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Settling Behaviour of Fine Grained Soils

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Introduction

General

The history of the study of the soils after their formation dates back very much even to the pre-origin of soil mechanics. However, the study of the behaviour of soils before and during their formation, from the point of view of soil mechanics, is relatively new. One of the important ways through which soil deposits are formed is by sedimentation. This results in a group of soils known as transported soils of which alluvial, lacustrine and marine sediments are some typical subgroups. It has been estimated that the sediments form about 75% of the surface of the continental platforms and a considerably higher proportion of the ocean floors and about 5% of the terrestrial and suboceanic earths (Winterkorn and Fang, 1986). These sediments are formed mainly through water as the transporting agent, either during running or stagnant conditions, due to the settling of soil particles in suspension.

When the velocity of flow is reduced sufficiently so as to allow settling, the soil particles/flocs start settling towards the floor. When more and more material gets added at the top, the voids between the soil particles/ flocs reduce, resulting in the expulsion of the pore water. The consolidation thus takes place as a result of the self weight of the soil particles and is regarded as the self weight consolidation (Been and Sills, 1981) which results is very soft sediments. These sediments exhibit varied amount of stratification, even in a sediment of the same soil, in terms of structures like loose, dense, unstable or in terms of the nature of sediment like

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homogeneous or heterogeneous. This may be attributed to different modes of settling of soil particles from suspension under different settling environments prevailing.

State of the Art

The studies on settling behaviour of soils done so far are very limited. McRoberts and Nixon (1976), while proposing a theoretical model for the hindered settling which is the settling in relatively thick soil-water suspension, observed that there was a maximum initial water content at which the hindered settling was not possible. Based on precise observation through photographs obtained with large magnification, of "the flocculation appearance" during settling, Imai (1980) classified the settling of soils in to four types:

- Dispersed free settling: Soil particles do not flocculate, but disperse and freely settle without mutual interactions. Coarser particles settle earlier than finer particles.
- Flocculated free settling: Soil particles flocculate. The flocs of different sizes settle freely with rates peculiar to their sizes with no sharp interface formation.
- Zone settling: Soil flocs formed due to flocculation settle with strong mutual interactions among them. They settle uniformly in the aggregate with the formation of a sharp interface. The settling rate is constant during the settling stage.
- Consolidation settling: Visible flocs can not be formed. The mixture settles as a whole mainly due to consolidation.

He concluded that the usual clay minerals would exhibit these four types of settling. He opined that the first type of settling was possible only in rivers and lakes, but not in marine environment and that the second and third types were not possible when the salt concentration was as low as in fresh water. He observed that the consolidation settling was possible irrespective of the salt concentration as long as the initial water content was lower than some value. His studies were focused much on zone settling and consolidation settling with particular reference to marine pore medium environment. He identified the salt concentration of the pore medium and the solid concentration of the suspension to be the two factors governing the type of settling. He distinguished three stages on the settlement – log t curve for zone settling – flocculation stage, settling stage and consolidation stage and concluded that the total solid weight of the soil in the suspension would influence the settling characteristics like rate of settling, average water content at the end of settling stage and critical initial water content, defined as the maximum initial water content below which only consolidation settling occurs.

Imai (1981) observed that it was not possible to determine the water content at which the suspension changed into a sediment for a soil and that it varied with initial water content of the suspension.

Been and Sills (1981) conducted experiments on estuarine mud-tap water suspensions and obtained the density profiles of the settling mud using non-destructive x-ray technique. They calculated the total vertical stress distribution in the settling column by integrating the density profile and measured the pore water pressures with the transducers fixed at various depths of the settling column. They concluded that no effective stresses were measurable in dilute suspensions and that there was a certain density at which a slurry could no longer exist in effective stress free condition, which depended on the soil type and pore medium chemistry. Their experiments also revealed that the flocculation would play an important role in determining the homogeneity of the sediment, in addition to affecting the settling behaviour.

Tan et al. (1991) made some studies on sedimentation behaviour of soils by varying the salt concentration and pH of the pore medium and by introducing some synthetic non-ionic polymers into the soil-water suspension. They also obtained the density profile of the settling soil using a gamma ray device. Their main aim was to study the gain in strength of the slurry as a function of initial water content of the slurry.

Scope of the Present Work

In the present experimental study, it has been felt that without varying the physico-chemical environment of the soil-water suspension, even in the fresh water environment itself, more information need be obtained regarding the settling behaviour of soil-water suspensions and the sediments formed. Even though many observations have been made during this study, all can not be covered in this article due to space limitation. Primarily, emphasis has been given to present the results on following aspects in this article:

- The effect of clay mineral type in the soil on the settling behaviour of soils.

- The classification of settling type which helps in explaining the structure of the soil sediment formed which in turn influences many engineering properties such as compressibility, strength and permeability of the soft sediments formed.

- The effect of initial water content on the settling behaviour of soils and on the nature of the final sediment formed.

During the initial stages of settling, even under negligibly low or zero effective stress condition, due to the continuous accumulation of soil particles/flocs above, the lower portion of the sediment being formed gets compressed. In this article, this process has been considered as self weight consolidation. In this article, a term 'effective stress' at the bottom of the suspension due to the effective weight of the soil mass in the suspension has been used as is denoted as $(\gamma' H)$ where γ' is the submerged density of the soil suspension and H is the height of the suspension. If W_d is the dry weight of the soil present in the suspension, A is the cross sectional area of the suspension and G_s is the specific gravity of soil particles, then it can be shown that

$$(\gamma' H) = \frac{(G_s - 1) W_d}{G_s A} \tag{1}$$

If γ'_i and H_i correspond to the submerged density and the initial height of the soil suspension respectively and γ'_f and H_f are the corresponding values of the same quantities for the final sediment formed out of suspension, then it can be noted that

$$\gamma'_i H_i = \gamma'_f H_f$$

Further, the terms 'void ratio' and 'water content' of the sediment used in this article indicate the void ratio and the water content of the sediment, considering the entire sediments as one unit and hence, they represent the average values.

Experimental Programme

Materials

Two natural soils – red earth (kaolinitic soil) and brown soil (montmorillonitic soil) and kaolinite were used in this experimental study. Their index properties are given in Table 1. Figure 1 shows the grain size distribution curves of the soils. The sedimentation analysis was carried out in a fresh water environment with a pH of about 7.2 ± 0.1.

Methods

The experiments were carried out in glass jars of diameter 61.1 mm and 62 mm. The required quantity of oven dried soil was initially mixed with water to form a slurry and then the water content was increased to desired value. The soil-water suspension was then subjected to thorough mixing to ensure uniformity.

Table 1 : Details of the Soils Studied

Soil	G_s	w_L (%)	w_P (%)	w_S (%)	Principal Clay Mineral
Red earth	2.64	38.6	18.0	14.7	Kaolinite
Kaolinite	2.60	48.0	35.6	35.9	Kaolinite
Brown soil	2.66	64.6	26.6	14.5	Montmorillonite

Experiments

Two series of experiments were run:

Series 1 : The initial height of the soil-water suspension was maintained constant at different known values. In each case, the initial dry density of the soil suspension was varied over a wide range of 0.245 kN/m^3 to 8.338 kN/m^3. Thus, the effective stress at the bottom of the suspension varied over a wide range of 0.05 kPa to 1.75 kPa, for each initial height of the soil-water suspension. This resulted in a wide variation in the initial water content of the suspension, between a value as high as about 4000% and a value as low as about 100%.

Series 2 : The initial water content of the suspension was maintained constant at different values. In each case, by varying the initial height of the suspension, the effective stress at the bottom of the suspension was varied over a range of 0.2 kPa to 1.0 kPa.

Some typical tests were also conducted with thick slurries whose initial water contents were as close to the liquid limits of the soils as practicable.

As a part of the above mentioned sedimentation experiments, the grain size distributions of the sediments formed with depth were also studied through wet sieving and conventional hydrometer analysis.

Experimental Results

Settling Behaviour

By varying the initial water content of the soil-water suspension with a constant initial height, different modes of settling behaviour of the suspension have been observed. Some of their important features observed during the present study are indicated below;

