AGGREGATES FOR CONCRETE

Aggregates are natural or artificial inorganic materials used in concrete production. They make up 70 to 80% of the concrete by volume. For this reason, aggregate quality is extremely important for the performance of concrete. Aggregates are important not only because they are cheap, but also because of their benefit to the durability and volume stability of concrete. Cement paste shrinks upon drying, if aggregate is included in the mix, shrinkage of the paste is significantly limited. It is economically advantageous to use as much aggregate and as little cement as possible in concrete, but this economic advantage should be balanced in terms of the desired fresh and hardened properties of concrete.

In order to produce concrete with the desired quality, the properties of the aggregates used in production must be known very well. Aggregate properties that are effective in terms of concrete performance can be given as chemical and mineral composition, specific gravity, water absorption, hardness, strength, modulus of elasticity, thermal properties, physical and chemical stability, granulometry, particle size and shape, and surface texture. Even if all this is known, it is not easy to define good aggregates for concrete. For example, an aggregate may be disrupted on freezing-thawing, but it need not to do so when embedded in concrete.

CLASSIFICATION OF AGGREGATES

Aggregates used in concrete production are classified according to their various features. Accordingly, aggregates can be classified according to their source, specific gravity, particle size, mineralogical composition, geological origin, particle shape and surface texture, whether they are reactive.

<u>Classification by source</u>:
Aggregates can be divided into two groups: natural aggregates (sand, gravel, crushed stone, pumice, barite, hematite, magnetite) and artificial aggregates (expanded perlite, expanded vermiculite, burned clay, fly ash aggregate, blast furnace slag aggregate).

Natural aggregates are obtained from riverbeds, sea and lake shores and quarries. These are aggregates that are broken in the crusher and obtained in the desired size. Those that are obtained at the desired size by breaking in the crusher are called "crushed stone" or "stone chips". Artificial aggregates are aggregates obtained as by-products in an industry branch that has no direct relation to concrete production or aggregates that are made suitable for concrete production by applying heat treatment.

<u>Classification by specific gravity</u>:
Aggregates can be divided into three groups according to the specific gravity. Aggregates with specific gravities of 2.4-2.8 g/cm^3 are considered as “normal-weight aggregates”. Those with a specific gravity less than 2.4 g/cm^3 are known as "lightweight aggregates" and those larger than 2.8 g/cm^3 are known as "heavyweight aggregates". Generally, normal-weight aggregate is used in conventional concrete production. The word “normal” is not used when it comes to normal-weight aggregate; they are only referred to as "aggregates".

Lightweight aggregate is used to produce lightweight concrete in applications where lightness is sought rather than high strength. Pumice stone, pumice, tuff are examples of natural lightweight aggregates. All of them are of volcanic origin and have porous-beady structures due to the gases formed in their composition during the solidification of the lava. Their specific gravities are around 0.75-1.5 g/cm^3. Some of these stones expand suddenly when heated and remain their structure when cooled. Separation of water in some of them can cause significant volume increase and expand in the form of popcorn.

Artificial lightweight aggregates are industrial waste materials and can be used before or after certain processes such as crushing, heat treatment. Well-burned sintered coal slag can be given as an example of artificial lightweight aggregates used without heat treatment. Foamed blast furnace slag and sintered fly ash are materials used after heat treatment.

Heavy aggregates are used in the production of very dense or heavy concrete where protection against harmful rays is required but thick sections are not possible. Examples of heavy aggregates are iron ores such as barite, magnetite, hematite, limonite, goethite and scrap iron. The specific gravity of these iron ores is over 3.5 g/cm^3.

Classification by particles size:
According to the relevant standard, the aggregate remaining on a square-hole sieve with an opening of 4 mm is called “coarse aggregate”, the aggregate passing through this sieve is called “fine aggregate”. The part of the fine aggregate passing through a 0.25 mm sieve is known as "dust stone" or "filler".

The mixture of fine and coarse aggregate is called "mixed aggregate". The natural aggregate, which is a mixture of sand and gravel, which is taken out of streams, seas, lakes, used as it is, without sieving and washing, is called "all-in aggregate" or “pit-run aggregate”. This type of aggregate is generally not used or used in low strength concrete produced for simple jobs.

Classification by mineral composition:
Aggregates can be divided into three groups as siliceous, aluminous and calcareous according to their mineralogical composition. Aggregates containing reactive silica soften and dissolve due to alkali-silica reaction in alkali environment formed by cement. Stones such as sandstone, flintstone, serpentine and schist are typical examples of this category.

Aluminous aggregates contain minerals consisting of aluminum and silica and some sodium, potassium, calcium, and magnesium composition. A good example of this category is feldspar, which is abundant in granite. This mineral decomposes under the influence of air and especially waters containing CO_2 and turns into clay. If decomposition occurs before using aggregate in concrete production, the surface of aggregate particles is covered with a layer of clay. When used in concrete production, this aggregate does not adhere well with cement paste. If decomposition occurs after concrete production, it does not cause much disadvantage. Although all types of feldspar do not decompose like this, aggregates such as granite should be used without waiting for a long time (within 3 months) after they are crushed.

Calcareous aggregates are also known as calcium carbonate aggregates. Such aggregates are not resistant to acids. They are affected by acids such as sulfuric acid and carbonic acid that can be found in the atmosphere and water. Such aggregates may also contain some carbonated components that can react with cement.

Classification by geological origin:
Rocks can be classified as magmatic, sedimentary and metamorphic in terms of their formation. Magmatic rocks are suitable for use as concrete aggregate due to their void-free and robust structure. Lightweight and porous types are used in the production of lightweight

concrete. Although the properties of sedimentary rocks are variable, limestone and dolomite are used as crushed stone. Hard ones of metamorphic rocks can be used in concrete production. Schists and rocks containing clay in their composition are not suitable for concrete production as they swell as they absorb water and cause an increase in volume.

Apart from that, aggregates are classified in different ways as reactive and non-reactive according to their reactive properties; round, angular, flat, long and flat according to grain shape; and smooth, granular, crystalline and honeycomb according to surface texture.

BASIC FEATURES SOUGHT IN AGGREGATES

By volume, aggregate constitutes most of the concrete. Therefore, the aggregate used has a significant effect on all properties of concrete. In order to produce a quality concrete, the following features are sought in the aggregate:

- The aggregate must be intact, abrasion resistant, and it should not soften in water.
- Aggregate should not form harmful compounds with cement components.
- The shape and surface texture of the aggregates should be suitable to produce concrete.
- Aggregate granulometry should conform to standards and objectives.
- No harmful substances should be present in the aggregate.
- Aggregate must be frost resistant.

DELETERIOUS SUBSTANCES IN AGGREGATES

Deleterious substances can occur in aggregates in relatively small amounts and are capable of adversely affecting the desired properties of concrete in its fresh and hardened state. Examples of such substances include the following:

i) Organic Impurities: These impurities usually appear in the form of organic matter in the natural aggregates as humus or organic loam. Organic impurities interfere with the setting and hardening process of cement and may cause deterioration of concrete.

ii) Fine or Washable Particles: The relevant standard (TS 3527) defines 63 μm (0.063 mm) screened materials as fine matter. These are substances such as clay, silt and very fine stone scattered in the aggregate or adhered to the aggregate particles in lumps. Although some of them are easily crushed during the mixing of the concrete, some of them are not crushed and act as a weak aggregate in the concrete. Since they reduce the bond between the cement paste and the aggregate, increase the need for water, and may cause pop outs they are not desired to be present in the aggregate in excess.

iii) Friable and Lightweight Particles: Light particles such as coal, lignite and wood pieces, which are easily crushed and broken, are weaker than aggregate and cement paste and have a specific gravity less than 2 g/cm^3. If there is a large amount in the aggregate, the strength and durability of the concrete are negatively affected.

iv) Other harmful substances in aggregate: These are sugars and soluble salts that adversely affect the hardening of concrete, alkali reaction compounds, sulfurous compounds, reinforcing corrosion nitrates and especially water-soluble chloride.

