Physico-Chemical Mechanisms Governing the Plasticity Behaviour of Soils

by

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Introduction

Despite their widespread use in soil mechanics for identifying and classifying soils the plasticity limits (particularly the liquid limit, plastic limit and the shrinkage limit) have received comparatively little attention from research workers. Although the Atterberg limits were derived originally for purposes of soil classification, in the recent past, various attempts have been made to correlate them with soil properties/parameters like surface area, cation-exchange capacity, swelling behaviour, California Bearing Ratio, compressibility, shear strength, compaction etc., and to use these correlations for purposes of checking new data or to predict soil behaviour for design work. But it should be remembered that the determination of Atterberg limits is by strictly empirical testing procedures. Hence it should be recognised that the correlations mentioned above become more useful only when the mechanisms controlling these tests and properties of the soil that control these behaviour are properly understood. In an attempt towards this, Sridharan and Venkatappa Rao (1971, 1975) have investigated the mechanisms governing the shrinkage and liquid limit behaviour of clays and brought out the role of the modified effective stress concept. These studies were mainly concerned with the behaviour of kaolinite and montmorillonite clays with the variation in interparticle electrical forces brought about by changing the nature of the pore fluid using different organic solvents. In nature, the variation in attractive and repulsive forces for soils can be brought about by stress history which changes the particle orientation and effective distance between particles. Changes in salt concentration, changes *in electrolyte fluid,* chemical changes comprising weathering and other similar actions may bring about significant changes in the electrical attractive and repulsive forces (Kenney *et al* 1967). Hence, the aim of the present study is to investigate the effect of change in electrical forces brought about by using different additives on the natural soils (alluvial silt and black cotton soil). Thus it has been attempted to bring out the physico-chemical mechanisms governing the shrinkage, liquid and plastic limits for a more natural system and verify the applicability of those proposed earlier. The chemical additives chosen are lime and the chlorides of calcium and sodium

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and the effect of addition of fly ash has also been studied. Thus in essence the behaviour is to be studied in detail for lime-fly ash systems (which are commonly used in stabilization work) but to bring out the overall mechanisms more thoroughly the sodium and calcium salts, have been made use of.

Literature Review

It is well known that clay particles carry overall negative charges and the surface area to mass ratio of most clay particles is sufficiently high. Because of this, the forces at particle surfaces strongly influence the behaviour of particles and their aggregations. The importance of interparticle attractive and repulsive forces in influencing the engineering behaviour of clays has been well established in literature (Rosenquist, 1955; Lambe, 1960).

Shrinkage limit

The shrinkage limit which is the lowest water content at which the sample can remain in a saturated state has been an important parameter in the identification of structural state of clay-water-electrolyte systems. It has great relevance in the control of stability of stabilized soils. Kingery and Fracl (1954) conducted experiments with solutions of different surface tensions, obtained by the addition of different surface active materials to water. Their results have shown that the amount of shrinkage from any given water content decreases linearly with decreasing surface tension. Lambe (1958) and Seed *et al* (1960) presented some data to support the fact that a soil with relatively parallel array should undergo more volume reduction upon drying than a soil with its particles in relatively random orientation. De Jong and Warkentin (1965) studied the influence of texture on shrinkage. Yong and Warkentin (1966) summarized the characteristics affecting shrinkage as the percent clay in the soil, the kind of clay minerals, the mode of geological deposition, the depositional environment which determines both particle arrangement and overburden pressure, and the degree of weathering. Though surface tension has been believed to be the cause of shrinkage, after theoretical and experimental studies, Sridharan and Venkatappa Rao (1971) have shown that shrinkage limit is governed by the contact stress at particle contact and (or) betweeen particles, as defined by the modified effective stress concept. (The mechanism and its implications are discussed elsewhere in the paper in detail). It is now proposed to verify the applicability of this mechanism to two naturally occurring and widely different (in their mechanical behaviour) soils viz., a silty soil and a black cotton soil, with the use of various additives.

