Chapter 3
Soil Classification

3.1 INTRODUCTION

Soils can behave quite differently depending on their geotechnical characteristics. In *coarse grained soils*, where the grains are larger than 0.075 mm (or 75 μm), the engineering behaviour is influenced mainly by the relative proportions of the different sizes present, the shapes of the soil grains, and the density of packing. These soils are also called *granular soils*. In *fine grained soils*, where the grains are smaller than 0.075 mm, the mineralogy of the soil grains, water content, etc. have greater influence than the grain sizes, on the engineering behaviour. The borderline between coarse and fine grained soils is 0.075 mm, which is the smallest grain size one can distinguish with naked eye.

Based on grain sizes, the Australian Standards AS1726-1993 groups soils into *clays* (<0.002 mm), *silts* (0.002-0.075 mm), *sands* (0.075-2.36 mm), *gravels* (2.36-63 mm), *cobbles* (63-200 mm) and *boulders* (>200 mm). Within these major groups, the soils can still behave quite differently and we will look at some systematic methods of classifying them into distinct sub-groups.

3.2 COARSE GRAINED SOILS

Relative proportions of the different grain sizes have significant influence on the engineering behaviour of a coarse grained soil. Other major factors that influence the geotechnical characteristics of a coarse grained soil are the density of packing of the soil grains and the shape of the soil grains.

Grain Size Distribution

The grain size distribution of a coarse grained soil is generally determined through *sieve analysis*, where the soil sample is passed through a stack of sieves and the percentages passing different sizes of sieves are noted. The grain size distribution of the fines are determined through *hydrometer analysis*, where the fines are mixed with distilled water to make 1000 ml of suspension and a hydrometer is used to measure the density of the soil-water suspension at different times. The time-density data, recorded over a few days, is translated into grain size and percentage finer than that size. Hydrometer analysis is effective for soil fractions down to about 0.5 μm (Das 1994).

Very often, soils contain both coarse and fine grains and it is necessary to do sieve and hydrometer analyses to obtain the complete grain size distribution data. Here, sieve analysis is carried out first, and on the soil fraction passing 75 μm sieve, a hydrometer analysis is carried out. The grain size data thus obtained from sieve and hydrometer analyses are generally presented graphically as shown in Fig. 3.1. Logarithmic scale is used for the grain sizes since they vary in a wide range. The percentage passing is generally cumulative.

The *grain size distribution curve* shown in Fig. 3.1 gives a complete and quantitative picture of the relative proportions of the different grain sizes within the soil mass. D_{30} is a size such that 30% of the soil grains are smaller than this size. D_{15}, D_{85}, D_{10}, D_{60}, etc. can be defined in similar manner. D_{10} is called the *effective grain size*, which gives a good indication of the permeability characteristics of a coarse grained soil. The shape of the grain size distribution curve can be described through two simple parameters, namely, *coefficient of uniformity* (C_u) and *coefficient of curvature* (C_c or C_z). They are defined as:

$$\boxed{C_u = \frac{D_{60}}{D_{10}}}$$

and

$$\boxed{C_c = \frac{D_{30}^2}{D_{60}\,D_{10}}}$$

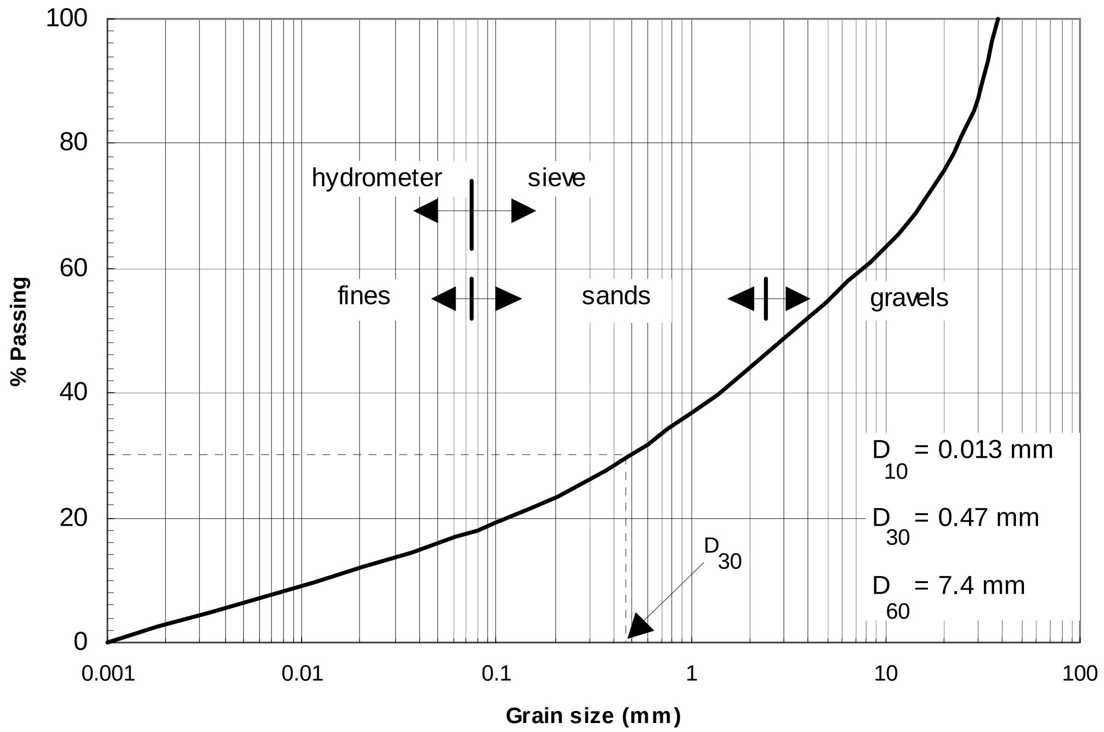

Figure 3.1 Grain Size Distribution Curve

A coarse grained soil is said to be *well graded* if there is a good distribution of sizes in a wide range, where smaller grains fill the voids created by the larger grains thus producing a dense packing. The grain size distribution curves for such soils would generally be smooth and concave as shown in Fig. 3.1. A sand is well graded if $C_u > 6$ and $C_c = 1\text{-}3$. A gravel is well graded if $C_u > 4$ and $C_c = 1\text{-}3$. For the grain size distribution curve shown in Fig. 3.1, $D_{10} = 0.013$ mm, $D_{30} = 0.47$ mm, $D_{60} = 7.4$ mm, $C_u = 569$ and $C_c = 2.3$. Therefore, it is a well graded soil. It can also be seen that this soil contains 53% gravels, 30% sands and 17% fines.

A soil that is not well graded is *poorly graded*. *Uniform soils* and *gap-graded soils* are special cases of poorly graded soils. In uniform soils, the grains are about the same size.

When there are smaller and larger grains, but none in an intermediate size range, the soil is known as a gap-graded soil. Typical grain size distribution curves of well graded (soil A), gap graded (soil B) and uniform (soil C) soils are shown in Fig. 3.2.

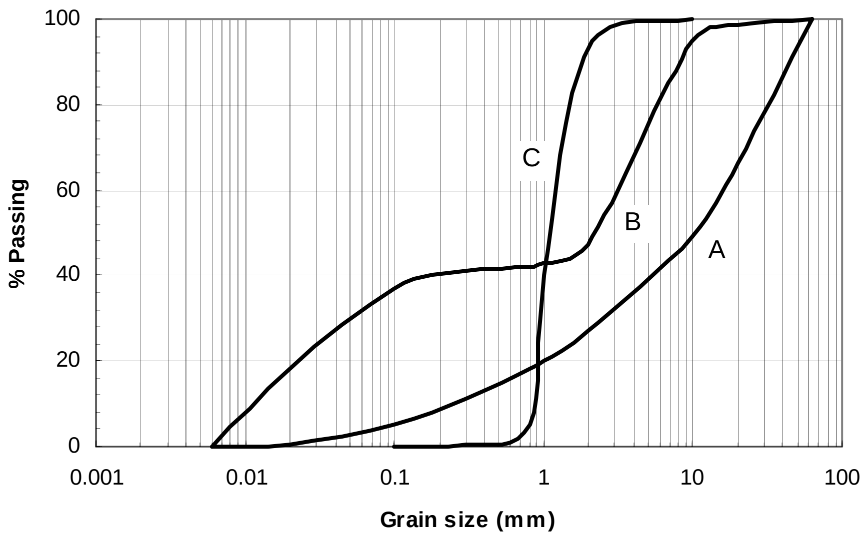

Figure 3.2 Different Types of GSD Curves

Relative Density

The geotechnical characteristics of a granular soil can vary in a wide range depending on how the grains are packed. The density of packing is quantified through a simple parameter *relative density* (D_r), also known as *density index* (I_D), defined as:

$$\boxed{D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \times 100\%}$$

where,

e_{max} = void ratio of the soil at it's *loosest* possible state
e_{min} = void ratio of the soil at it's *densest* possible state
e = current void ratio (i.e., state where D_r is being computed)

e_{max} is generally obtained by measuring the void ratio of the soil when it is "rained" over a short height, where the soil is assumed to be very loosely placed. e_{min} is obtained by measuring the void ratio of the same soil subjected to vibration or compaction, where it is assumed that the soil is placed at it's densest possible state. Relative density ranges from 0 to 100%.

Terms such as *"loose"* and *"dense"* are often used when referring to the density of packing of coarse grained soils. On the basis of D_r, AS 1726 recommends the terms shown in Fig. 3.3.

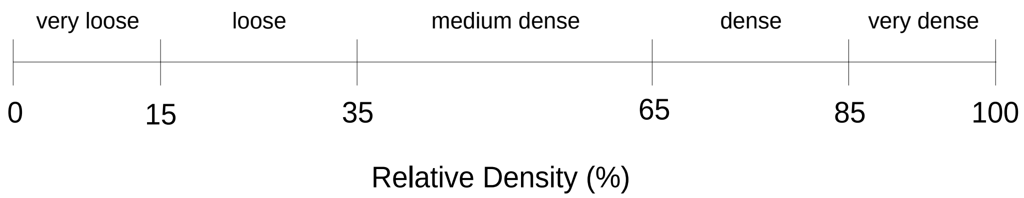

Figure 3.3 Designations based on Relative Density

Grain Shape

Shape of the grains in a coarse grained soil can be *angular*, *subangular*, *subrounded* or *rounded*. When the grains are angular, there is more interlocking between the grains, and therefore the strength and stiffness of the soil will be greater. For example, in roadworks, angular aggregates would provide better interlocking and resistance to get dislodged with traffic.

3.3 FINE GRAINED SOILS

While the gravels, sands and silts are equi-dimensional (same order of magnitude in all three directions), clay particles are like plates or needles. Their surfaces are electrically charged due to a charge imbalance between the cations and anions within the atomic structure. The *microstructure* or *microfabric* of the clay depends on the mineralogy of the clay and the valence, concentration and the type of the cations present in the pore water.

Clay Mineralogy

Mineralogy and microfabric of the clay structure are studied by x-ray diffraction, differential thermal analysis and scanning electron microscope. These sophisticated techniques are, however, not suitable for the routine geotechnical works. Atterberg limits discussed below, are directly related to the clay mineralogy and provide a simple means of characterising fine grained soils.

Atterberg Limits

The *consistency* (degree of firmness. i.e., soft, firm, stiff) of a fine grained soil varies significantly with the water content. As the water content of a fine grained soil is increased gradually from 0%, it goes through different consistencies, namely, brittle solid, semi-solid, plastic and liquid states (Fig. 3.4). *Atterberg limits* are the border line water contents between two such states. They were developed in early 1900's by a Swedish soil scientist A. Atterberg, working in ceramics industry. Later, K.Terzaghi (in late 1920's) and A. Casagrande (early 1930's) modified them to suit geotechnical works.