ALKALI-SILICA REACTION

The alkali-silica reaction is a chemical reaction between the alkalis in the cement (Na_2O and K_2O) and the reactive silica compounds present in the aggregate. Alkali-silica gel occurs due to this reaction. This gel absorbs the moisture in the environment and swells, causing the hardened concrete to expand over time. As a result, concrete cracks.

The following conditions must be present for the alkali-silica reaction:

<u>Alkali oxide content in cement</u>: In case the equivalent alkali content $\left(Na_2O + 0.658 \times K_2O\right)$ in the cement is greater than 0.6% and in the presence of opal, rhyolite, tridymite and rhyolite tuffs, dacite tuffs, andesite and andesite tuffs and phyllites in the aggregate, which are sensitive to alkaline reactivity.

<u>Alkaline sensitive aggregates</u>: The aggregates may contain reactive siliceous compounds. These compounds react chemically with alkali hydroxides dissolved in concrete pore water. As a result of this reaction, these alkaline sensitive compounds soften and dissolve. The resulting gel causes swelling and expansion of the concrete.

<u>Ambient conditions</u>: The most important factor is moisture. The reaction can take place at temperatures between +10°C and + 60°C as long as moisture is enough.

Practically the following measures can be taken to prevent the alkali-silica reaction:

- Using aggregate without reactive silica.
- Using low-alkaline cement
- Using pozzolanic substances
- Preventing water from entering concrete.

MECHANICAL PROPERTIES OF AGGREGATES

Concrete aggregates must have high strength first; it should be strong, high abrasion resistance, high adherence with cement paste and it should be resistant to frost.

One of the most important properties in aggregate is compressive strength. The compressive strength of the aggregate used in quality concrete production is required to be greater than 100 MPa. The compressive strength is closely related to the porosity of the aggregate. Low porosity increases the compressive strength. It is the adherence with cement paste that is more critical than compressive strength. Aggregate strength is more important for high strength concrete compared to normal strength concrete. The compressive strength of normal aggregates varies between 70-275 MPa.

The aggregate that does not contain cracks, defects and foreign substances is considered as "intact". In other words, sound aggregate is aggregate that shows high resistance against harmful environmental effects such as freeze-thaw, wetting-drying and heating-cooling. Aggregates that do not possess these characteristics are "weak". Weak aggregates show volume changes under such harmful effects and have a negative impact on the strength of concrete. Easily crushed sandstone, soft limestone, clay lumps, clay-containing limestone and porous cherts are examples of non-sound aggregates.

Abrasion is the wear on the surface of the material under the effect of repeated friction force. Wear resistance is very important for aggregate used especially on roads exposed to dynamic effects such as heavy traffic load. The wear value is the loss in aggregate mass in percent due to the wear effect. High wear value refers to low wear resistance. Los Angeles test (Ball Drum) is the most common method used to determine the wear resistance of the aggregate. Oven dry 5 kg aggregate sample is generally used for the test. For aggregate to be used in concrete exposed to abrasion, the abrasion value should be less than 30% after 500 revolutions. The abrasion resistance of the rock from which the aggregate is obtained is determined by the Bohme test. For the test, rock samples, which are cut to have a surface area of 71x71 mm, are used.

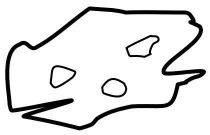
The abrasion resistance of glassy aggregates, schists, marl limestone and coarse crystalline stones are low. High specific gravity and hard stones, such as basalt, have high resistance to abrasion. Rocks with high abrasion resistance naturally also have high compressive strength.

In terms of adherence, aggregate particle shape and surface texture are the most important factors. Adherence is more effective on tensile strength rather than compressive strength. Adherence between angular aggregate and cement paste is higher than smooth aggregate. This is because the surface area of angular aggregate particles is larger than those with smooth surfaces. The greater the surface area in contact with the cement paste, the stronger the adherence. In general, when the adhesion is good, broken aggregate particles are seen on the fracture surface of the concrete. However, the presence of a large number of crushed aggregates indicates that the aggregate is very weak. Another important factor that is effective in terms of adherence is whether the aggregate is clean or not.

PHYSICAL PROPERTIES OF AGGREGATES

When it comes to aggregate physical properties, properties such as porosity, water absorption, specific gravity, unit weight, and frost resistance are considered.

<u>Porosity</u>: Porosity is defined as the ratio of total void volume in aggregate grain to aggregate grain volume. The space between aggregate grains is not considered here. Accordingly, porosity can be expressed numerically as follows:



$$p = (V_p / V_b) \times 100$$

Here, V_p represents the volume of voids in the aggregate grain, and V_b represents the total volume of the aggregate.

The voids in the aggregate particle are of two types: discontinuous and interconnected. Water can easily enter the aggregate through these voids when the interconnected voids are open to the aggregate surface. Porosity has a significant effect on many properties of aggregates. As porosity increases, the density, strength, modulus of elasticity and wear resistance of the aggregate decrease significantly.

The voids content in an aggregate sample is the volume of the space between the aggregate particles, the interparticle volume. As a percentage, the voids content is defined as follows:

$$v = (V_v / V_t) \times 100$$

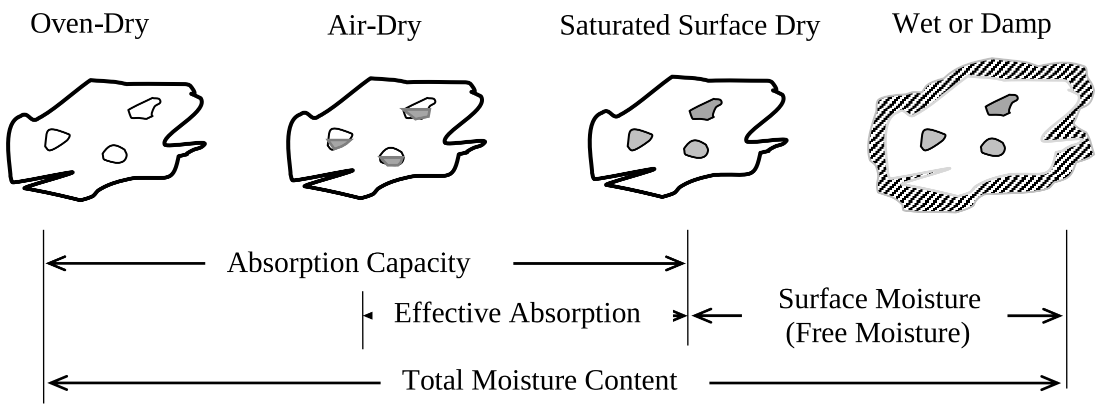
Here, V_v is the total volume of the space between the aggregate particles, and V_t is the total volume of the sample, including the space between the aggregate particles in the sample.

Moisture Content and Absorption: Aggregate grains can absorb water because they contain a little space. Moisture status is related to how much water is present in these spaces and on the aggregate surface and it is the ratio of the amount of water in the aggregate to the full dry weight of the aggregate. The amount of water in the aggregate depends on the size of the voids inside the aggregate, their continuity and their total volume.