Liquid limit

Many investigations have been conducted in the past to determine the influence of clay mineral composition, type and concentration of adsorbed complex on the plasticity limits. The liquid limit of clays is regarded as the water content at which sufficient free water is present to allow clay particles to slip one another under certain applied force and then retain these new positions (Warkentin, 1960). The plastic limit is the lower water content at which these properties are exhibited. The work of Warkentin (1960) recognises the influence of electrolyte concentration on the Atterberg limits for different types of exchangeable cations and the changes in their magnitudes have been attributed to changes in interparticle forces. The work of Lambe (Scott 1963) shows that the Atterberg limits are affected by the type of ion and to a greater degree in the case of montmorillonite. Nagaraj and Somasekhar (1969) investigated the effect of electrolyte concentration and type of clay on inferential testing of clays, and brought out the role of cation factor '*f*'.

In retrospect, these and many more inadvertently omitted investigations clearly recognise the influence of clay mineral composition and electrolyte concentration on the plastic limits. But no attempt has been made to bring out a unified approach for understanding the liquid limit behaviour of the clayey soils.

Towards this, Sridharan and Venkatappa Rao (1975) conducted a detailed investigation on the mechanisms controlling the liquid limit of kaolinite and montmorillonite clays with the use of various organic pore fluids of different dielectric constant values and water, and it was brought out that the liquid limit of clays is primarily controlled by (*i*) the shearing resistance at particle level and (*ii*) the thickness of diffused double layer. For non-expanding lattice type of clay like kaolinite, it was observed that the contribution due to diffuse double layer is insignificant and the liquid limit is primarily controlled by the shearing resistance at particle level. Although for montmorillonite also, the liquid limit should be governed by the shearing resistance, being an expanding lattice type of clay, the contribution due to the diffuse double layer overrides and primarily governs the liquid limit.

It is the aim of this paper to study whether the mechanism proposed earlier, as above for liquid limit would apply to a more natural system with or without additive.

Plastic limit

The physical mechanism for plastic limit is much less understood than for liquid limit. According to Yong and Warkentin (1975) the plastic limit is both a measure of cohesion of the soil particles to cracking when the sample is worked. The cohesion between particles or units of particles must be sufficiently low to allow movement between particles to slide past each other and yet sufficiently high to allow the particles to maintain the new moulded position. In other words it may be stated that plastic limit is a measure of the water content of the soil when it approaches a particular shearing resistance and it is the amount of water which must be added to a soil in order to wet all the surfaces and to fill the small pores. At this water content, the particles will slide past one another on application of force, but there is still sufficient cohesion to allow them to retain shape. If this mechanism were to govern the plastic limit behaviour of soils, then varying the exchangeable cations and changing the salt concentration which will in turn change the interparticle shearing resistance (cohesion) and the double layer thickness should cause considerable changes in the plastic limit. Thus, any change in cation type or salt concentration which increases the shearing resistance, should bring up the plastic limit and the same should be the case when the double layer thickness increases. It is proposed to verify the existence and validity of this mechanism by using silt and black cotton soil and with various chemical additives of differnt concentrations and also by the use of fly ash.

Experimental work

Soils studied

In this investigation two soils were used, one an alluvial silty soil and the other, black cotton soil. The silty soil was obtained from the area adjacent to the soil mechanics laboratory of Indian Institute of Technology, Delhi. The black cotton soil was obtained from near Bina Ganj on Agra-Bombay Road. The physical properties of these soils are given in Table 1. The grain size distribution curves of the soils are presented in Figure 1.