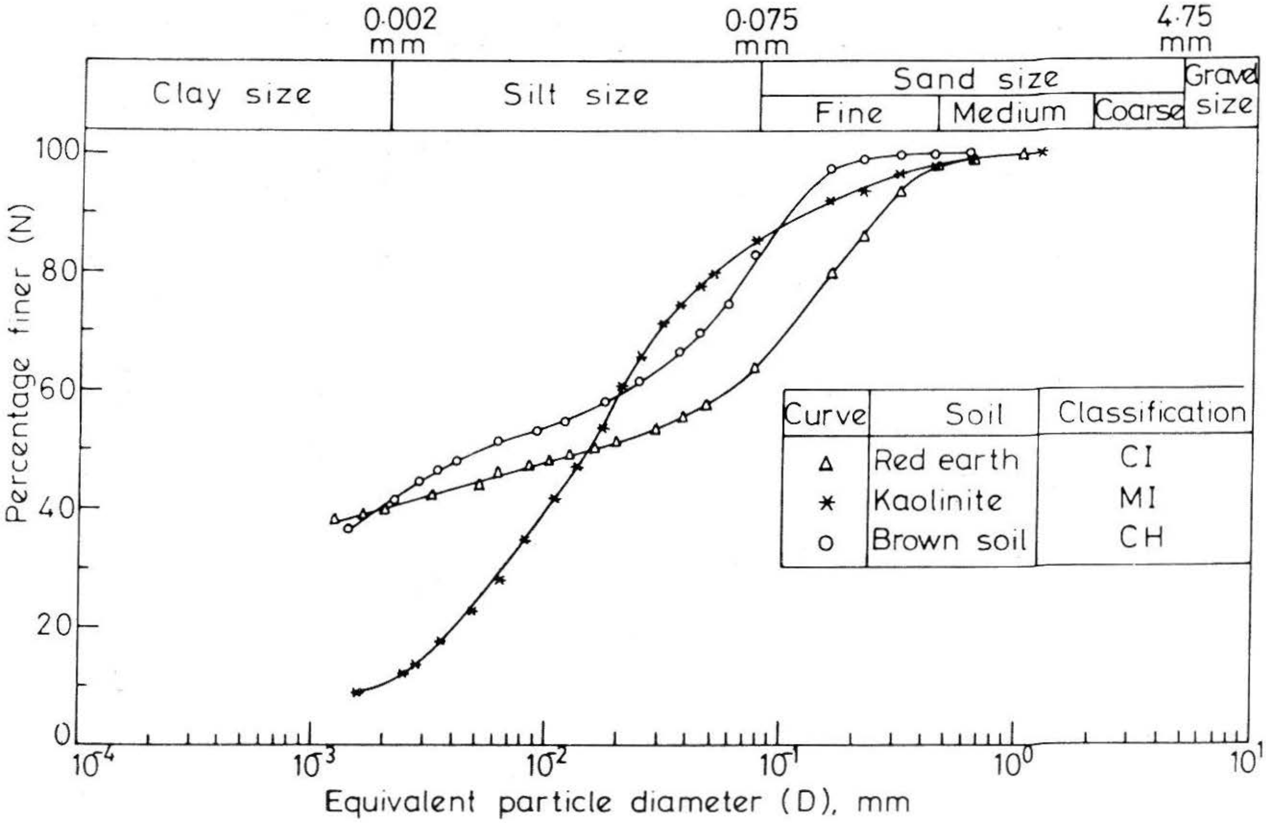

FIGURE 1 : **Grain Size Distribution Curves for the Soils Studied.**

i) At very high water contents, the soil particles fall freely to build-up the sediment at the bottom of the jar, coarser particles occupying the base portion of the sediment followed by finer particles towards the top of the sediment. This type of settling was called as dispersed free settling of soil particles by Imai (1980).

ii) When the water content is less than a particular value, which depends upon the type of soil, one can observe the building up of the sediment at the bottom of the jar due to the settling of particles/flocs, with a cloudy suspension above. After some time, the top surface of the upmoving bottom sediment vanishes. After some more time, a layer of flocs settling enmass appears at some height, with a cloudy suspension of relatively low intensity above it which diminishes with time quickly. This type of settling is the flocculated free settling of soil particles defined by Imai (1980).

iii) With a further reduction in the initial water content, one can observe the simultaneous movement of two layers – one at the bottom, moving upwards and the other at the top, moving downwards. The top layer has a free surface with the water above. This type of settling is referred to as the zone settling by Imai (1980).

iv) With a very low initial water content, the soil layer starts moving down enmass with a very clear interface between it and the water above with no separate layer formation at the bottom. This mode of settling behaviour corresponds to the consolidation settling as per Imai (1980).

Figures 2(a) and (b) show the settling behaviour of kaolinite and red earth respectively. Kaolinite exhibited dispersed free settling upto initial water content range of about 1295% to 960% (i.e. 27 w_L to 20 w_L, where w_L is the liquid limit water content), below which flocculated free settling took place upto about w_i = 360% (i.e. 7.5 w_L). The top surface of the sediment was not visible at all during that stage of flocculated free settling indicated by dotted curves. When w_i was reduced to about 360%, zone settling occurred and below w_i = 145% (i.e. about 3 w_L) was the region of consolidation settling.

Red earth, being a kaolinitic soil, exhibited similar settling characteristics as that of kaolinite. However, due to its lower liquid limit, the range of initial water content between the dispersed free settling and flocculated free settling was lower than that of kaolinite (i.e., w_i = 960% to 630% which corresponds to about 24.9 w_L to 16.3 w_L).

Figure 2(c) represents the settling behaviour of brown soil which contains the montmorillonite as the principal clay mineral, which is a typical expanding lattice type of clay mineral. The effect of clay mineral on the