Aggregates can exist in four moisture states:

- Oven-Dry (OD): It is the state that there is no water in the aggregate and its moisture content is 0%.
- Air-Dry (AD): When the outer surface of the aggregate looks dry but there is some water in its cavities.
- Saturated-Surface-Dry (SSD): The aggregate surface is dry; the voids are filled with water.
- Wet or Damp: All the voids in the aggregate are filled with water and there is an excess of water on the aggregate surface.

Depending on the moisture, the unit weight of the aggregate varies. For this reason, it is imperative to determine the unit weight of the aggregate and the amount of aggregate used in the concrete mixture in SSD state. If the aggregate is not in SSD state, these values should be corrected. For this, the amount of water in the aggregate at any time, which is called *moisture content*, and the amount of water in SSD state, which is called *absorption capacity* or *free moisture*, must be known.



Schematic representation of moisture state in aggregate

If the difference between moisture content and absorption capacity is positive (+), the aggregate is wet, if it is negative (-), the aggregate is dry, and if it is zero, the aggregate is in the state of SSD. Mixing water is increased or decreased by the surface moisture. If the surface moisture takes (+) value, the amount of mixing water is decreased as much as the surface moisture, while the amount of aggregate is increased as much as the surface moisture. If the surface moisture takes (-) value, the reverse is done. Although these corrections are small, the effect on the properties of concrete is significant.

The water absorption capacity and moisture content of the aggregate must be known in order to determine the addition or reduction in the mixing water depending on the moisture condition of the aggregate. This is done for all aggregate groups. The water absorption capacity is the maximum amount of water that the aggregate can absorb and is the difference between the full dry state of the aggregate and the saturated-surface-dry state. Accordingly, the water absorption capacity is calculated as follows:

Absorption capacity: $AC\ (\%) = \frac{W_{SSD} - W_{OD}}{W_{OD}} \times 100$

Here, W_{OD} and W_{SSD} are the full dry and saturated-surface-dry weights of the aggregate.

The moisture content of the aggregate at any moment can be calculated as follows:

Moisture content: $MC\ (\%) = \frac{W_{AGG} - W_{OD}}{W_{OD}} \times 100$

Here, W_{FK} and W_{AGG} are the weights of the aggregate in full dry and natural environment.

To determine the saturated-surface-dry state for the aggregate sample, the aggregate is first soaked in water for 24 hours. Then the aggregate is rolled in a cloth and the surface is dried. Although the procedure is easy for coarse aggregate, it is quite difficult for fine aggregate, it requires skill and practice.

Similarly, the fine aggregate is kept in water for 24 hours and then filtered. It is dried for a while. It is checked by some methods whether SSD has become or not during the drying process. For example, the moment when the sand color changes from dark to light, or squeezed in the palm, or the cut cone method.

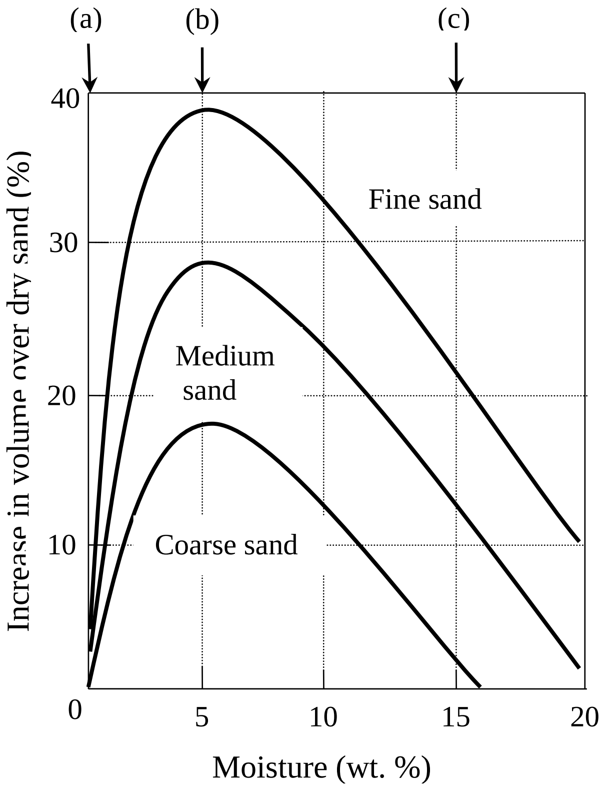
Using the moisture content and water absorption capacity values, the surface moisture content (SMC) for each aggregate group can be determined in percent as follows:

$SMC\ (\%) = MC\ (\%) - AC\ (\%)$

Saturated surface dry (SSD) state means "balance" in terms of water requirement of the mixture. That is, the aggregate put in the mixture neither absorbs from the mixing water nor gives water to the mixture. Concrete mix calculation is made by assuming that the aggregates are saturated and dry. The water to cement ratio and the quantities of materials are determined accordingly. Unfortunately, aggregates are often not saturated surface dry state on the job site. For this reason, when making concrete design calculations, necessary corrections should be made considering the moisture condition of the aggregates.

If the moisture content is less than the absorption capacity, the aggregate is dry, the required amount of water must be added to the concrete mixture, if the moisture content is higher, the aggregate is wet and the excess amount of water is reduced from the mixing water. This is vital to maintain the original water to cement ratio, thus providing the required level of workability, which greatly affects the strength and other properties of the concrete.

Coarse aggregate in the construction site is generally air dry and has an effective moisture content of approximately 1%. In contrast, the fine aggregate is often wet and typically has surface moisture in the range from 0 to 5%. The reason for this is the addition of water held by the fine aggregate surface as well as additional water between the sand grains. This water pushes sand grains apart and causes the visible volume of sand to increase. This is known “bulking” and causes an error when proportioning by volume. In this respect, the drawback that will arise in the absence of moisture correction is very important in terms of sand. Because the amount of sand may decrease significantly depending on the amount of moisture it contains. As a result, the sand put into the concrete becomes less than necessary and the amount of water becomes more than necessary. Excess water is inconvenient in terms of the strength of the concrete. For this reason, aggregate is taken by weighing while designing the concrete and unit weight is generally done on the dry aggregate. As shown in the figure below, coarse aggregate makes less bulking than fine aggregate.



Bulking phenomenon of aggregate: (a) dry; (b) partially saturated; (c) fully saturated

<u>Specific gravity</u>: Specific gravity is required for concrete mix calculation. When calculating the specific weight for the aggregate, the volume of the voids in the aggregate is reduced from the volume of the aggregate. Since the concrete mixture design is generally made considering that the aggregates are in the state of SSD, the saturated surface dry specific gravity of the aggregate is used in calculations as follows:

Specific gravity, in SSD, is $\delta = \dfrac{W_{SSD\ air}}{W_{SSD\ air} - W_{water}}$

where $W_{SSD\ air}$ is the weight of saturated-surface-dry aggregate in air and W_{water} is the weight of SSD aggregate in water suspended.

However, it is possible to define several types of specific gravity, depending on the moisture condition in the aggregate. Such as actual specific gravity (δ_A), apparent specific gravity (δ_V), saturated surface dry specific gravity (δ_{SSD}), and dry specific gravity (δ_D). Specific gravity is ordered from largest to smallest as $\delta_A > \delta_G > \delta_{DYK} > \delta_D$.

The specific gravities are sometimes given proportionally to the specific gravity of the water. Since the specific gravity of the water is 1 g/cm^3, the specific gravity is usually unitless.