TABLE 1

Soil Characteristics

Property	*Soil* *Silt*	 *Black Cotton Soil*
Liquid Limit (per cent)	27	56
Plastic Limit (per cent)	18	26
Plasticity Index (per cent)	9	30
Shrinkage Limit (per cent)	17.5	16.1
Per cent finer than 2 μ	13	39
Specific gravity of solids	2.72	2.77
Base exchange capacity meq/100 gm	6.5	21.0
Angle of shearing resistance	34°	28°
Angle of shearing resistance (fly-ash)	43°	

Chemicals

Reagent grade hydrated lime, calcium chloride and sodium chloride were used to minimise compositional variables. The cation factors for the different chemicals used have been presented in Table 2.

TABLE 2

Cation Factors for Different Chemicals

%	*Silt*			*Black Cotton Soil*		
Chemical	$Ca(OH)_2$	$CaCl_2$	NaCl	$Ca(OH)_2$	$CaCl_2$	NaCl
1	4.16	2.77	2.63	1.29	0.86	0.82
2	8.32	5.54	5.26	2.57	1.72	1.63
4	16.63	11.09	10.53	5 15	3.43	3.26
6	24.95	16.63	15.75	7.72	5.15	4.89
8	33.26	22.18	21.06	10.30	6.86	6.52

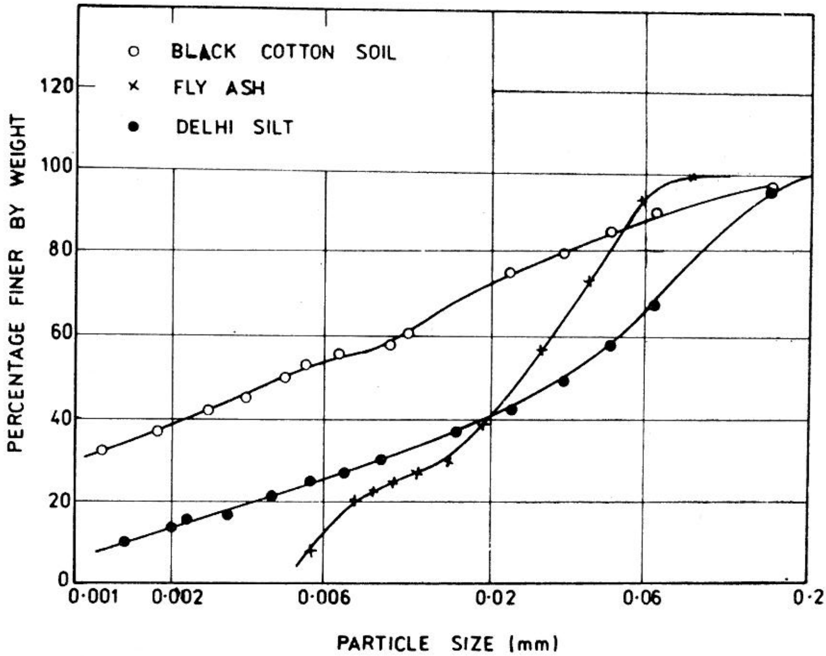

FIGURE 1: **Grain size distribution curves**

Fly ash

The fly ash used in this study was collected from Indraprastha thermal power station, Delhi. The grain size distribution of fly ash is given in Figure 1.

Test procedure

Oven dried soil passing No. 425 micron sieve was mixed with the desired percentage of chemical or fly ash. The mixture was thoroughly mixed first in dry state and then with distilled water. The paste so obtained, was cured in all cases for at least two hours, before actual testing was carried out.

Shrinkage void ratio:— In this study, instead of shrinkage imit which is conventionally represented as the percent water content, the void ratio at shrinkage limit is used. It is appropriate to use void ratio at shrinkage limit rather than the conventional one as it facilitates the comparison when different chemicals and other additives of different specific gravities are ussd. Shrinkage limit tests were performed as per IS : 2720 (Part VI)—1972.

Liquid limit:—The liquid limit tests have been conducted using the cone penetration method. The cone penetrometers have been widely used with success for determination of the liquid limit due to their simplicity and less human error. The penetrometer used in this study was as per IS : 2720 (Part V)—1970.