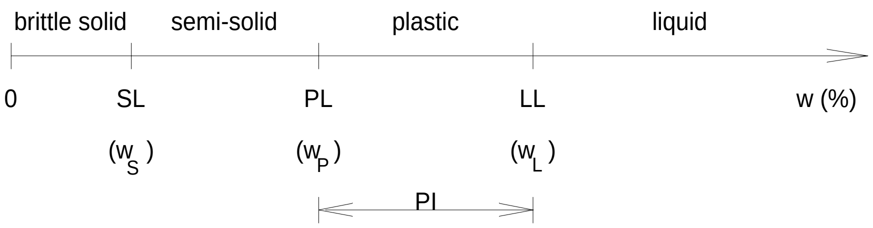

Figure 3.4 Atterberg Limits

Liquid limit (LL or w_L) is the lowest water content at which the fine grained soil behaves like a viscous mud, flowing under its own weight. It is the transition water content between plastic and liquid states. At liquid limit, the soil has very little strength. *Plastic limit* (PL or w_P) is the lowest water content at which the soil exhibits plastic characteristics (i.e., the lowest water content at which the clay can be rolled into a 3 mm diameter thread). The range of water content, over which the soil remains plastic is called the *plasticity index* (PI or I_P). Therefore, PI = LL - PL. Silts are non-plastic and thus PI ≈ 0. *Shrinkage limit* (SL or w_S) is the water content below which a soil sample will not shrink when dried.

The Atterberg limits are of empirical nature. However, they had been correlated very well with the geotechnical characteristics of fine grained soils and are therefore very valuable in soil classification.

Liquidity index (LI or I_L) is a parameter used to define the consistency of a fine grained soil with respect to LL and PL. It is defined as:

$$\boxed{LI = \frac{w - PL}{LL - PL}}$$

where w is the current water content at which LI is being computed. Some sensitive marine clay deposits exist at LI greater than 1 (i.e., at in situ water content greater than LL).

Fine grained soils often contain clays and silts. Here, clays are plastic and silts are non-plastic. Therefore, the plasticity index of a fine grained soil will depend on the relative proportions of the clays and silts within the soil. Skempton (1953) coined the word "*activity*" to separate the plasticity of the clay fraction. Activity (A) is defined as:

$$\boxed{A = \frac{PI}{\%\ \ of\ \ clay}}$$

Activity is a good indicator of the potential swell-shrink problems associated with a specific clay. Higher the activity, higher is the swell-shrink potential. Clays with $A<0.75$ are classified “normal”; clays where $0.75<A<1.25$ are active and clays where $A>1.25$ are active.

3.4 SOIL CLASSIFICATION

A soil classification system is a universal language which all the geotechnical engineers understand, where soils of similar behaviour are grouped together, and systematic and rational ways are proposed to classify and describe them. The use of such standard and precise terms eliminates any ambiguity in communicating the soil characteristics. There are several soil classification systems currently in use. The Unified Soil Classification System (USCS) is the most popular one, currently being used in many parts of the world. The AASHTO (American Association of State Highway and Transportation Officials) classification system is quite popular in road works, where the soils are grouped according to their suitability as subgrade or embankment materials. In Australia, AS 1726-1993 is being used in most geotechnical works.

Coarse and fine grained soils are classified based on grain size distribution and Atterberg limits respectively.

AS 1726 - 1993

Australian Standards AS 1726 and the Unified Soil Classification System divide the soils into four major groups, and describe them using standard descriptors. The major soil groups, the descriptors and the recommended symbols are shown in Table 3.1. AS 1726-1993 recommends describing the soil as “XY”, where the prefix “X” is the major soil group and the suffix “Y” is the descriptor.

Table 3.1 Soil Groups, Descriptors and Symbols

Major Soil Group	Descriptor
	Well graded (W)
Gravel (G)	Poorly graded (P)
Sand (S)	Silty (M)
	Clayey (C)
Silt (M)	Low plasticity (L)
Clay (C)	Medium plasticity (I)
Organic (O)	High plasticity (H)

A fine grained soil is classified as clay or silt, depending on the Atterberg limits and not on the percentages. Casagrande (1948) proposed the PI-LL chart shown in Fig. 3.5, where the A-line separates the clays and silts. If the LL and PI values of a fine grained soil plot above the A-line, it is clay. If they plot below the A-line, the soil is silt. “L”, “I” and “O” symbols are used to describe a fine grained soil when LL is less than 35, 35-50 or greater than 50 respectively. AS1726-1993 does not recommend “I” for silts. Thus fine grained soils can be CL, CI, CH, ML or MH as shown in Fig. 3.5. An organic clay has low plasticity and plots below the A-line and is assigned a symbol of “OH” or “OL”. A coarse grained soil, whether sand or gravel, can have any one of the four descriptors given in Table 3.1.

A fine grained soil is classified as clay or silt, based on the Atterberg limits and not the relative proportions of the grains.