Unit Weight: The aggregate unit weight is calculated by dividing the total weight of the aggregate grains that fill a container of a certain volume by the volume of the container. The unit weight of aggregates is calculated as follows:

Unit weight is $\Delta = \frac{W}{V}$

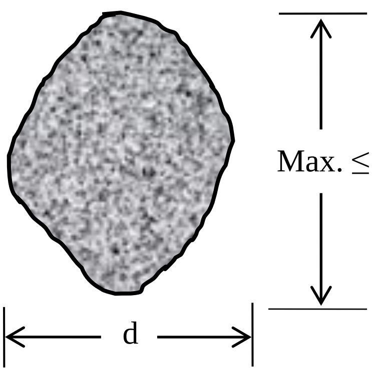
Here, Δ is the unit weight of the aggregate sample in g/cm^3, kg/l, or t/m^3; W is the aggregate weight filling the container with a volume of V.

As can be seen from the definition, unit weight is the unit weight of the aggregate pile. The weight of the amount of aggregate filled in the container depends on the granulometry of the aggregate sample, the grain shape, the moisture state of the aggregate, the aggregate placed in the container in a loose or compacted fashion. Therefore, two-unit weights are generally defined as "dry loose unit weight" and "dry compacted unit weight".

Freeze-Thaw Resistance: Frost resistance depends on the amount, size and interconnection of the voids in the aggregate. When the water freezes in the voids in the aggregate, its volume increases and creates pressure to the void walls. The resulting pressure is directly proportional to the amount of water in the void. This is in a way related to the water absorption capacity of the aggregate. The freeze-thaw resistance of the aggregate increases as the water absorption decreases. It is stated that the aggregates with water absorption greater than 0.5% in the relevant standards are not suitable for use in concrete production without undergoing freezing-thawing test. The relevant Turkish standard (TS 3655) confines the mass loss to 15% for sand and 18% for gravel in the freeze-thaw experiment with Na_2SO_4 of aggregate.

GEOMETRICAL PROPERTIES OF AGGREGATES

Grain Shape and Surface Texture: Aggregate grains can be round, angular, flat, long and even shapeless. “Shape index” is generally used to define the grain shape. This value is obtained by dividing the largest edge of the aggregate grain to the smallest edge of the aggregate grain. Ideally, this index is desired to be 1.0; however, should not exceed 3.



As of the surface texture, aggregate grains can be smooth, grained, rough, crystalline, glassy, and multi-cavity. Shape and surface texture affect the workability of concrete and consequently the water requirement. Concrete containing rough, angular and flat grains requires more water for certain workability than concrete containing smooth, round and cavity-free grains. In addition, more cement is needed for concrete containing angular aggregate for the same water to cement ratio.

It is more difficult to mix, pump and place concretes containing angular aggregate and poor grain distribution. As the aggregate grains go from round and smooth shape to angular and rough shape, the adherence between cement paste and aggregate is strengthened. This strengthening in adherence is directly reflected on strength. Smooth and flat grains should be found in the aggregate as little as possible.

The aggregate, consisting of round grains, is better and easier to fit in a given volume and less space is left. For this reason, it is considered that the concrete produced with round aggregate (gravel) will have less space and hence higher strength compared to those produced with crushed stone (stone chips). In contrast, crushed stone aggregate has a rougher surface. This roughness provides a better adherence between the cement paste and aggregate grains, and therefore the strength of concrete increases. Therefore, concrete produced with crushed stone gives higher strength than concrete produced with round aggregate despite the difficulty in compaction.

Grain Size and Grain Distribution: There are grains of various sizes in an aggregate pile. The process of determining the ratio of grains of various sizes in the aggregate pile is called *granulometry*. In other words, the process of separating aggregate grains in an aggregate sample into various grain size groups is called *granulometry*.

The presence of different grain groups in the aggregate pile is important in terms of obtaining a more void-free and dense concrete. Due to its effect on workability, proper granulometry is vital for a quality concrete. Since an aggregate with poor granulometry will increase the water requirement of the concrete, it has a negative effect on strength and durability.

Several types of granulometry can be mentioned. Aggregates with aggregate groups of all sizes are called aggregates with *continuous granulometry*. This is the most widely used. Those with uniform size aggregates are called *uniform granulometry*, and those with one or more aggregate groups removed are called *gap-graded granulometry* aggregates.

SIEVE ANALYSIS AND DETERMINATION OF GRANULOMETRY

Granulometry is an important factor affecting the placement, compaction and strength of hardened concrete produced with any aggregate. The largest size of the grains in an aggregate pile is called *the largest aggregate size* and is denoted by D_{max}. For example, there is no aggregate larger than 31.5 mm in the aggregate pile with D = 31.5 mm.

As D gets big values, the amount of water and cement put into the concrete generally decreases and the strength of the concrete increases. However, the largest aggregate size is limited by the dimensions of the members in the structure where concrete will be used.

Standard sieves are used for sieve analysis. One of the most widely used sieve sets is a square hole sieve system, which consists of 125, 90, 63, 31.5, 16, 8, 4, 2, 1, 0.5, 0.25 mm sieves.

An aggregate pile can be divided into groups according to grain sizes and the amounts in each group can be determined by sieving the aggregate sample through various sieves. Naturally, a sieve set suitable for this process is required to accomplish this. In sieving process, these sieves are placed on top of each other with the largest mesh size sieve at the top. A pan is placed at the bottom where the fine material passing through the smallest mesh screen is collected.

When the aggregate sample is poured into the top sieve, the aggregate grains are retained on various sieves according to their size and thus the aggregate is divided into groups. After the amount of aggregate retaining on each sieve is determined by weighing, their ratio to the total amount of aggregate is calculated and the result is given in a table. Sieve analysis for an aggregate sample is given below.

Sieve size (mm)	Weight remained, g	Percentage remained	Cumulative % remained	Cumulative % passing
31.5	0	0.0	0.0	100.0
16.0	912	19.0	19.0	81.0
8.0	1152	24.0	43.0	57.0
4.0	720	15.0	58.0	42.0
2.0	864	18.0	76.0	24.0
1.0	672	14.0	90.0	10.0
0.5	240	5.0	95.0	5.0
0.25	144	3.0	98.0	2.0
Pan	96	2.0	100.0	
Total	4800			

The granulometry of aggregates is usually defined by the proportions of grains smaller than a certain sieve size, rather than the material proportions remaining on each sieve.

The granulometry of aggregates is usually defined by the proportions of grains smaller than a certain size, rather than the material proportions in each grain group. If we look at the example, the proportion of the grains smaller than 1 mm is 10%, while the proportion of the grains smaller than 4 mm is 42%.