Plastic limit:—The plastic limit tests were conducted as per IS : 2720 (Part V)—1970.

Experiments conducted

The experimental investigation consisted of the following series of tests:

I. Shrinkage Limit:

(1) Tests on soils with different percentages (upto 80%) of fly ash

(2) Tests on fly ash with different percentages of lime (up to 8%)

(3) Tests on soils with/without fly ash with different percentage (upto 8%) of lime, $CaCl_2$ and NaCl

II. Liquid Limit and Plastic Limit:

(1) Tests on soils with different percentages of fly ash (up to 50%)

(2) Tests on soils with addition of different percentages (up to 8%) of lime, $CaCl_2$ and NaCl)

Test Results and Discussion

Shrinkage void ratio

Effect of fly ash: – Figures 2 and 3 present the effect of addition of fly ash on shrinkage void ratio of silt and black cotton soil, respectively. It is seen that for both soils addition of fly ash increases the shrinkage void ratio. At this juncture, it may be pertinent to bring out, the mechanism for shrinkage, brought out earlier (Sridharan and Venkatappa Rao, 1971). Shrinkage phenomana could be broadly explained as being initiated by capillary forces due to the surface tension of the pore fluid, but the resulting shrinkage void ratio is dependent on the resistance offered between the soil particles and/ or at the particle contacts which is governed by the modified effective stress equation as follows:

$$\bar{C} = \sigma - \bar{u}_w - \bar{u}_a - R + A \qquad \ldots(1)$$

where $\bar{C}$ = effective contact stress

σ = total stress

$\bar{u}_w$ = effective pore water pressure

$\bar{u}_a$ = effective pore air pressure

R = total interparticle electrical repulsion divided by total interparticle area

A = total interparticle electrical attraction divided by total interparticle area.

For an initially saturated soil mass $\bar{u}_a = 0$ and σ in this case is none other than the force due to surface tension (σ_{ts}) and pore water term becomes zero and thus the equation (1) becomes

$$\bar{C} = \sigma_{ts} + A - R \qquad \ldots(2)$$

Thus the greater is the shear resistance at particle contact (governed by (2)), the greater is the resistance against volume change and smaller is the volume change and vice versa. The shear resistance is function of normal forces acting between particles and (or) at the particle contacts, the frictional properties, and the electrical attractive and repulsive forces.

In the light of the above, the effect of addition of fly ash to silt and black cotton soil could be observed.

From Table 1, it is seen that the angle of shearing resistance for fly ash is relatively very high compared to that of the soils used in this investigation. The addition of fly ash to the soil is likely to increase the average shear resistance between particles. Thus with increase in percentage of fly ash either to silt or black cotton soil, the average shear resistance that can be mobilized at particle contacts increases, thus greater is the resistance against volume change and smaller is the volume change or greater the shrinkage void ratio, as clearly seen in Figure 2 and 3.

Further it may be noted that it is not possible to view the results in terms of a packing theory (for eg. Das *et al*, 1969) because, the particle size