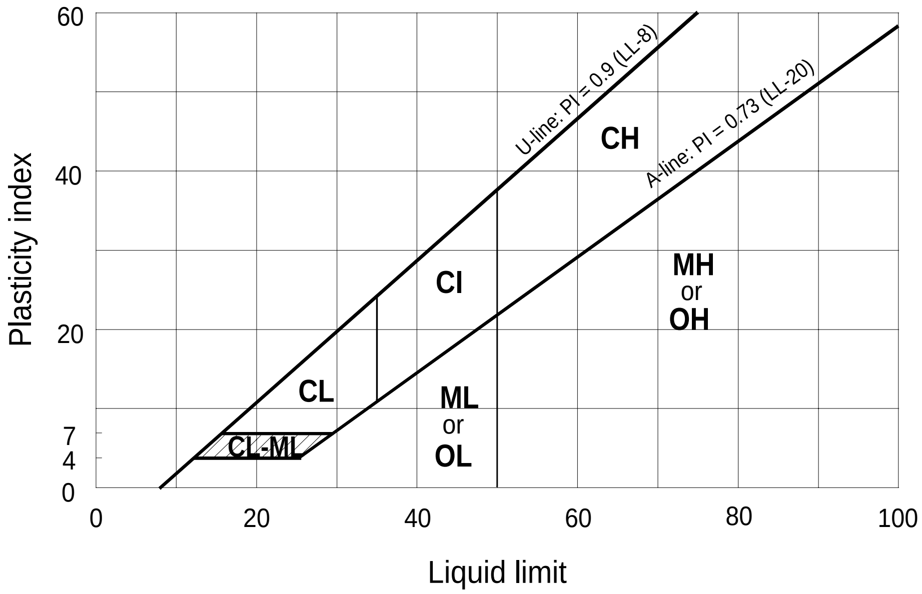

Figure 3.5 Casagrande's PI-LL Chart

Note that there is a U-line in Casagrande's PI-LL chart. This is approximately the upper bound for the PI-LL relation. One should be question the Atterberg limit values plotting above this line.

The geotechnical characteristics of a soil are significantly influenced by the percentage of fines present. Therefore, this must be taken into consideration when classifying the soil. When the percentage of fines is greater than that of coarse grained soils, it is a fine grained soil and vice versa. In a coarse grained soil, if the gravel content is more than that of sands, it is gravel and vice versa. AS 1726-1993 divides the soils into four cases, based on the fine content (Fig. 3.6).

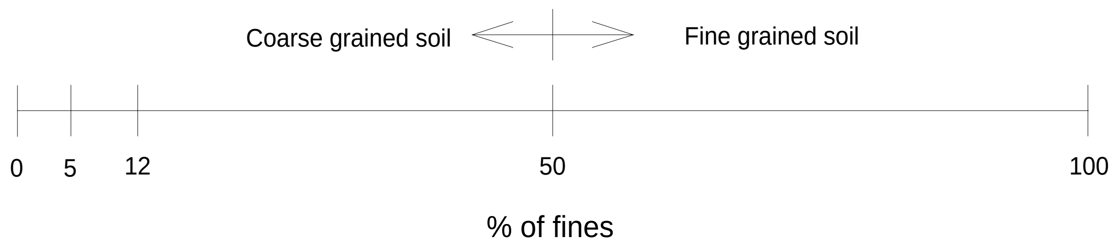

Figure 3.6 AS1726-1993 Soil Classification Cases

When the fine content is greater than 50%, it is a fine grained soil which may be given a symbol such as XY where X is the symbol for the fines and Y is the descriptor (see Table 3.1). A soil in this case can be ML, MH, CL, CI, CH, OL or OH. If the PI and LL values plot in the hatched area, the soil is given a dual symbol CL-ML.

The influence of fines is insignificant when they are less than 5%, and the soil is assigned a symbol XY where X is the major coarse grained soil present and Y is the descriptor describing the gradation of the coarse grained soil. A soil in this case can be GW, GP, SW or SP.

When the fine content is in the range of 12-50%, it is a coarse grained soil with substantial fines. The soil is assigned a symbol XY where X is the major coarse grained soil present and the descriptor Y is the symbol of the fines present. A soil in this case can be GM, GC, SM or SC.

The first thing one should know when classifying a soil is the % of fines. This influences the way in which the symbols are assigned.