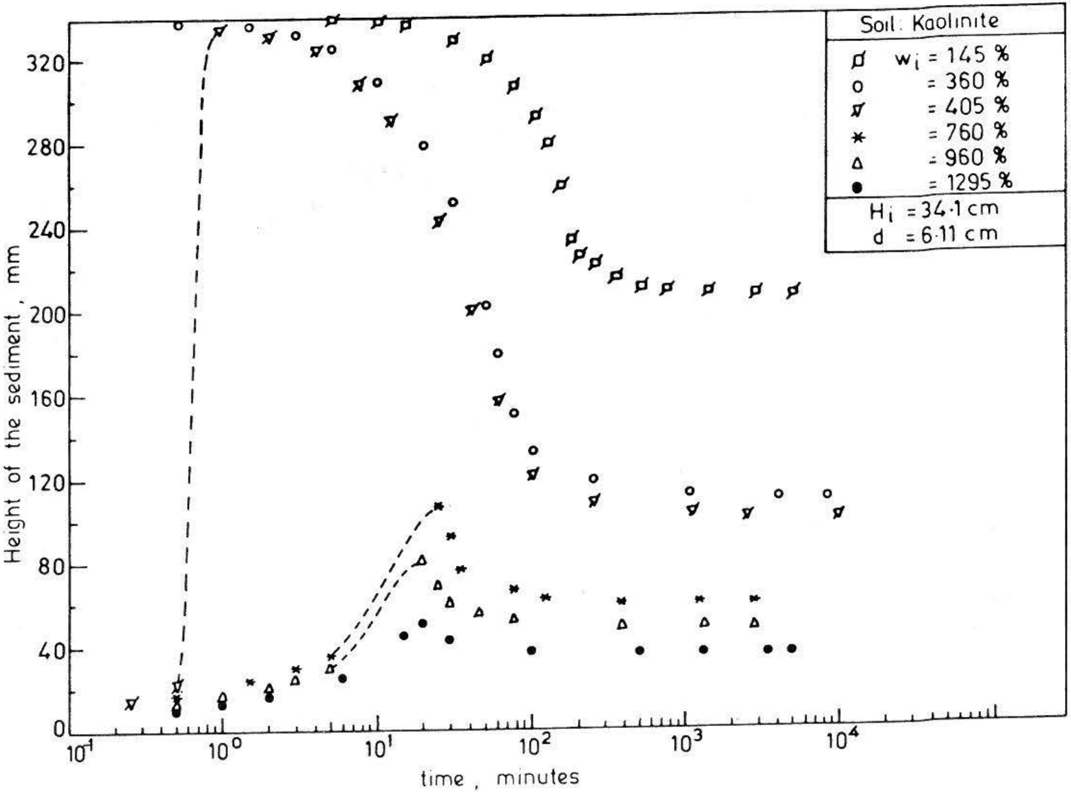

FIGURE 2(a) : Settling Behaviour of Kaolinite

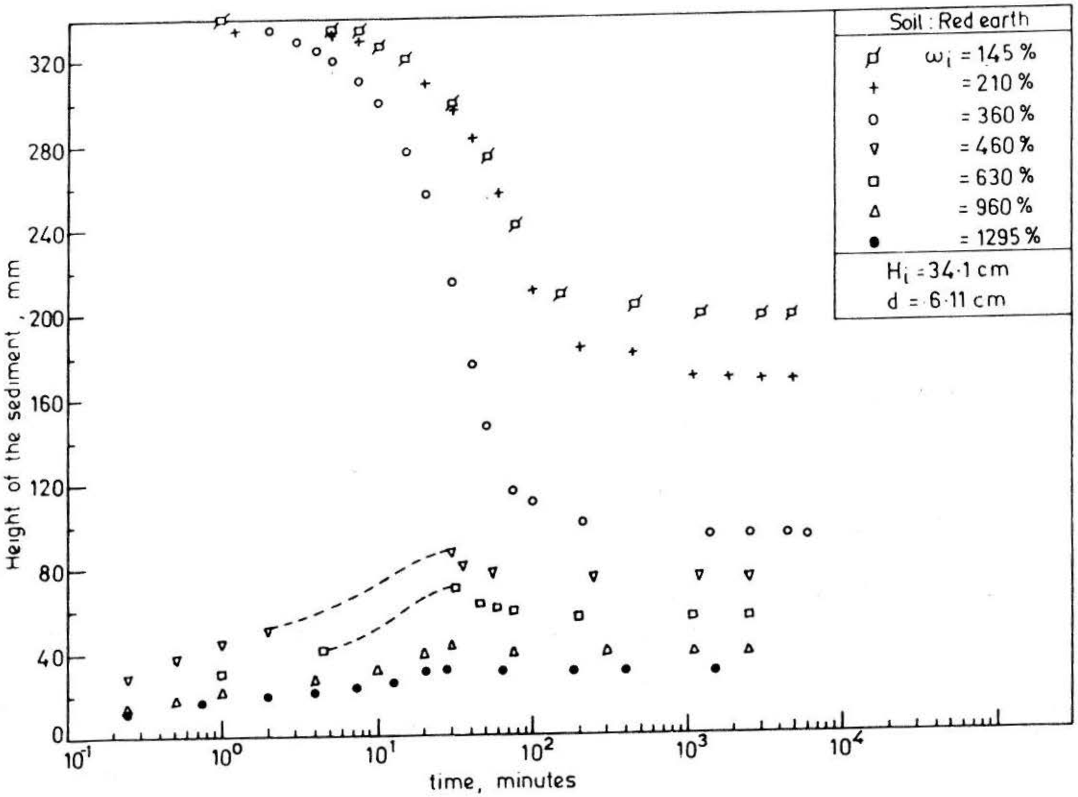

FIGURE 2(b) : Settling Behaviour of Red Earth

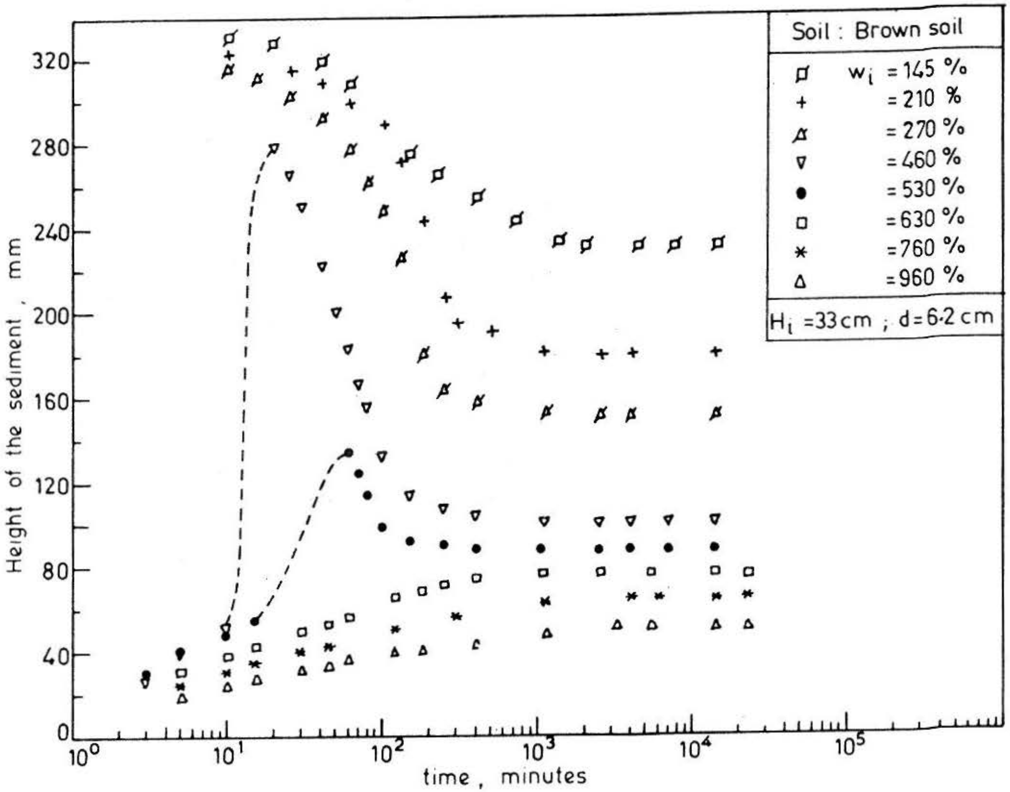

FIGURE 2(c) : Settling Behaviour of Brown Soil

Table 2 : Range of Water Content Over Which Change of Type of Settling Takes Place

Change of Settling Type	Kaolinite	Red earth	Brown soil
Dispersed free settling to Flocculated free settling	1295% to 960%	960% to 630%	630% to 530%
Flocculated free settling to Zone settling	405% to 360%	460% to 360%	295% to 270%
Zone settling to Consolidation settling	360% to 145%	360% to 210%	210% to 145%

settling behaviour of the soil is clearly seen by comparing Figs. 2(a) and (b) with Fig. 2(c). Brown soil showed dispersed free settling even at an initial water content as low as 630% (i.e. about 9.75 w_L), compared with w_i = 1295% (i.e. about 27 w_L) for kaolinite and w_i = 960% (i.e. 25 w_L) for red earth. Table 2 compares the ranges of water contents over which the three soils have exhibited the transition from one type of settling to the next type.

Kaolinitic soils are known to have flocculated fabric and montmorillonitic soils, dispersed fabric. With the result, flocculation took place at much higher initial water content in kaolinitic soils whereas initial water content had to be reduced for the flocculation to occur in the case of brown soil.

Figure 3 shows the settling behaviour of very dilute soil-water suspensions of the three soils. The interesting feature of kaolinitic soils is that even at very high w_i, their sediments exhibit self weight consolidation, unlike brown soil which shows the building up of the sediment till a constant level is maintained with a little self weight consolidation. Even at w_i as low as 630% (i.e. 9.75 w_L), brown soil does not show any visible self weight consolidation (Fig. 2c).

It is well known that the compressibility behaviour of the montmorillonitic soils is governed by the diffuse double layer repulsion (Sridharan and Rao, 1973). This repulsive force is responsible for the brown soil sediment not to undergo any compression and to resist the self weight of the sediment even at relatively low initial water content.

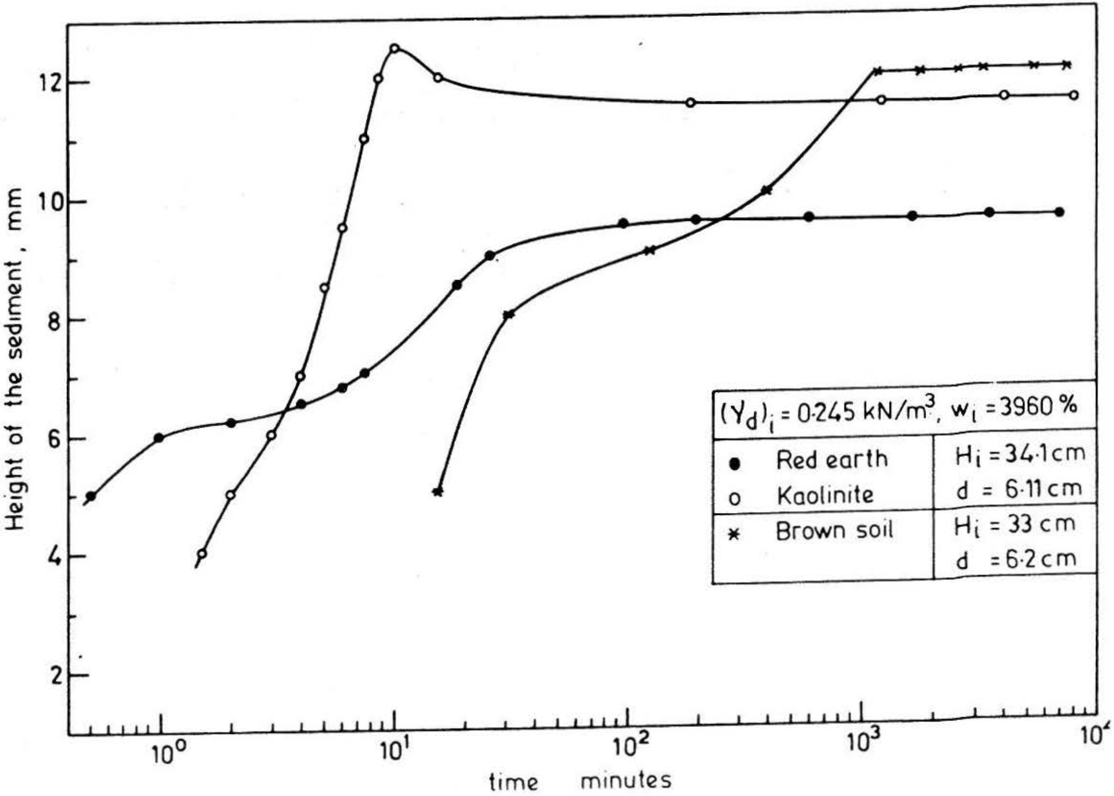

FIGURE 3 : Dispersed Free Settling of Soils.

Further, it is interesting to note that all four types of settling defined by Imai (1980) have been observed in fresh water environment itself, depending upon the initial water content of the soil-water suspension.

Types of Settling

One of the important observation made during the above sedimentation experiments was about the grain size sorting. Irrespective of the type of settling – dispersed free or flocculated free or zone settling, it was possible to observe sorting of the soil particles during their settling. At very high initial water contents, particularly during dispersed free settling, separation of coarser and finer particles was observed to be total with a very clear line of separation between the bottom layer of coarser particles and the top layer of finer particles which had distinctly different colours. With the reduction in the initial water content of the suspension, the degree of sorting was observed to reduce, and the interference among the particles/flocs dominated. When the initial water content of the suspension was reduced to that corresponding to consolidation settling, no grain size sorting took place and the soil sediment formed was uniform over its entire thickness.

This observation was further supported by the grain size analysis. Keeping the effective stress at the bottom of the suspension constant, sediments of kaolinite, red earth and brown soil were obtained with extreme initial water contents possible. After the equilibrium was reached, samples were extracted from different depths of the sediments and wet sieve analysis and conventional hydrometer analysis were conducted.

Figures 4(a) to (c) illustrate the grain size distribution curves for kaolinite, brown soil and red earth at w_i = 250% respectively. These curves indicate well sorted sediments with finest particles at the top layer gradually changing to layer of coarsest particles at the bottom.

Figures 4(a) and (b) also include grain size distribution curves for kaolinite and brown soil respectively at w_i = 100% and Fig. 4(d), for red earth at w_i = 50%. They indicate the sediments to be uniform over the entire depth of the sediment, suggesting maximum interference among the particles.

With the decrease in the initial water content from that required for well sorted sediments, particle entanglement starts increasing gradually which finally becomes maximum resulting in uniform sediment at some lower initial water content, depending upon the soil type. Fig. 4(d) represents the grain size distribution curves for red earth (w_i = 75%) during such a transition.

These observations have lead to classify the settling of soils in

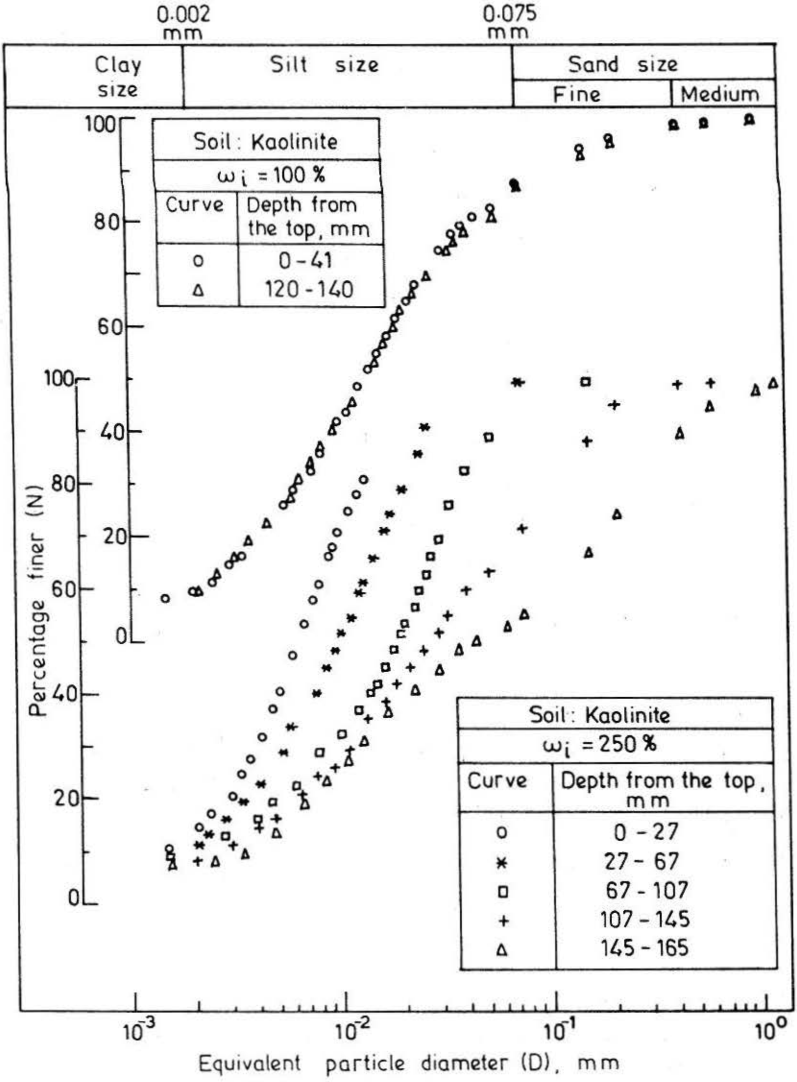

FIGURE 4(a) : Variation of Particle Size Distribution with Depth for Kaolinite Sediment.