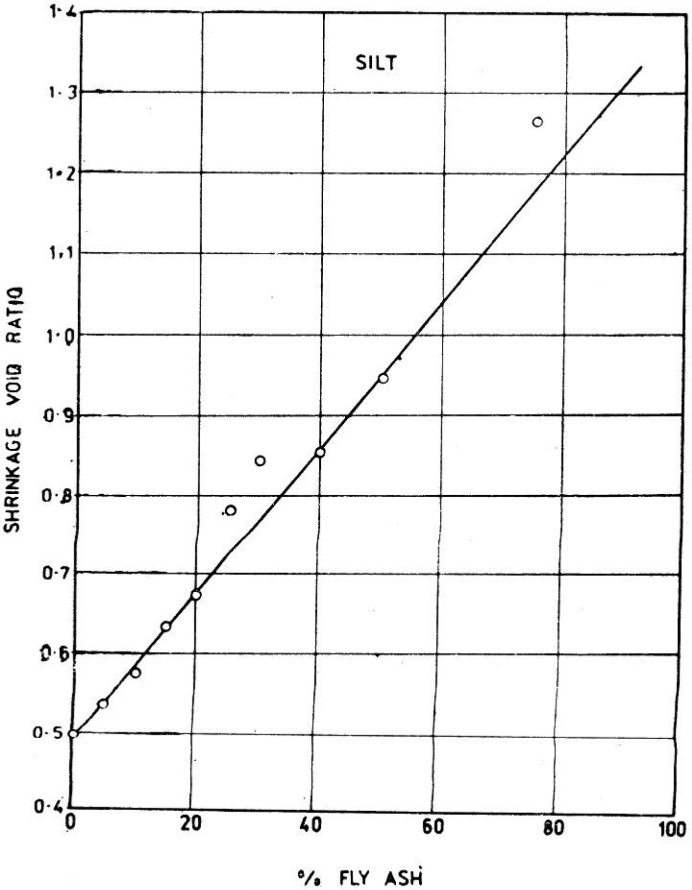

FIGURE 2. Effect of fly ash on shrinkage void ratio of silt

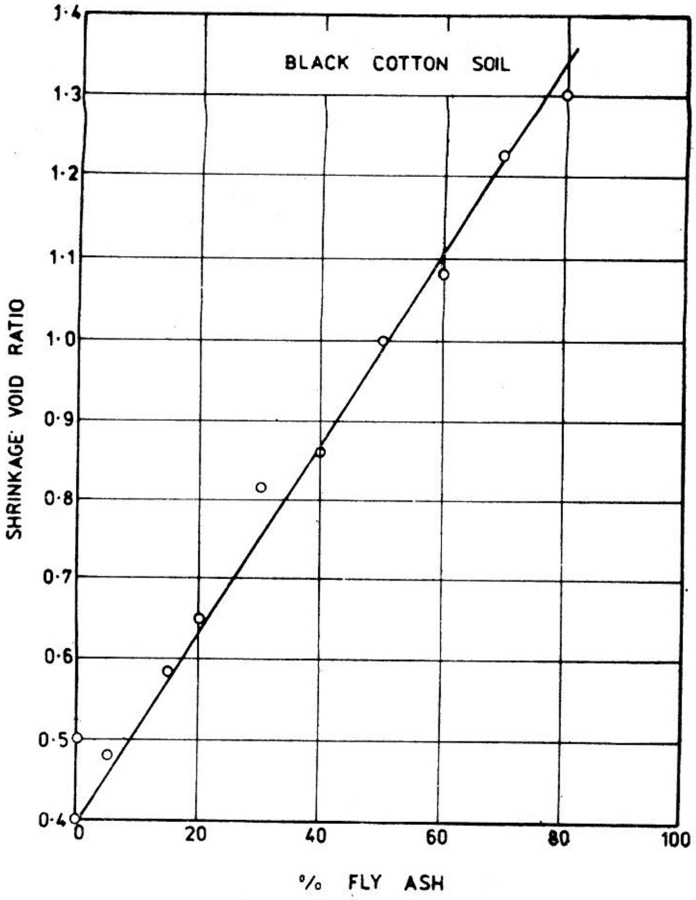

FIGURE 3. Effect of fly ash on shrinkage void ratio of black cotton soil

distribution range is rather wide both for the soils as also the inert material—fly ash, as is clear from Figure 1.