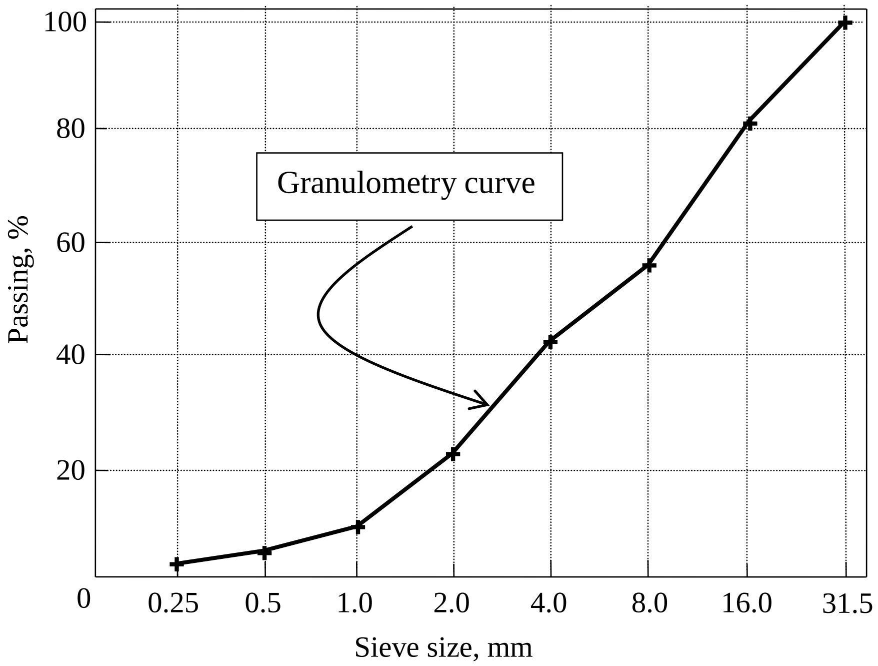
As seen from the example given above, granulometry is a cumulative sum of material ratios in various grain groups. Since the aim is to obtain this cumulative summation, the sieve analysis can be performed accordingly. That is, after the sieving process is done as described before, the aggregate remained in the top sieve is weighed, and then another weighing is made by adding the remaining aggregate to the lower sieve.

Weighing process is completed by adding the grains remained in each sieve. Thus, the aggregate sum of the aggregate groups remaining on each sieve is obtained. Since the total amount of aggregate passing through each sieve is necessary, these values are obtained by subtracting the total amount of aggregate remaining in each sieve from the total amount of aggregate.

[Cumulative sum on each sieve] ⇨ [Total amount of aggregate] - [Cumulative sum on each sieve] = [Cumulative sum passing from each sieve]

$$\text{Passing (\%)} = \frac{\text{Cumulative sum passing from each sieve}}{\text{Total amount of aggregate}}$$

Granulometries of aggregates can be presented in tables or can be displayed graphically. In the graph, the horizontal axis shows the sieve opening and the vertical axis shows the material passing under the sieve in percent. Due to the ratio of approximately 1 to 2 between the successive sieves, the sieve openings are shown at fixed intervals on the logarithmic scale axis. The granulometry curve of the aggregate sample given above is given below.



Features of the granulometry curve:

- They are always ascending curves. Even if they have horizontal segments, they never descending.
- The difference between the granulometric values of the two sieves gives the proportion of material remaining between these sieves.
- The closer the granulometry curve to the upper edge of the graph, the finer material in the aggregate. Similarly, the granulometry curve of aggregate containing large amount of coarse grains will be close to the bottom edge of the graph.

BOUNDARY CURVES FOR GRADATION

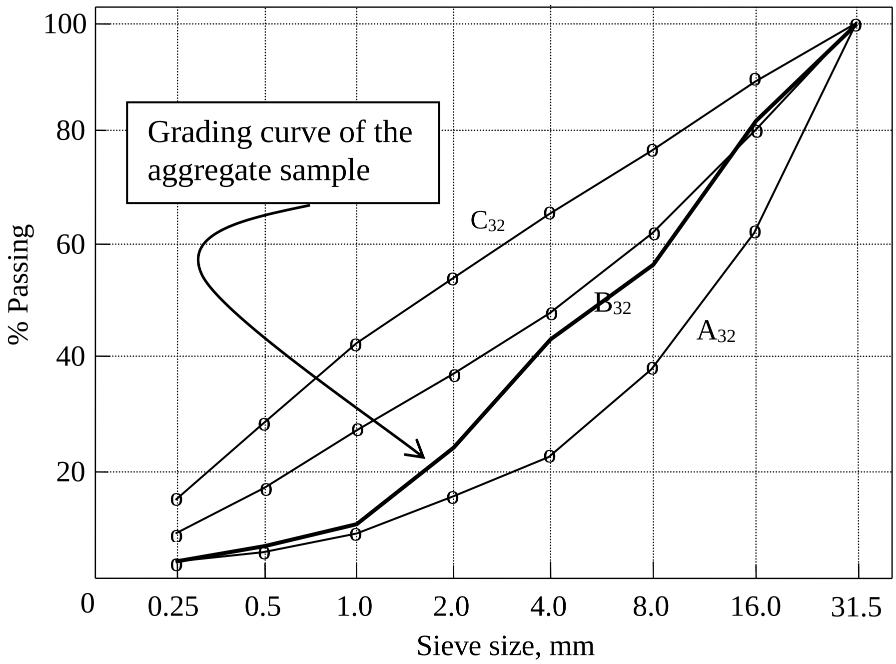
Aggregate mixtures to be used in concrete production are required to have a certain granulometry. Good granulometry means that the workability of the concrete is good, the concrete is very dense and uniform and does not segregate. Which granulometry is suitable for concrete production has been determined by conducting long researches. There is no single “ideal granulometry curve” that provides all the desired properties from concrete. Based on this, the standards imposed some limitations on granulometry curves. Accordingly, for an aggregate to be suitable for concrete production, aggregate granulometry should fall between the upper and lower *boundary curves* determined by the relevant standard.

The boundary curves defined for the largest aggregate size 16 mm and 31.5 mm according to the relevant standard square-hole sieve system are given below.

The relevant standard defines three boundary curves, A, B and C, for the largest aggregate size 8, 16, 31.5 and 63 mm separately. The region surrounded by the A and B boundary curves on the granulometry curve shows the *ideal granulometry*, the region surrounded by the B and C boundary curves shows *usable granulometry*. It is desirable that the aggregates to be used in concrete production preferably remain within the area surrounded by the A and B boundary curves, and that the granulometry curve is similar to the boundary curves, that is, the curves going parallel to them with their general lines, do not change the region, do not make sudden exits and jumps.

Sieve size, mm	Boundary curves (% Passing)					
	A_{16}	B_{16}	C_{16}	A_{32}	B_{32}	C_{32}
31.5	---	---	---	100	100	100
16.0	100	100	100	62	80	89
8.0	60	76	88	38	62	77
4.0	36	56	74	23	47	65
2.0	21	42	62	14	37	53
1.0	12	32	49	8	28	42
0.5	(7)	(20)	(34)	(5)	(18)	(28)
0.25	3	8	18	2	8	15

An aggregate whose granulometry curve is outside the A and C boundary curves is not suitable for concrete production in terms of granulometry, and therefore it is inconvenient to use that aggregate in concrete production. In the example given above, the largest aggregate size is 31.5 mm. The granulometry curve of this aggregate, along with the related boundary curves are given in the graph below.



Boundary curves for D_{max} 31.5 mm and granulometry curve for aggregate sample

FINENESS MODULUS

Although the fineness modulus gives a general idea about the average particle size of the aggregate, it does not provide any information about its granulometry. Briefly, the fineness modulus is to express the average size of the aggregate particles in an aggregate pile with a single number. However, aggregates with different granulometry can have the same fineness modulus. In other words, the granulometries of two aggregates with the same fineness modulus can be quite different. The fineness modulus of an aggregate depends on the sieve system used. The greatest value that the fineness modulus can take is the number of sieves in the sieve system and the smallest value that it can take is zero.

The fineness modulus is obtained by dividing the sum of cumulative percentages of aggregates remaining on the standard sieves by 100.