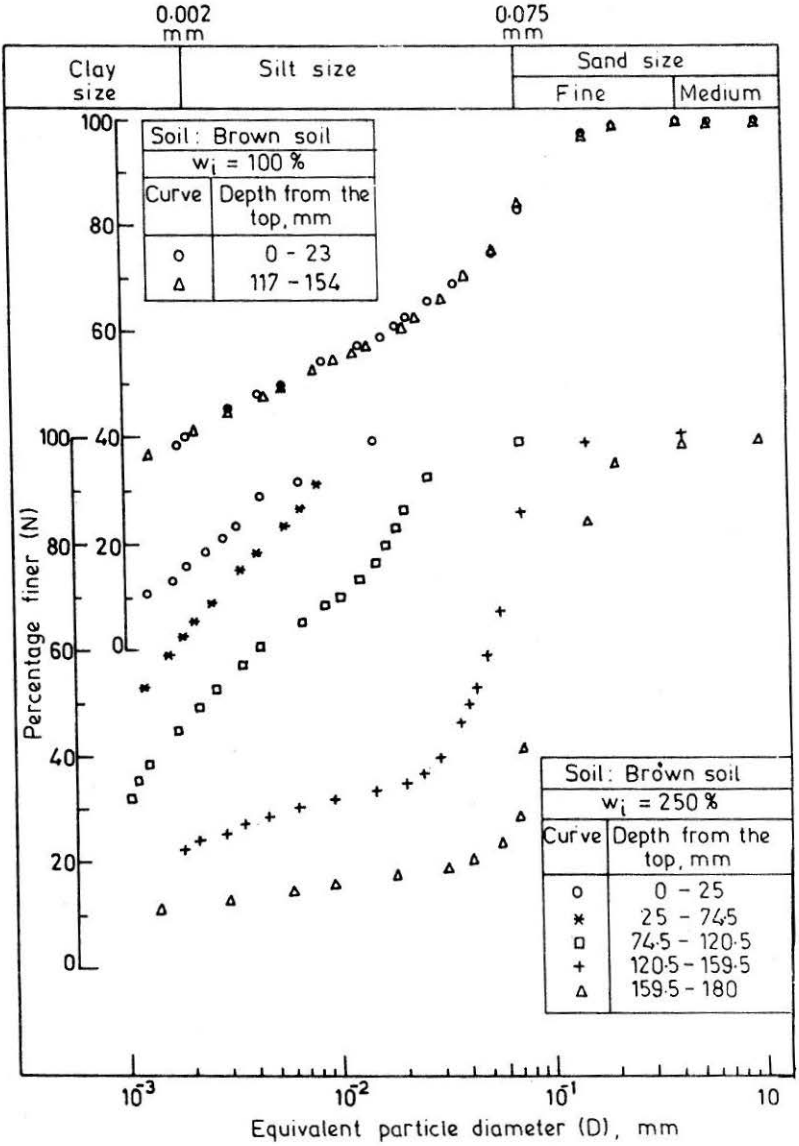

FIGURE 4(b) : Variation of Particle Size Distribution with Depth for Brown Soil Sediment.

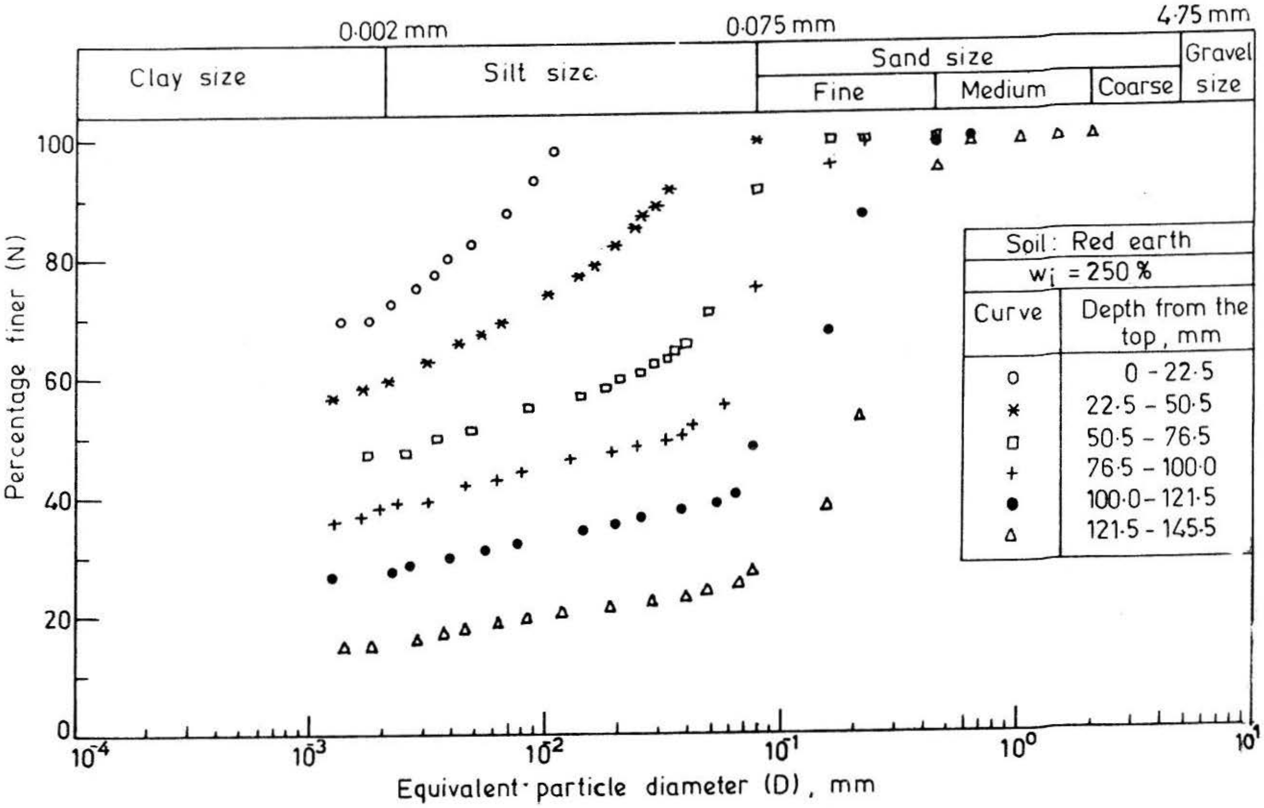

FIGURE 4(c) : Variation of Particle Size Distribution with Depth for Red Earth Sediment.

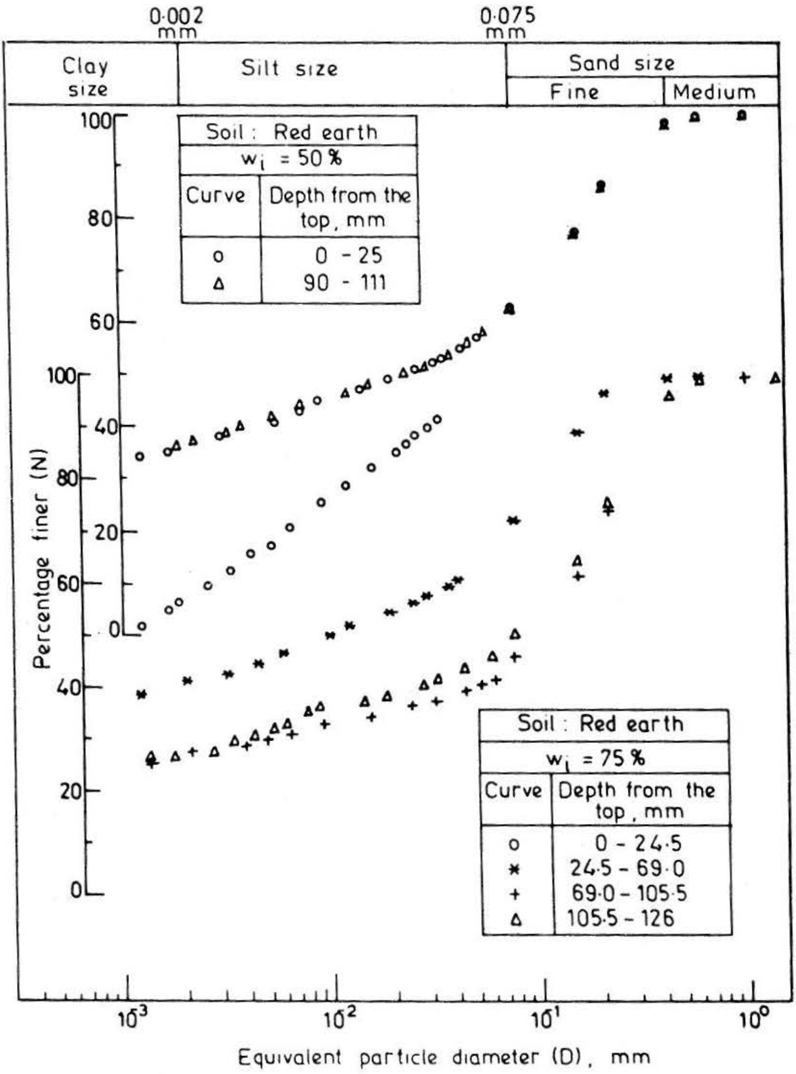

FIGURE 4(d) : Variation of Particle Size Distribution with Depth for Red Earth Sediment.

suspension into three types, based on the grain size distribution of the sediments formed which is a function of the initial water content of the soil-water suspension;

i) Homogeneous or uniform settling — This takes place below a limiting water content which varies with the soil type. This results in a sediment which has identical particle size distribution over its entire thickness.

ii) Segregational settling — This takes place at high water contents for all soils. This results in a sediment which has different well sorted layers, with coarsest particles at the bottom most and finest particles at the top most layers. During this kind of settling, mutual interference among the settling particles well be the least or zero.

iii) Transitional settling — When the initial water content is slightly more than that required for homogeneous settling, this type of settling occurs. Here, the sediment formed will be neither well sorted nor uniform. The maximum initial water content at which homogeneous settling takes place varies with the soil type. This maximum initial water content has been observed to be about 2.1 w_L for kaolinite, 1.55 w_L for brown soil and 1.3 w_L for red earth.

