...	...	...
25-9.5	...	...	...	...	...	100	90-100	40-85	10-40	0-15	0-5	...	...	...
25-4.95	...	...	...	...	...	100	95-100	...	25-60	...	0-10	0-5	...	...
19-9.5	...	...	...	...	...	...	100	90-100	20-55	0-15	0-5	...	...	...
19-4.75	...	...	...	...	...	...	100	90-100	...	20-55	0-10	0-5	...	...
12.5-4.75	...	...	...	...	...	...	...	100	90-100	40-70	0-15	0-5	...	...
9.5-2.36	...	...	...	...	...	...	...	...	100	85-100	10-30	0-10	0-5	...
9.5-1.18	...	...	...	...	...	...	...	...	100	90-100	20-55	5-30	0-10	0-5
4.75-1.18	...	...	...	...	...	...	...	...	...	100	85-100	10-40	0-10	0-5

3.6 Mechanical Properties of Aggregates

3.6.1 Bond of Aggregate

Bond between aggregate and cement paste is an important factor in the strength of concrete, especially the flexural strength (bending strength) is very related.

Bond is due, in part, to the interlocking of the aggregate and the paste resulting from the roughness of the surface of the aggregates. A rough surface, such as that of crushed particles, results in a better bond; better bond is also usually obtained with softer, porous and mineralogically heterogeneous particles.

Because it depends on the paste strength as well as on the properties of aggregate surface, bond strength increases with the age of concrete.

3.6.2 Strength of Aggregate

It is obvious that the compressive strength of concrete cannot significantly exceed the compressive strength of aggregate contained, although it is not easy to state what is the strength of the individual particles. Indeed, the crushing strength of aggregate cannot be tested with any direct test. There are some indirect tests to inform us about the crushing strength of aggregate.

Phases of concrete

In the total concrete volume, there are two important phases, namely:

- Paste phase.
- Aggregate phase

In most of the cases of concrete failure, it is the paste phase which is a weaker link. The paste phase of concrete has the following characteristics:

- i- It is weaker than aggregate.
- ii- It is vulnerable to most of the ill effects on concrete.
- iii- It is more permeable than any of the mineral aggregates.
- iv- It is susceptible to aggressive chemicals.

Therefore, effort should be made to use minimum volume of paste in the concrete. It should just be sufficient to fill the voids left out by the aggregates and lubricate them properly. This can be achieved by using "**well graded aggregates**" so that the voids are minimum.

3.6.3 Other Mechanical Properties of Aggregates:

a) Impact value: Impact value of aggregates measures the toughness of particles by impact.

b) Abrasion: Abrasion of aggregates measures the resistance of aggregates against wearing.

It is an important property of concrete in roads and in floor surfaces subjected to heavy traffic. The most frequently used test method is the **Los Angeles Abrasion Test**.

3.7 Deleterious Substances in Aggregates

a) Organic Impurities:

The organic matter found in aggregate consists of products of decay of vegetable matter. The organic impurities may interfere with the process of hydration of cement. This affects the rate of gaining strength.

b) Clay and Other Fine Materials:

Clay may be present in aggregate in the form of surface coatings which interfere with the bond between aggregate and the cement paste. This is an important problem and affects the strength and durability of concrete.

Other types of fine material that can present in aggregate are silt and crusher dust. Silt and crusher dust also adversely affect the bond between cement paste and aggregates.

Find Standard limits for the fine materials (passing sieve 200 or less than 75µm) in aggregates.

c) Salt Contamination:

Aggregates obtained from the seashore contain salt and have to be washed with fresh water. The aggregate washed even with the sea water do not contain harmful quantities of salts.

If salt is not removed, it will absorb moisture from the air and cause efflorescence (white deposits on the surface of the concrete). A slight corrosion of reinforcement may also result, but this is not believed to progress to a dangerous degree, especially when the concrete is of good quality and adequate cover to reinforcement is provided.

d) Alkalinity of Aggregates:

Some reactive forms of silica may occur in some types of rocks, like siliceous limestone. The reaction takes place between the siliceous minerals in the aggregate and the alkaline hydroxides derived from the alkalis (Na_2O , K_2O) in the cement. The resulting gel tends to increase in volume in a humid medium and causes cracking of concrete. In this case, it is recommended to control the limit of alkalis in the cement.

3.8 Soundness of Aggregate

This is the name given to the ability of aggregate to resist excessive changes in volume as a result of changes of physical conditions.

Aggregate is said to be unsound when volume changes, induced by the freezing and thawing result in deterioration of the concrete.