Fineness modulus, $$f_m = \frac{\Sigma \text{ Cumulative \% Remained on Standard Sieves}}{100}$$

Accordingly, the fineness module of the previous aggregate sample can be calculated as follows.

$$f_m = \frac{0.0 + 19.0 + 43.0 + 58.0 + 76.0 + 90.0 + 95.0 + 98.0}{100} = 4.79$$

The fineness modulus gets small values as the particles become finer and the amount of the smaller sized particles increases. As the quantity of coarse particles in the pile increases, the fineness modulus gets large values. Accordingly, considering the fineness modulus value, it is possible to find out which sieve size the average size of aggregate particles corresponds to. The sieves are given increasing numbers from the small mesh sieve to the large mesh sieve. The sieve number corresponding to the fineness modulus value gives the average grain size.

In the example above, since the fineness modulus is 4.79, it is seen that the average particle size is between the fourth and fifth sieves from the bottom towards the top. So, the average aggregate particle size is between 2 and 4 mm. However, it should be noted that there may be aggregates with a large number of granulometry curves with the same average particle size.

The fineness module can also be calculated as follows:

Fineness modulus; $$f_m = \frac{\text{Number of sieves x 100-}\Sigma \text{ \% Passing}}{100}$$

Hence, the fineness modulus for the above aggregate sample can be calculated as follows:

$$f_m = \frac{8 \times 100 - (100 + 81 + 57 + 42 + 24 + 10 + 5 + 2)}{100} = 4.79$$

The fineness modulus can be used to detect small changes in aggregate supplied from the same source. However, it is not used to compare the particle distributions of aggregates from two different sources.

MAXIMUM AGGREGATE SIZE (D_{max})

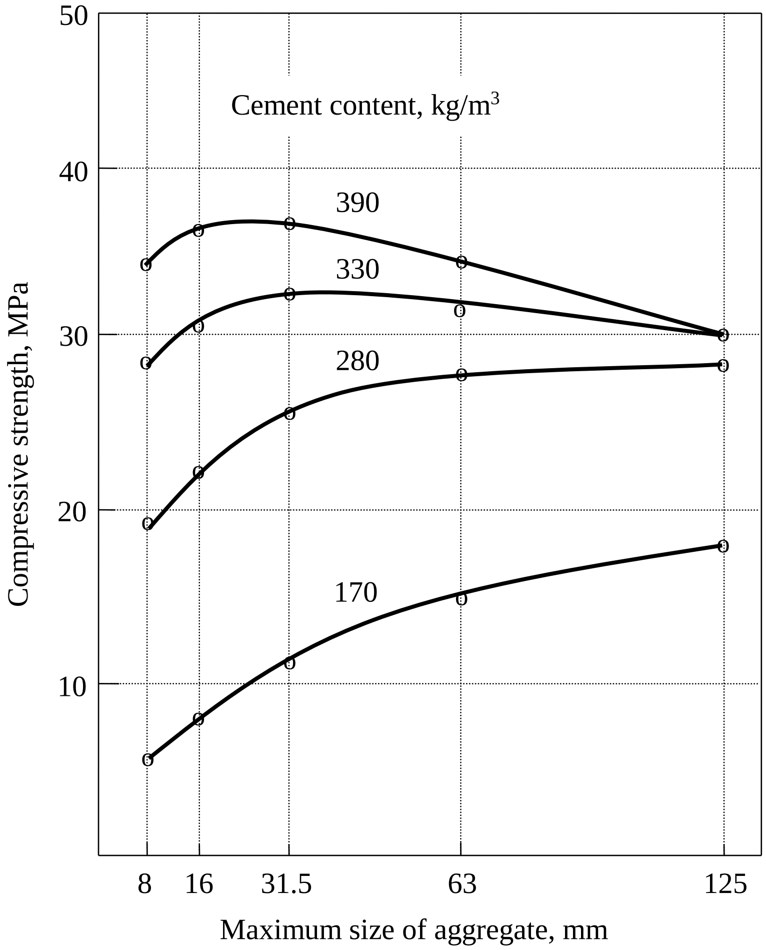
The “largest aggregate size” in an aggregate is the smallest mesh opening that the entire aggregate can pass. If the amount of cement used in concrete is kept constant, the water to cement ratio decreases as the largest grain size of the aggregate used increases.

Possible advantages that can be obtained when using the largest possible size aggregate in concrete production can be summarized as follows:

- Water requirement of the concrete mixture decreases. Therefore, the drying shrinkage of concrete would decrease.
- Cement requirement of the mixture is reduced. Therefore, economy is achieved, and less hydration heat is released, which is especially important for mass concrete applications.
- Water to cement ratio of the concrete produced for a constant workability and with a fixed amount of cement decreases. Thus, higher strength is obtained.

However, the advantages listed above are only valid if the largest aggregate size does not exceed 40 mm. The largest aggregate size used in the structural concrete design generally does not exceed 25 mm. When grains exceeding 40 mm are found in the aggregate, the strength of the concrete is negatively affected. The reason for this is that as the largest aggregate grain size increases in the aggregate pile, the total surface area of the existing grains in the pile decreases. Therefore, the adherence between cement paste and aggregate decreases.

Due to volume changes in cement paste, great stresses occur at the interface of cement paste and aggregate grains. In addition, as the largest aggregate grain size increases the homogeneity of concrete decreases. After all, all this has a negative effect on the strength of the concrete and causes the strength to decrease. The figure below shows the influence of largest aggregate size on the 28-day compressive strength of concrete of with different cement contents.



The effect of the maximum aggregate size on the compressive strength of concrete

The largest aggregate grain size used in concrete production generally depends on the size, shape and amount of reinforcement of the concrete element and its distribution. The largest aggregate size to be used in concrete production must meet the following criteria.

- $D_{max} \leq 1/5 \times$ the width of the narrowest structural member
- $D_{max} \leq ⅓ \times$ the depth of the slab or deck
- $D_{max} \leq ¾ \times$ the smallest distance between two reinforcements
- $D_{max} \leq ⅔ \times$ the concrete cover; for conditions exposed to soil and atmospheric effects
- $D_{max} \leq ½ \times$ the concrete cover; for conditions exposed to chloride

The amount of cement used in concrete production is a factor affecting the relationship between the largest aggregate size and concrete strength. Experimental studies showed that using the largest possible aggregate size in concretes with low cement amount increases the concrete strength, but the maximum aggregate size should not exceed 25-30 mm in concrete mixtures with high cement amount. If the largest aggregate grain size exceeds 25-30 mm in concretes with very high cement amount, there is no increase in concrete strength despite the decrease in water to cement ratio.

In the aggregate used in the production of high strength concrete (higher strength than 50 MPa), it is preferred that the largest aggregate grain size is generally 16 mm or smaller.

METHODS OF MAKING AGGREGATE GRANULOMETRY SUITABLE

The aggregate available at the construction site sometimes does not have the desired granulometry. In this case, by mixing this aggregate with other aggregate or aggregates, an aggregate mixture with the desired granulometry is obtained. The methods used for this purpose are given below:

1. Trial and Error Method: Here, an estimate is made for the mixing ratios by looking at the granulometry of the aggregates that will form the mixture. Using these ratios, the granulometry of the mixture is calculated. If the granulometry curve of the mixture does not fall between the desired limits, these ratios are changed a little and the calculations are repeated.

Example: Find the mixing ratios to obtain a mixture that falls in the ideal region (between the A and B boundary curves) by using the X and Y aggregates, the granulometry of which is given below.