It is worth mentioning here that the homogeneous settling type of present classification refers to the consolidation settling (Imai, 1980); the transitional settling refers to a part of zone settling (Imai, 1980) and the remaining part of the zone settling as well as dispersed free and flocculated free settling (Imai, 1980) are covered under segregational settling.

Unlike the classification of the settling types based on "the flocculation appearance" (Imai, 1980), the proposed classification has practical relevance with respect to the nature of the sediments formed due to settling.

The nature of the sediments formed out of running waters (i.e., alluvial deposits) is a function of flow velocity and sediments load in the flow. However, when moving soil-water suspension is brought to rest, as in the case of discharge into a stilling basin or lakes, depending upon the initial water content of the suspension, any of the three types of settling may occur. This may be the reason for the formation of soft, stratified sediments (even of the same soil type), having different structures like dense or loose, with varying degrees of softness with depth. These structures in turn govern the compressibility, strength and permeability behaviours of the sediments formed. Further, the proposed classification of the settling types can be considered to have significance in judging and if necessary, in controlling the nature of the manmade sediments as in reclamation projects, mine tailings, silt disposal after dredging, etc.

Effect of Effective Stress

The soil-water suspensions with different initial water contents, having the same effective stress at the bottom of the suspension, $(\gamma' H)_i$ and zero effective stress at the top can be had by setting the initial height of the suspension at different values. The results of the experiments of Series 1 have been used to plot, e_f vs. $(\gamma' H)_i$ curves where e_f is the final void ratio of the sediments formed (Fig. 5). From this figure, it can be seen that for the same effective stress at the bottom of the suspension, e_f varies appreciably (i.e. along any vertical line parallel to y-axis). In addition, different effective stresses obtained by varying the initial dry density of the soil-water suspension results in same e_f value. (i.e. along any horizontal line parallel to x-axis). These indicate that the effective stress (by conventional definition) does not control the volume changes during settling stage. Sridharan and Rao (1973) while discussing the effective stress concept brought out that mineral-mineral contact is essential for the manifestation of effective stress. Thus in these experiments while settling takes place, there is lack of continuous effective particle-particle contact which is required for the effective stress to mobilise or manifest itself. Hence, the final void ratio does not bear any relationship with the effective stress. Further, for the same effective stress value at the bottom of the suspension, the soil suspension can exhibit all three types of settling defined in this article, depending upon the initial water content of the soil-water suspension.

Effect of Initial Water Content

As long as the initial water content of the suspension is maintained constant, irrespective of the cross sectional area of the soil – water suspension, identical settling behaviour can be observed for a given value of effective stress at the bottom of the suspension. This finding has been illustrated through Fig. 6 which shows the variation of water content of the settling soil column with time, for two known values of effective stresses with three different cross sectional areas of the suspension, keeping the initial water content the same.

Each of the Figs. 7(a) and (b) shows the variation of water content of two soil-water suspensions having w_i = 250% and w_i = 150% respectively with three different values of effective stresses, for kaolinite. In spite of exhibiting different rates of settling in the initial stages, the curves of constant w_i meet at about the same point, irrespective of effective stress values. However, the sediment having higher effective stress value equilibrates at relatively lower final water content with time. This indicates the onset of self weight consolidation during settling stage itself which increases with an increase in the value of effective stress. Similar trend has been observed for red earth and brown soil also (Figs. 8 and 9).

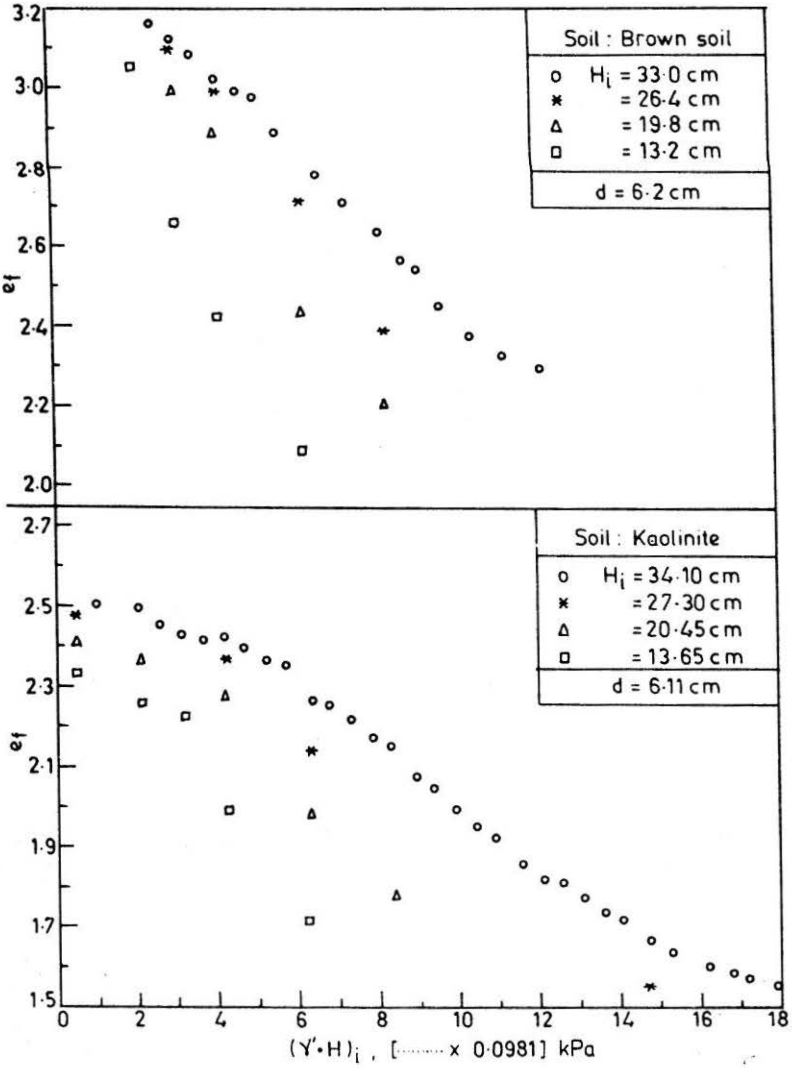

FIGURE 5 : e_f vs. $(\gamma' H)_i$ Curves.

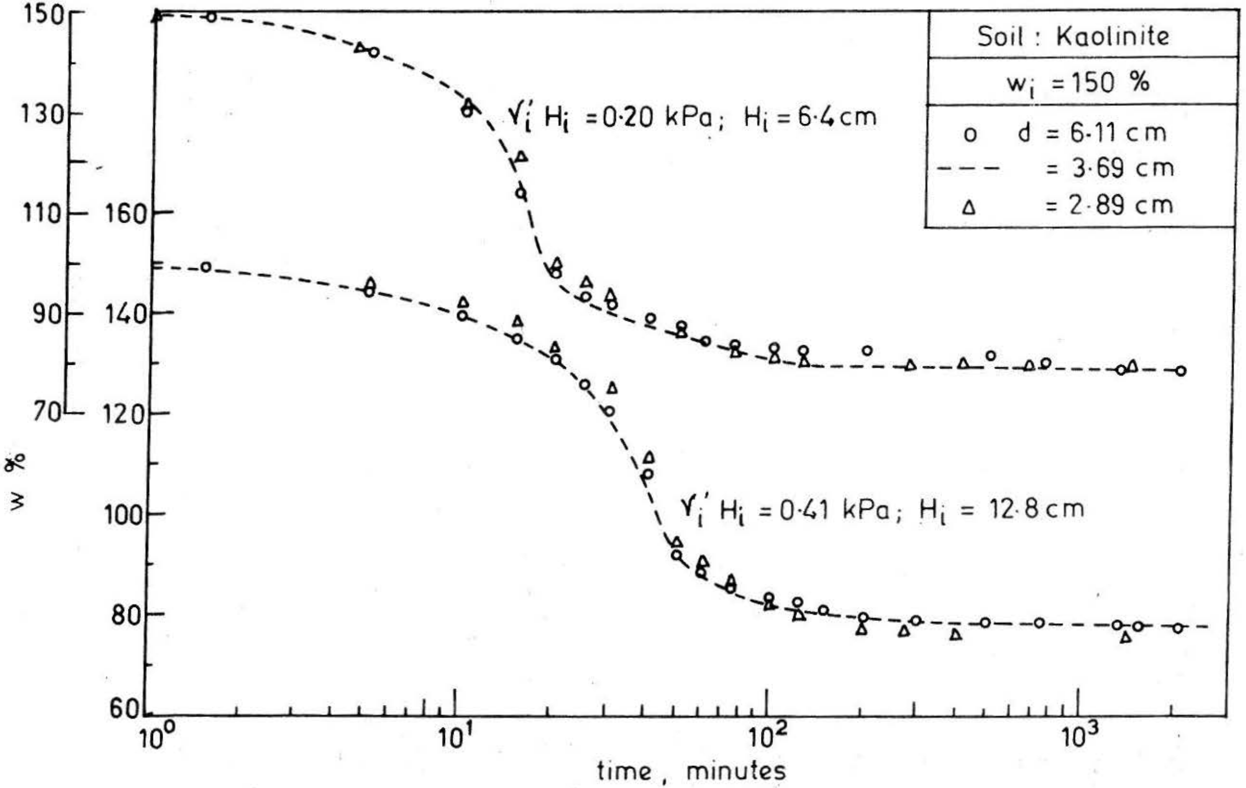

FIGURE 6 : Effect of $(\gamma' H)_i$ on Settling Behaviour of Soils (i.e. with Different Diameter Jars).