When the fine content is in the range of 5-12%, the fine content as well as the gradation of the coarse grained soil are important. The soil is assigned a symbol of XY-XZ where X, Y and Z are the major coarse grained soil present (G or S), the gradation of the soil (W or P) and the fines present (M or C) respectively. Therefore, a soil in this case can be GW-GM, GW-GC, GP-GM, GP-GC, SW-SM, SW-SC, SP-SM or SP-SC.

Unified Soil Classification System

In Unified Soil Classification System (USCS), the border line between sands and gravels is 4.75 mm (Remember it is 2.36 in AS 1726). In classifying the soils based on the fine content, USCS has a special case where fine content = 45-55%, in addition to the four cases discussed above. When the fine content is in the range of 45-55%, the fine grained soils and coarse grained soils are in approximately equal proportions. Here, the soil is assigned a symbol of XY-YZ, where X and Y are the symbols for the coarse and fine grained soils respectively. Z is the descriptor of the fines (L or H). USCS does not recommend the use of "I" as a descriptor for fines.

3.5 VISUAL IDENTIFICATION OF SOILS

A good geotechnical engineer must be able to identify soils in the field simply by the feel. Coarse grained soils are easy to identify. Fine grained soils are identified on the basis of some simple tests for *dry strength*, *dilatancy* and *toughness*. Dry strength is a qualitative measure of how hard it is to crush a dry mass of fine grained soil between the fingers. Clays have very high dry strength and silts have very low dry strength. Dilatancy is an indication of how quickly the moisture from a wet soil can be brought to the surface by vibration. Here, a pat of moist clay is placed on the palm and struck against the other hand several times. In silty soils, within a few strikes water rises to the surface making it shine. In clays, it may require considerable effort to make the surface shiny. In other words, dilatancy is quick in silts and slow in clays. Toughness is a qualitative measure of how tough the soil is near its plastic limit (where the soil crumbles when rolled to a 3 mm diameter thread). Toughness increases with plasticity. Silty soils are soft and friable (crumble easily) at PL, and clays are hard at PL. The fines can also be identified by feeling a moist pat; clays feel sticky and silts feel gritty. The stickiness is due to the cohesive properties of the fines, which is also associated with the plasticity, and therefore clays are called *cohesive soils*. Gravels, sands and silts are called *granular soils*.

EXAMPLES

1. The grain size distribution curves for three soils X, Y and Z are shown in Fig. Ex. 3.1. Atterberg limit tests on the soil fraction of Z, passing 0.425 mm sieve, showed that LL = 46 and PL = 24.
   (a) Find the percentages of gravels, sands and fines in all three soils.
   (b) Classify the three soils, giving them AS 1726 symbols and brief descriptions.
   (c) What is the activity of soil Z?

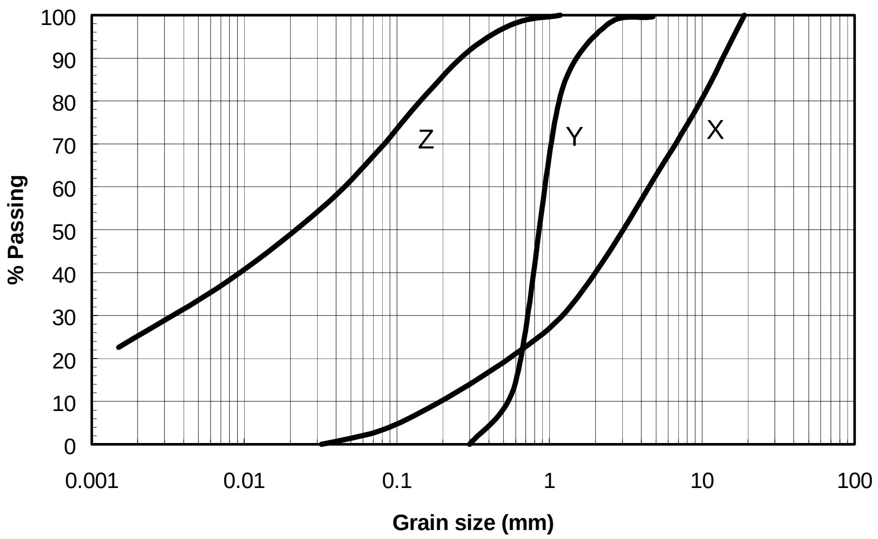

Figure Ex. 3.1 GSD Curves of Soils X, Y and Z

Solution:

(a) Let's summarise the percentages, D_{10}, D_{30}, D_{60}, C_u and C_c values as read from the above GSD curves:

soil	% of gravels	% of sands	% of fines	D_{10}	D_{30}	D_{60}	C_u	C_c
X	55.5	41	3.5	0.2	1.3	4.5	22.5	1.9
Y	3	97	0	0.53	0.71	0.90	1.7	1.1
Z	0	32	68	Not important				

(b) Soil X: Well graded sandy gravel
AS 1726 symbol: GW
Soil Y: Poorly graded sand
AS 1726 symbol: SP
Soil Z: LL = 46 & PI = 22 plots above the A-line (Fig. 3.5).

∴The fines are clays.
It is a sandy clay of medium plasticity.
AS 1726 symbol: CI

(c) For soil Z, PI = 22
% of clay = 26
∴activity = 22/26 = 0.85

2. Classify the following soils, using the grain size distribution and Atterberg limit test data given.

(a) Soil A: 70% retained on 2.36 mm sieve;
10% passed 0.075 mm sieve;
fines had very low dry strength;
$C_u = 12$ and $C_c = 2.1$

(b) Soil B: 74% passed 2.36 mm sieve;
33% passed 0.075 mm sieve; and
fines had high dry strength.

(c) Soil C: 75% passed 2.36 mm sieve;
61% passed 0.075 mm sieve;
LL = 45 and PL = 29

(d) Soil D: 79% passed 2.36 mm sieve;
4% passed 0.075 mm sieve;
$C_u = 45$ and $C_c = 0.8$

Solution:

(a) Soil A: gravels = 70%, sands = 20%, fines = 10%
Fines are silty.
The coarse fraction is well graded.
It is a well graded silty sandy gravel.
AS 1726 symbol: GW-GM

(b) Soil B: gravels = 26%, sands = 41%, fines = 33%
Fines are clays.
It is a gravelly clayey sand.
AS 1726 symbol: SC

(c) Soil C: gravels = 25%, sands = 14%, fines = 61%
LL = 45 & PI = 16 plots below the A-line.
∴The fines are silts
The soil is sandy gravelly silt.
AS 1726 symbol: MH

(d) Soil D: gravels = 21%, sands =75% , fines = 4%
The coarse fraction is poorly graded.
The soil is poorly graded gravelly sand.

AS 1726 symbol: SP

PROBLEMS

1. State whether the following are true or false:
   (a) Plastic limit is always greater than the plasticity index.
   (b) Liquidity index can not be negative.
   (c) Relative density can not exceed 100%.
   (d) Clays have higher plasticity than silts.
   (e) Percentage of clays in a fine grained soil can be determined by sieve analysis.
   Ans. F, F, T, T, F

2. Classify the following two soils, giving their AS 1726 symbols and descriptions:
   (a) A soil having C_u = 42 and C_c = 1.8, where 4% passed 0.075 mm sieve and 63% passed 2.36 mm sieve.
   (b) A soil where 61% is retained on 2.36 mm sieve, 20% passes 0.075 mm sieve and the fines have LL = 40 and PL = 28.
   (c) A fine grained soil having liquid limit and plastic limit of 63 and 29 respectively.
   (d) A well graded soil having D_{10} and D_{30} of 0.075 mm and 2.36 mm respectively, where the fines have high dry strength.
   Ans. (a) SW: well graded gravelly sand (b) GM: sandy silty gravel (c) CH: clay of high plasticity (d) GW-GC: well graded clayey sandy gravel

3. The grain size distribution of a granular soil, selected for a road work, is given by:

$$p = \sqrt{\frac{D}{D_{\max}}} \times 100\%$$

   where,
   D_{max} = size of the largest grain within the soil mass
   D = grain size
   p = percentage passing
   (a) Show that this soil is well graded.
   (b) If D_{max} = 19 mm and the fines have high dry strength, classify the soil .
   Ans. (a) C_u = 36, C_c = 2.25; therefore well graded (b) GW-GC: well graded clayey sandy gravel.

4. In a granular soil where the grains are perfect spheres of the same size, show that e_{max} and e_{min} are 0.91 and 0.35 respectively.

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