Sieve size (mm)	% Passing		Boundary curves		Mixed aggregate (60%X+40%Y)	
	X	Y	A_{32}	B_{32}		
31.5	100	100	100	100	60+40 =100	√
16.0	80	40	62	80	48+16 = 64	√
8.0	70	20	38	62	42+8 = 50	√
4.0	60	10	23	47	36+4 = 40	√
2.0	40	5	14	37	24+2 = 26	√
1.0	20	0	8	28	12+0 = 12	√
0.5	10	0	(5)	(18)	6+0 = 6	√
0.25	5	0	2	8	3+0 = 3	√

According to the trial-and-error method, when the X aggregate is mixed at 60% and the Y aggregate at 40%, the aggregate mixture obtained falls between the A and B boundary curves.

2. Method of Passing Through a Point: Here, a point is selected where the granulometry curve of the mixture is desired to pass. Then, the mixing ratios are calculated for the curve to pass through this point. The points to be considered while choosing a point are given below:

- The point should be between the granulometry curves of the aggregates entering the mixture.
- The selected point must also lie between the boundary curves.
- Part of the region defined by the boundary curves, part of the region bounded by the granulometry curves of the aggregates should interfere for all grain sizes.

Example: Considering the previous example, find the mixing ratios of the X and Y aggregates so that 50% of the aggregate mixture passes through the 8 mm sieve.

The ratios of X and Y aggregates passing through 8 mm sieve are X_X=70 and X_Y=20, respectively. Similarly, the range of granulmetric values of the boundary curves corresponding to the same sieve is X_A=38 and X_B=62. From here, using the mixing rule, the mixing ratios for aggregates can be determined as follows:

$$X_m = X_X \times X\% + X_Y \times Y\% \qquad X+Y=100 \qquad Y=100-X$$

$$50 = 70 \times X\% + 20 \times Y\% \qquad 50 = 70 \times \left(\frac{X}{100}\right) + 20 \times \left(\frac{100-X}{100}\right)$$

$$5000 = 70 \times X + 2000 - 20 \times X \qquad X=60\% \qquad Y=40\%$$

3. The Fineness Modulus Method: Here, first, a value for the fineness modulus of the aggregate mixture is selected. Since the granulometry and thus the fineness modulus of the aggregates entering the mixture are known, an aggregate mixture with the desired fineness modulus can be calculated using the mixture rule in which proportions it can be obtained from the aggregates entering the mixture.

$$f_m = f_x \times X\% + f_y \times Y\% \qquad X+Y=100 \qquad Y=100-X$$

Here; f_m is the fineness modulus of aggregate mixture, f_x is the is the fineness modulus of aggregate X and f_y is the fineness modulus of aggregate Y. f_x and f_y values are known, f_m is selected.

When selecting the fineness modulus, f_m, of the aggregate mixture, the following points should be considered:

- f_m can take a value between the fineness modules of the aggregates entering the mixture.
- f_m must lie between the fineness modulus of the boundary curves.

However, providing these points does not require that the granulometry curves remain between the boundary curves.

Example: Considering the previous example and assuming that the fineness modulus of the aggregate mixture is 4.99, determine the mixing ratios to obtain an aggregate mixture that falls between the A and B boundary curves.

$f_m = f_x \times X\% + f_y \times Y\%$ X+Y=100 Y=100-X

$4.99 = 4.15 \times X\% + 6.25 \times Y\%$

$4.99 = 4.15 \times \left(\frac{X}{100}\right) + 6.25 \times \left(\frac{100-X}{100}\right)$ X=60% Y=40%

GRANULOMETRY OF A SIEVED AGGREGATE

If the aggregate present at the construction site is not suitable to produce concrete in terms of granulometry and there is no other aggregate to use with it on the construction site, this aggregate can be sieved and divided into two parts. The granulometry of the parts remaining in and under the sieve can be calculated and these two aggregates can be mixed for certain amounts and made suitable for concrete production.

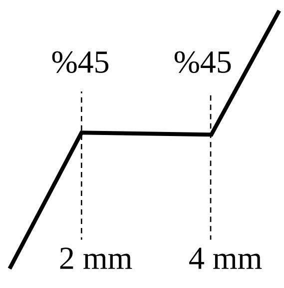
Let`s split the X aggregate present at the construction site into two parts by sieving it through 4 mm sieve and then calculate the granulometry of each part as follows:

Sieve size (mm	X	Proportions of fine and coarse parts	Gradation of fine part	Gradation of coarse part
31.5	100		100	(100-40/60=100
16	80	100%-40%=60%	100	(80-40)/60 = 67
8	60	60% coarse	100	(60-40)/60 = 33
4	40	↓	(40/40)×100 =100	0
2	30	40% of the aggregate	(30/40)×100 = 75	0
1	10	passing through a	(10/40)×100 = 25	0
0.5	6	4 mm sieve	(6/40)×100 = 15	0
0.25	1		(1/40)×100 = 2.5	0

GAP-GRADED AGGREGATE

In the absence of certain aggregate grain groups in an aggregate stockpile, the aggregate granulometry will be “intermittent” or “discontinuous”. This discontinuity corresponding to the missing grain groups in the granulometry curve is shown as a "horizontal line". This type of granulometry is called "gap-graded".

Sieve size (mm)	Passing (%)
31.5	100
16	90
8	75
4	45
2	45
1	30
0.5	20
0.25	10



There is no aggregate between 2 mm and 4 mm sieves.

Aggregates of gap-graded granulometry are expected to form a less void stockpile than aggregates with continuous granulometry. However, this depends on which grain group or groups are eliminated. Otherwise, removal of any group may not provide the desired effect. Generally, medium-sized aggregate grains are removed. Boundary curves are also different for aggregates with gap-graded granulometry. The U curves specified in the relevant standard are for aggregates with discrete granulometry and replace the A boundary curve. There is no change in the B and C boundary curves.

Aggregates of gap-graded granulometry can be used in any concrete. In addition, aggregate of gap-graded granulometry is used to obtain pre-pact (pre-placed aggregate concrete) concrete and aggregate-like surfaces. In addition, aggregates of gap-graded granulometry can be used in normal concrete production for the purpose of providing improvements in properties such as density, compaction, permeability, shrinkage and strength.

Gap-graded granulometry is generally recommended to prevent the segregation of dry consistency and very low slump mixtures to be vibrated. This is an application that requires attention and care. In an aggregate stockpile with the largest aggregate grain size of 20 mm, grains of 5 to 10 mm can be discarded without any risk of segregation. When the largest aggregate grain size is 40 mm, grains of 5 to 20 mm are usually discarded.

A special case of the gap-graded granulometry is that there is no fine part in the aggregate. Concrete produced with this aggregate is known as "no-fines concrete". Concrete without fines has low strength and high permeability. These types of concretes are slightly lightweight and have low drying shrinkage and have thermal insulation properties.

HANDLING AND STORAGE OF AGGREGATES

Aggregates should be used and stored in a way that minimizes decomposition and prevents contamination by harmful substances. In order to prevent the aggregates from getting dirty, they can be stored on hard and dry ground, if there is no such ground, on grobeton (concrete with little cement). The concrete flooring thickness prepared for this purpose should be 10 cm, the required slope should be given for the water to flow, and it should be slightly larger than the area covered by the stockpile. Aggregates of different groups entering the concrete mix should be stored separately; they must be separated by sufficiently high partitions to prevent them from mixing with each other.

If the aggregates are carried and stored with conveyor belts, the stacks should be formed in thin layers and should not be stacked as high peaks. In very high conical piles, coarse grains can roll towards the skirt of the heap and segregation may occur. Cigarette butts, tea waste, leaves and wood pieces thrown into aggregate can damage the concrete. If the concrete casting will be interrupted for a long time, the stockpile must be covered.