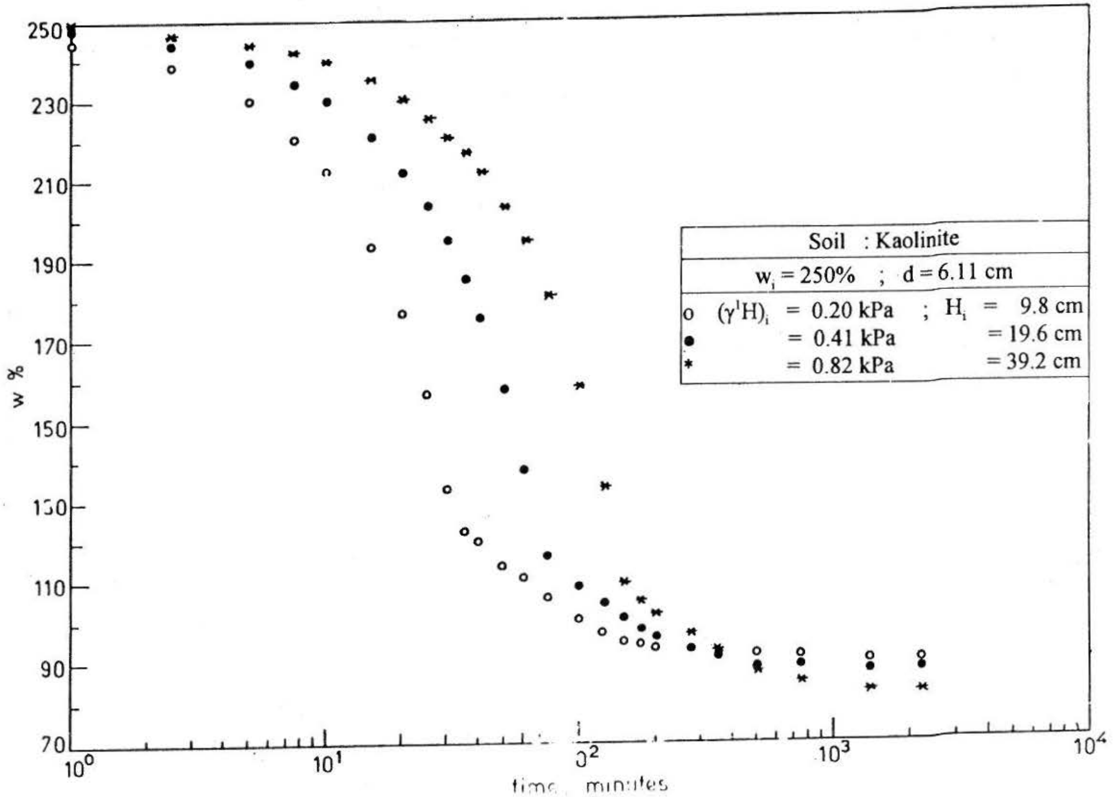

FIGURE 7(a) : **Variation of Water Content of the Sediment During Settling for Kaolinite.**

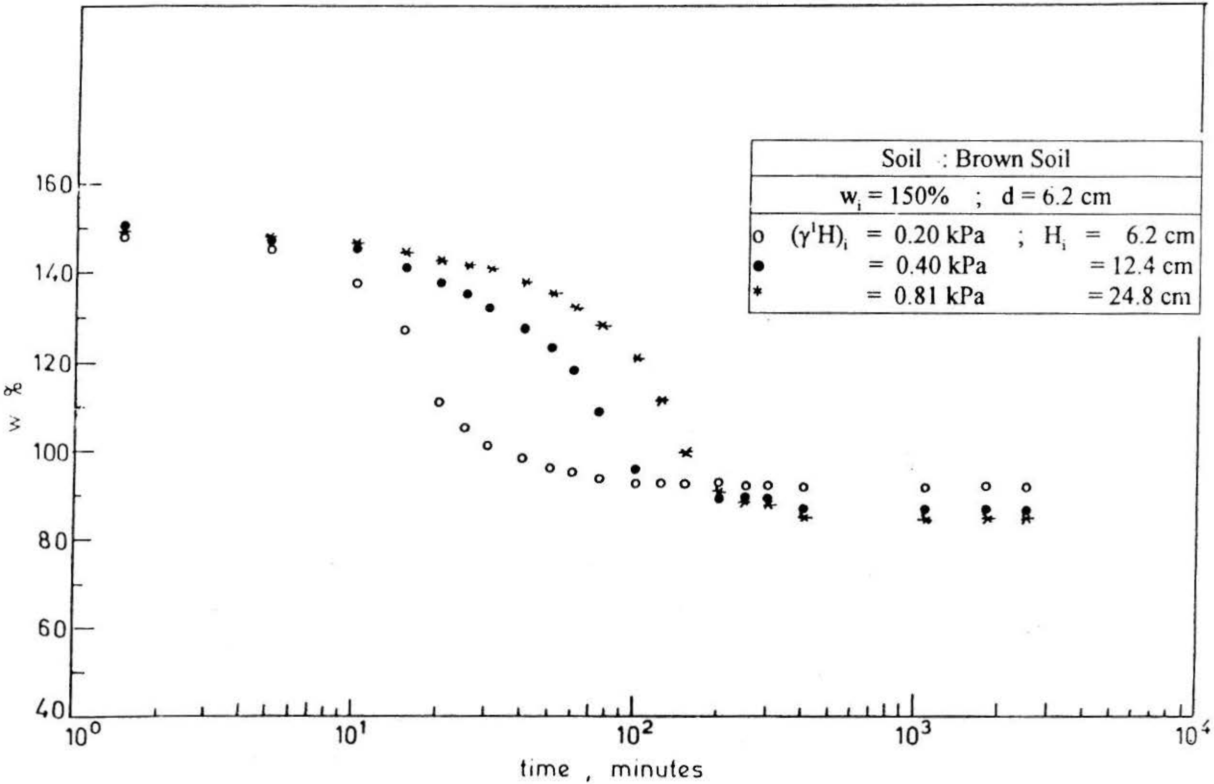

FIGURE 7(b) : Variation of Water Content of the Sediment During Settling for Kaolinite.

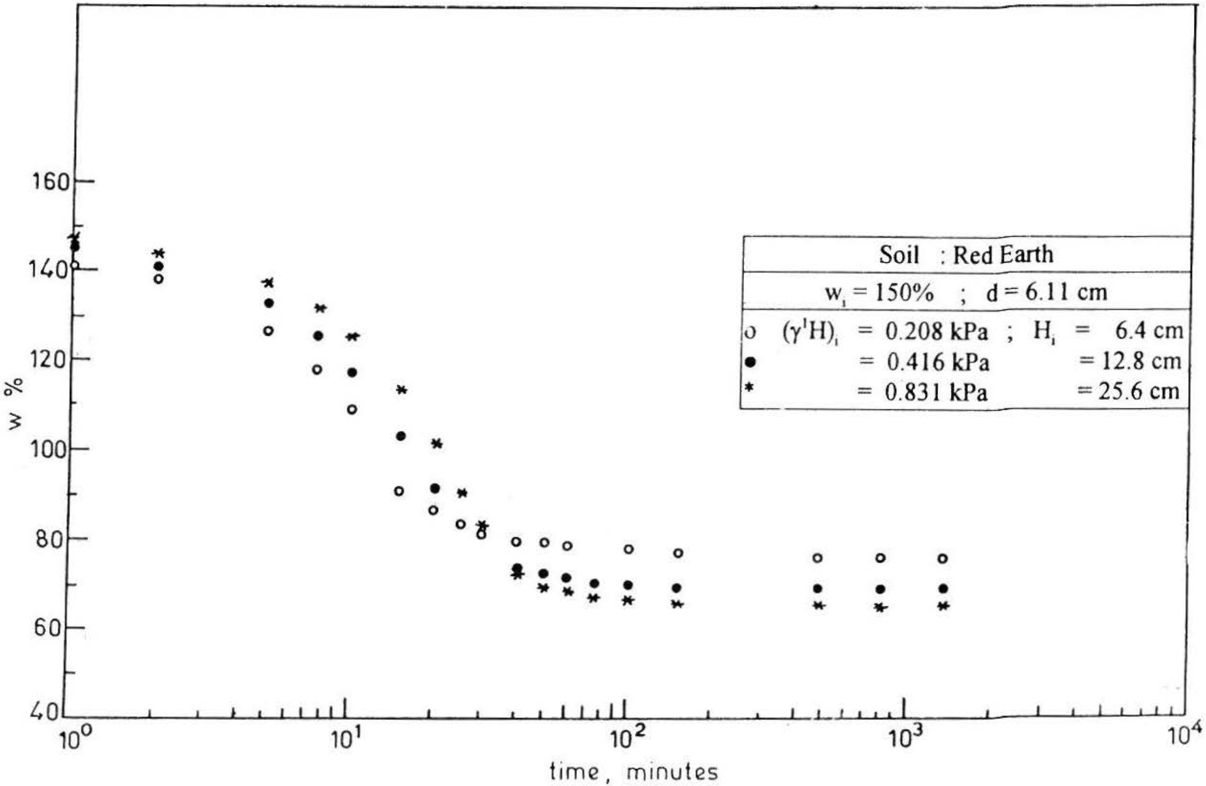

FIGURE 8 : **Variation of Water Content of the Sediment During Settling for Red Earth.**