Crushed stone is difficult to segregate compared to round aggregate. Similarly, fine grains are harder to segregate compared to coarse grains. One way to prevent the segregation of the coarse aggregate is that aggregates are stacked in grain groups and then the groups are mixed with each other as desired. This may not be needed if the stockpile is properly formed.

For uniform moisture content, the washed aggregate should be stocked sufficiently before use. Wet aggregate has a very low tendency to decompose compared to dry aggregate.

SAMPLING FROM THE AGGREGATE PILE

Sample quantities to be taken for various tests on aggregates are specified by relevant standards. These are the quantities that may be needed for the relevant test. However, the quantities (actual quantities) used in the tests are often less than half of these quantities.

How to do sampling is explained in the standard related to the experiment. The point to be considered while taking the sample is that it represents the mass from which the sample was taken. For this, a large number of samples are taken from various parts of the aggregate pile and these are blended. Since the amount of blend formed is more than necessary for the experiment, the sample is reduced accordingly. Two methods are generally used for the reduction process.

The first of these is quartering-quadrupling-method. Here, after the aggregate spreads in a circle on a flat surface, the circle is divided into four and the opposite two quarters are removed; the other two quarters are taken. If this amount is more than necessary, a similar reduction is made again.

The other method used in the reduction process uses a tool called rifle-type sample separator. The aggregate sample used for the test is divided into two uniform parts by this tool. One of these parts is removed and the other is used. The procedure is performed repeatedly until the desired sample size is obtained.

Example: There are three classes of aggregates on a job site where you work as an engineer. The granulometries of these aggregates, along with the related boundary curves are given below:

Sieve size (mm)	Granulometries of the aggregates X	Y	Z	Boundary Curves A_{32}	B_{32}	C_{32}
31.5	100	100	100	100	100	100
16.0	100	80	50	62	80	89
8.0	100	60	35	38	62	77
4.0	70	48	20	23	47	65
2.0	50	40	10	14	37	53
1.0	30	26	5	8	28	42
0.5	20	18	0	(5)	(18)	(28)
0.25	10	8	0	2	8	15
Specific gravity (g/cm^3)	2.50	2.60	2.70			

a) Using all three of the aggregates provided, find the mixing ratios to obtain a mixture that falls between the A and C boundary curves. Use trial and error method for solution.

b) Using all aggregates, find the mixing ratios to obtain a mixture aggregate with a fineness modulus of 4.28 and a specific gravity of 2.59 g/cm^3.

c) Using all aggregates, find the mixing ratios to obtain a mixture with a fineness modulus of 3.77 and 42% of which passes through a 2 mm sieve.

d) Separate the Y aggregate from 2 mm sieve and divide it into two parts and calculate the granulometry of each part. When these two parts are mixed equally, what is the fineness modulus and specific gravity of the mixture? Calculate.

Solution:

a) The solution is left to the students.

b) Three equations must be established to determine mix ratios. Therefore,

1 $\delta_x \times X\% + \delta_y \times Y\% + \delta_z \times Z\% = 2.59$ — δ_x, δ_y, and δ_z are the specific gravity.

2 $f_x \times X\% + f_y \times Y\% + f_z \times Z\% = 4.28$ — f_x, f_y, and f_z are the fineness modulus.

3 $X + Y + Z = 100 \qquad X = 100-(Y+Z)$

$2.50\,(X/100) + 2.60\,(Y/100) + 2.70\,(Z/100) = 2.59$

$3.20\,(X/100) + 4.20\,(Y/100) + 5.80\,(Z/100) = 4.28 \qquad f_x=3.20 \quad f_y=4.20 \quad f_z=5.80$

If statement 3 is provided in statements 1 and 2,

$$250 - 2.5\times Y - 2.5\times Z + 2.6\times Y + 2.7\times Z = 259$$
$$320 - 3.2\times Y - 3.2\times Z + 4.2\times Y + 5.8\times Z = 428$$
$$0.1\times Y + 0.2\times Z = 9 \rightarrow \quad Y + 2\times Z = 90$$

$$1.0\times Y + 2.6\times Z = 108 \rightarrow \quad Y + 2.6\times Z = 108 \quad 0.6\times Z = 18 \quad \rightarrow \quad Z = 30\%$$
$$Y + 2\times Z = 90 \quad \rightarrow \quad Y + 2\times 30 = 90 \quad \rightarrow Y = 30\% \qquad X = 40\%$$

c) Since 42% of the mixture passes through a 2 mm sieve,

1 $X_m = X_X \times X\% + X_Y \times Y\% + X_Z \times Z\%$

$42 = 50 \times \frac{X}{100} + 40 \times \frac{Y}{100} + 10 \times \frac{Z}{100} \qquad 50 \times X + 40 \times Y + 10 \times Z = 4200$

2 $f_x \times X\% + f_y \times Y\% + f_z \times Z\% = 3.77 \quad \rightarrow \quad 3.2 \times \frac{X}{100} + 4.2 \times \frac{Y}{100} + 5.8 \times \frac{Z}{100} = 3.77$

$3.2 \times X + 4.2 \times Y + 5.8 \times Z = 377$

3 $X + Y + Z = 100 \quad \rightarrow \quad Z = 100 - (X + Y)$

By providing Equation 3 into Equations 1 and 2,

$$4200 = 50 \times X + 40 \times Y + 10 \times Z$$
$$4200 = 50 \times X + 40 \times Y + 10 \times [100 - (X + Y)]$$
$$3200 = 40 \times X + 30 \times Y \qquad 320 = 4 \times X + 3 \times Y \qquad Y = \frac{320 - 4 \times X}{3}$$
$$3.2 \times X + 4.2 \times Y + 5.8 \times [100 - (X + Y)] = 377 \qquad 2.6 \times X + 1.6 \times Y = 203$$
$$2.6 \times X + 1.6 \times \frac{320 - 4 \times X}{3} = 203 \qquad 7.8 \times X + 512 - 6.4 \times X = 609 \qquad 1.4 \times X = 97$$
$$X = 69\% \qquad Y = \frac{320 - 4 \times 69}{3} = 15\% \qquad Z = 100 - (69 + 15) = 16\%$$

The specific gravity of the mixed aggregate is

$$\delta_m = 0.69 \times \delta_x + 0.15 \times \delta_y + 0.16 \times \delta_z = 0.69 \times 2.50 + 0.15 \times 2.60 + 0.16 \times 2.70 \cong 2.55 \text{ g/cm}^3$$

d) If the Y aggregate is sieved through 2 mm sieve,

Sieve size (mm)	Y	Proportions of the fine and coarse parts	Grading of the fine part	Grading of the coarse part	50% fine + 50% coarse
31.5	100		100	(100-40)/60=100	100.0
16.0	80	100-40=60	100	(80-40)/60 = 67	83.5
8.0	60	60% coarse	100	(60-40)/60 = 33	66.5
4.0	48		100	(48-40)/60 = 13	56.5
2.0	40	↓	40/40 = 100	0	50.0
1.0	26	40% fine,	26/40 = 65	0	32.5
0.5	18	passing from	18/40 = 45	0	22.5
0.25	8	the 2-mm sieve	8/40 = 20	0	10.0

The fineness modulus of the mixed aggregate is $f_m = (800 - 421.5)/100 = 3.785$

The specific gravity of the mixed aggregate is equal to the specific gravity of the Y aggregate. Hence, the specific gravity of aggregate Y is, $\delta_y = 2.60$ g/cm^3.