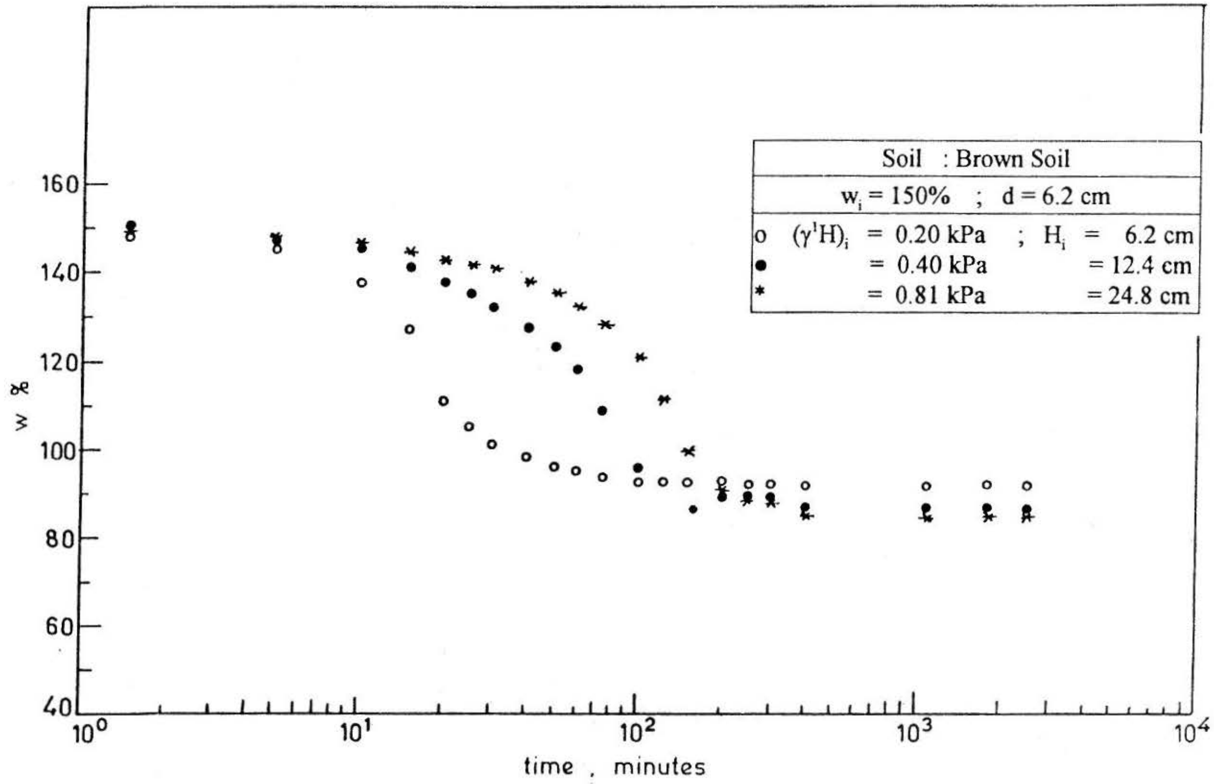

FIGURE 9 : Variation of Water Content of the Sediment During Settling for Brown Soil.

The presence of mutual interference among the particles/flocs of different sizes during settling when the initial water content of the suspension approaches that which results in homogeneous settling has already been illustrated through grain size distribution curves (Fig. 4d). This observation is further supported by Fig. 10, which is different from Figs. 7 to 9. Hence, one can judge whether the settling is of segregational type or not by observing the w% vs. log t curves. However, differentiation between transitional settling and homogeneous settling just by the observation of w% vs. log t curves appears to be not possible.

Figure 11 shows w_f vs. $\log_{10} w_i$ relationship for kaolinite, encompassing all the results of the two series of experiments conducted, where w_f is the final water content of the sediment formed. The w_f vs. $\log_{10} w_i$ curve corresponding to experiments of Series 1 is observed to represent an unique relationship for a given soil irrespective of initial height of soil-water suspension which varied from 13.65 cm to 34.1 cm as shown in Fig. 11.

The results from the experiments of Series 2, when represented in the above form, is observed to generate a family of curves each corresponding to a particular value of effective stress at the bottom of the suspension, although initial height of the soil-water suspension varies along each curve. However, the difference among these curves appears to be small. These curves appear to converge with the decrease in the initial water content (Fig. 11). The divergence of these curves with the increase in the initial water content can be attributed to the self weight consolidation that takes place during the settling stage itself. This point has been further supported by the observation that top most curve represents a sediment of lower effective stress value whereas a sediment of higher effective stress value is represented by the bottom most curve. Even when the results from the experiments of both the series are put together, they are observed to lie within a narrow range (Fig. 11). Thus, it may be concluded that, from engineering point of view, the relationship between w_i and w_f can be treated as unique.

Figures 12 and 13 represent w_f vs. $\log_{10} w_i$ relationships for red earth and brown soil respectively. They support the observations made with the behaviour of kaolinite. At higher initial water contents, the divergence of the curves of different effective stress values has been observed to be more for soils of lower liquid limit. Montmorillonitic soils which can resist the self weight to some extent through the double layer repulsion, show relatively less divergence.

Conclusions

From the study of settling behaviour of soils in the fresh water environment, under different initial conditions, following observations are made and conclusions can be drawn;

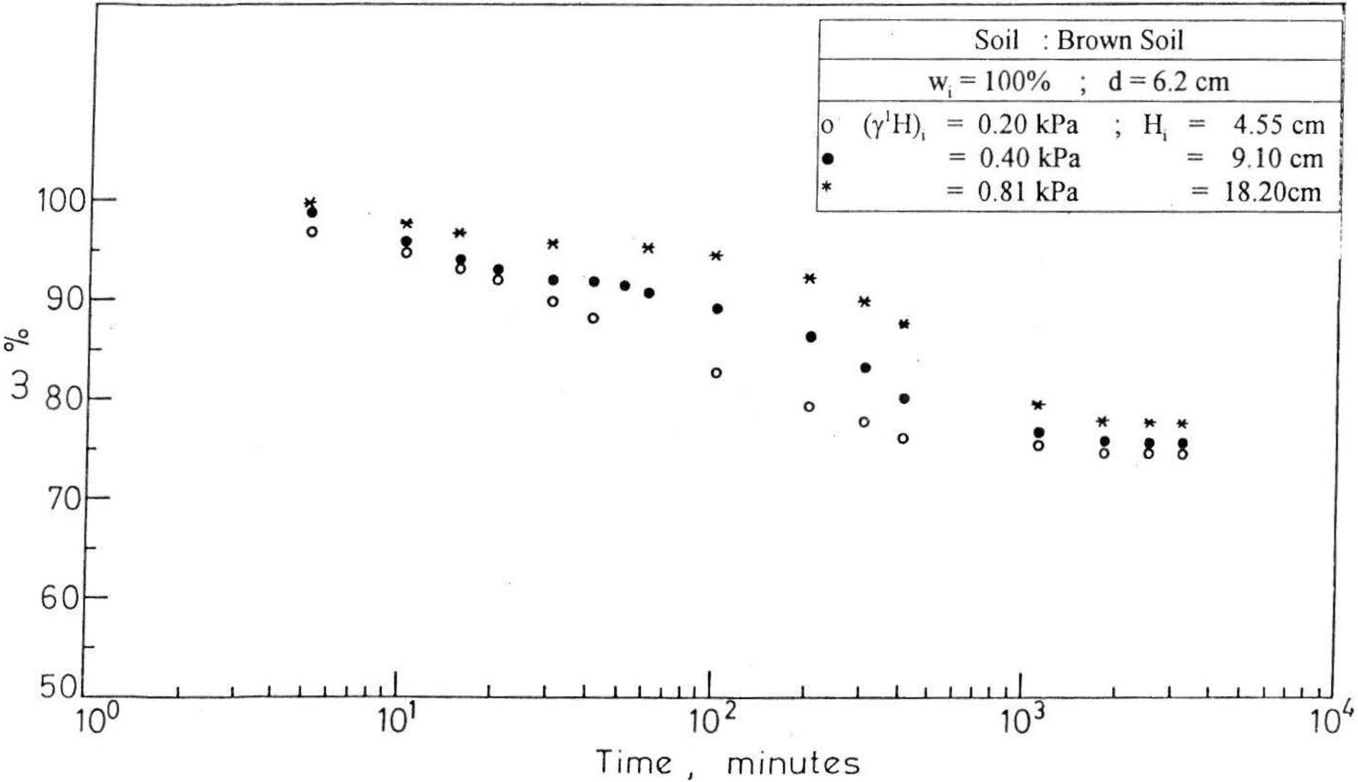

FIGURE 10 : Time-water content curves showing the particle interference during settling.

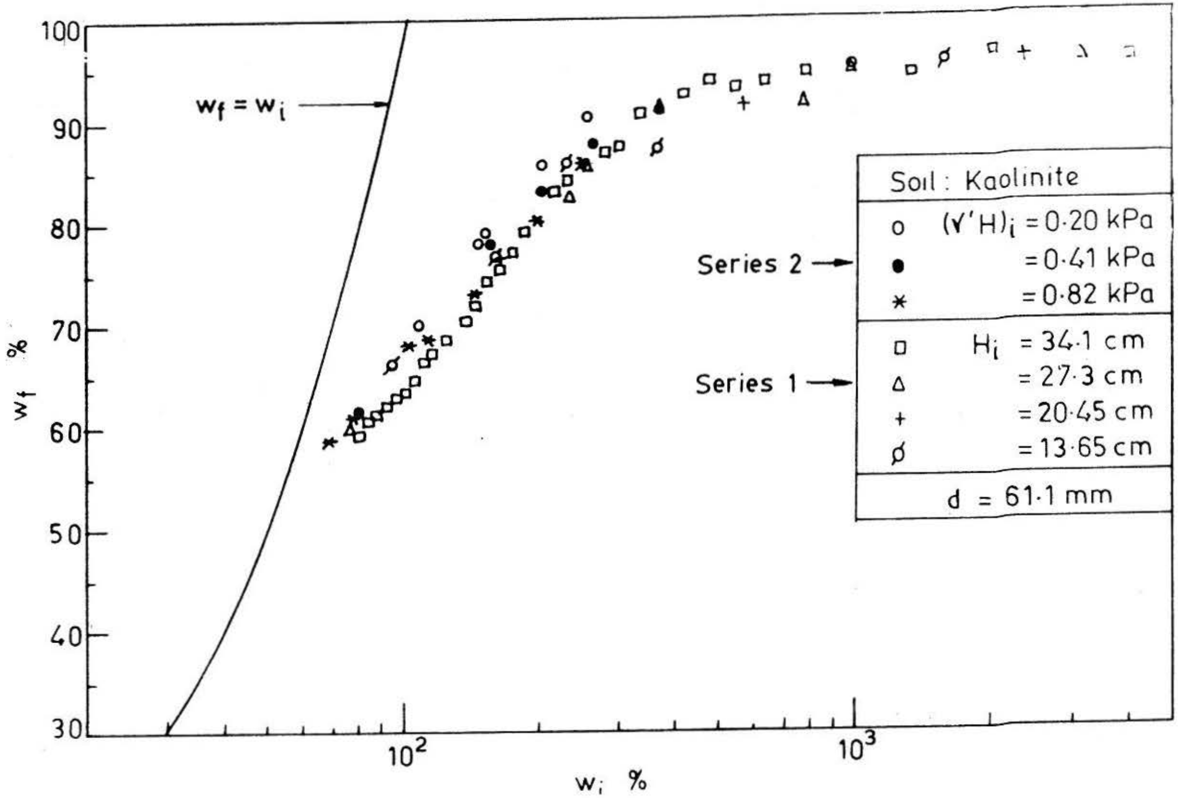

FIGURE 11 : w_f vs. $\log_{10} w_i$ Relationship for Kaolinite.

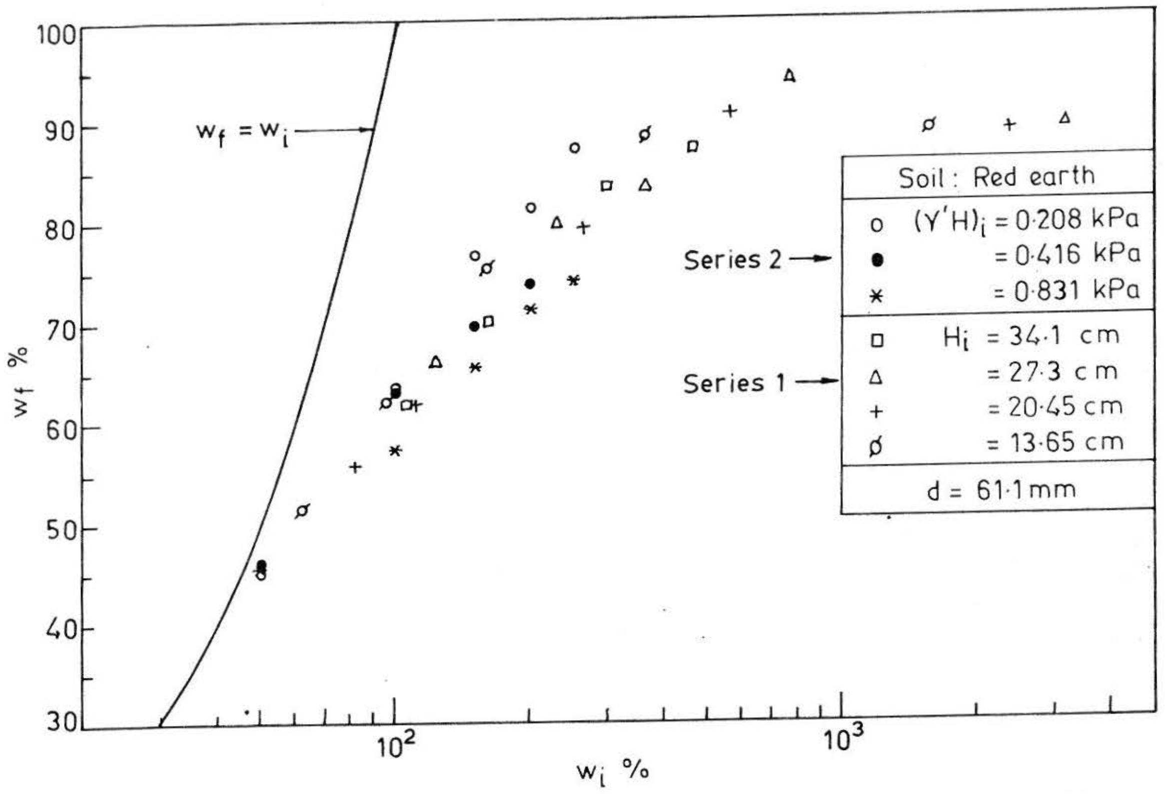

FIGURE 12 : w_f vs. $\log_{10} w_i$ Relationship for Red Earth.

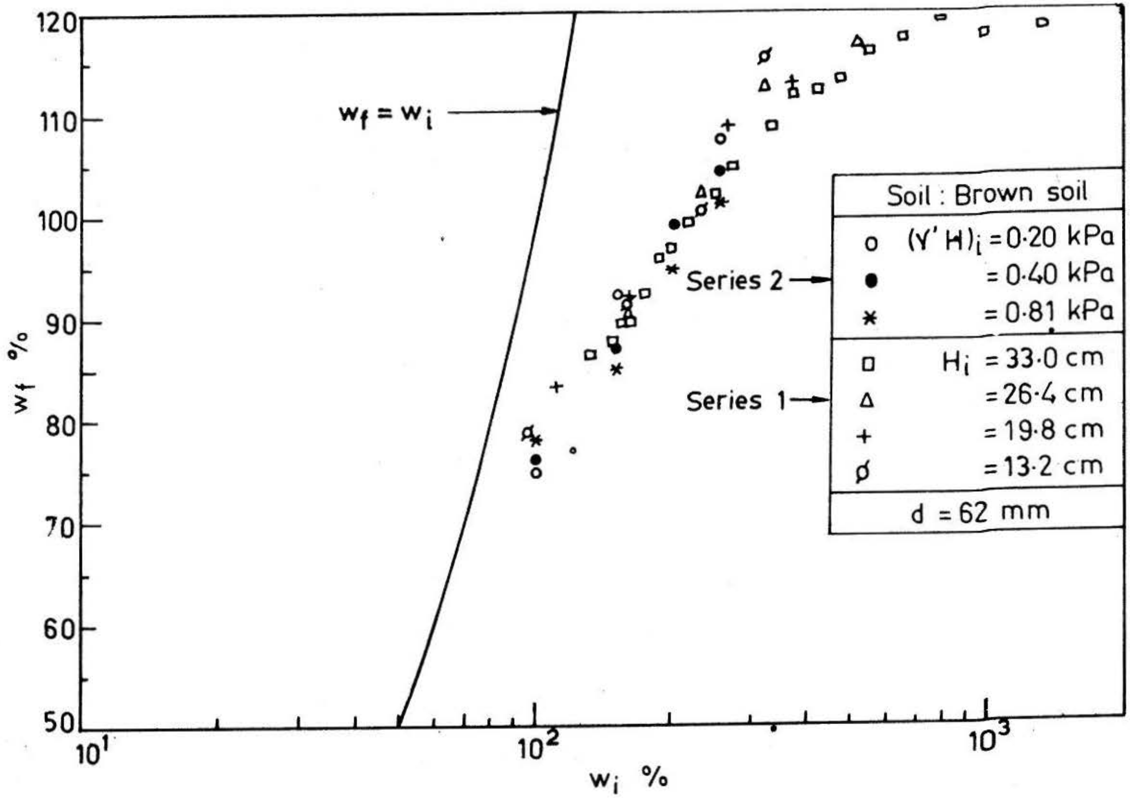

FIGURE 13 : w_f vs. $\log_{10} w_i$ Relationship for Brown Soil.

1) Settling behaviour of soil-water suspension mainly depends upon the clay mineral constituent of the soil and initial water content of the suspension.

2) Even at very high initial water contents of the soil-water suspension which results in the free settling of soil particles (particulate settling), consolidation due to self weight takes place during the formation of the sediment. This appears to be more with a decrease in the liquid limit of the soil, with kaolinite as the principal clay mineral. Montmorillonitic soils appear to resist the self weight consolidation during particulate settling which can be attributed to the double layer repulsion between the clay particles.

3) The settling behaviour of the soil-water suspension is not governed by effective stress. This is attributed to the lack of contact among particles. Soil suspensions with the same effective stress at the bottom of the suspensions, but with different initial water contents (w_i) behave differently, resulting in different final equilibrium water contents (w_f).

4) Final water content, w_f vs. of initial water content, w_i relationship for a sediment of soil formed by the settling from suspension is almost unique, particularly at lower initial water contents. The deviations at higher initial water contents, if any, may be attributed to the self weight consolidation which takes place during the settling stage itself.

5) Depending upon the initial water content of the soil – water suspension, the soil settling can be classified into three groups:

   - Homogeneous or uniform settling which results in uniform sediment which is characterised essentially by the identical particle size distribution over the entire thickness of the sediment, devoid of any segregation.

   - Segregational settling which is characterised by the grain size sorting during settling to a marked extent.

   - Transitional settling wherein neither the sediment formed is homogenous nor the segregation is appreciable.

   The interference among the settling particles in the case of segregational settling is the least or zero. On the other hand, it is maximum in the case of homogeneous settling.

6) The nature of the sediment formed in practice depends upon the type of settling the soil suspension undergoes after deposition, which further depends upon primarily the initial water content of the soil suspension.

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Notations

A = Cross sectional area of the soil-water suspension.

e_f = Final void ratio of the sediment formed.

G_s = Specific gravity of soil particles

H_f = Final height of the sediment formed

H_i = Initial height of the soil-water suspension

t = Time

W_d = Dry weight of the soil present in the soil-water suspension

w_f = Final water content of the sediment formed

w_i = Initial water content of the soil-water suspension

w_L = Liquid limit

w_p = Plastic limit

w_s = Shrinkage limit

γ'_f = Final submerged density of the sediment formed

γ'_i = Initial submerged density of the soil-water suspension.