Effect of lime on silt-fly ash admixtures :—The effect of lime on silt, silt and fly ash in the ratio 90:10 and 75:25 on shrinkage void ratio is presented in Figure 4 similar results are presented in Figure 5 for black cotton soil and fly ash 75:25). It is seen that in general there is significant increase in shrinkage void ratio with increase in percentage of lime for all the admixtures. It is well known that addition of divalent lime increases the net interparticle attractive force (Warkentin and Yong, 1962; Venkatappa Rao and Moondra, 1976) and also at high salt concentration there is tendency towards flocculation which decreases interparticle repulsive forces. These cause an increase in the effective stress $\overline{C}$ (Equation 1). Thus it is obvious that increase in percent lime increase $\overline{C}$, causing greater shear resistance at particle level which results in smaller volume change.

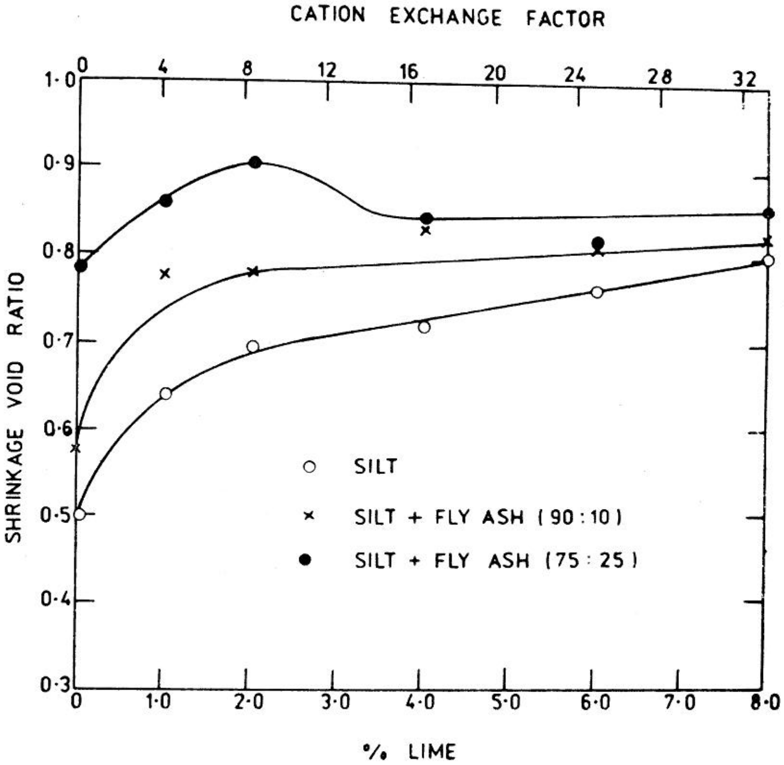

FIGURE 4. Effect of lime on shrinkage void ratio of silt and fly ash admixtures

To better understand the results from physico-chemical view point the cation factors are also given in Figures 4 and 5. These factors (calculated after Nagaraj and Somashekhar, 1969) enable us to know the percentage lime added in terms of the base exchange capacity, a factor of unity representing the amount of lime sufficient to satisfy the cation exchange requirements of the soil concerned. Thus it may be noted that an addition of 8 per cent lime to black cotton soil means a cation factor of about 5 whereas same amount of lime to silt gives a cation factor of 32. Thus any comparison between the two soils should normally be restricted to similar cation factors. It is seen from Figure 4 that the topmost curve referring to an admixture of silt and fly ash (75:25) shows a decrease in shrinkage void ratio after 2 per cent lime or cation exchange factor of 8. This behaviour will be clear when the effect of addition of lime to fly ash alone is considered, which is presented in Figure 6. Fly ash though inactive by itself, reacts well in the presence of lime because of the high percentages of silica and alumina present. The shrinkage behaviour of silt-fly ash (75:25) (Figure 4) is very similar to what is observed in Figure 6 for fly ash alone. That is, a peak is observed at 2 per cent lime content. Further experimentation is necessary for satisfactorily explaining the occurence of the peak. But the similarity leads us to the observation that with increase in the percentage of fly ash to silt, the shrinkage behaviour is tending towards that of fly ash.

It may further be seen from Figures 4 and 5 that, in general, increase in

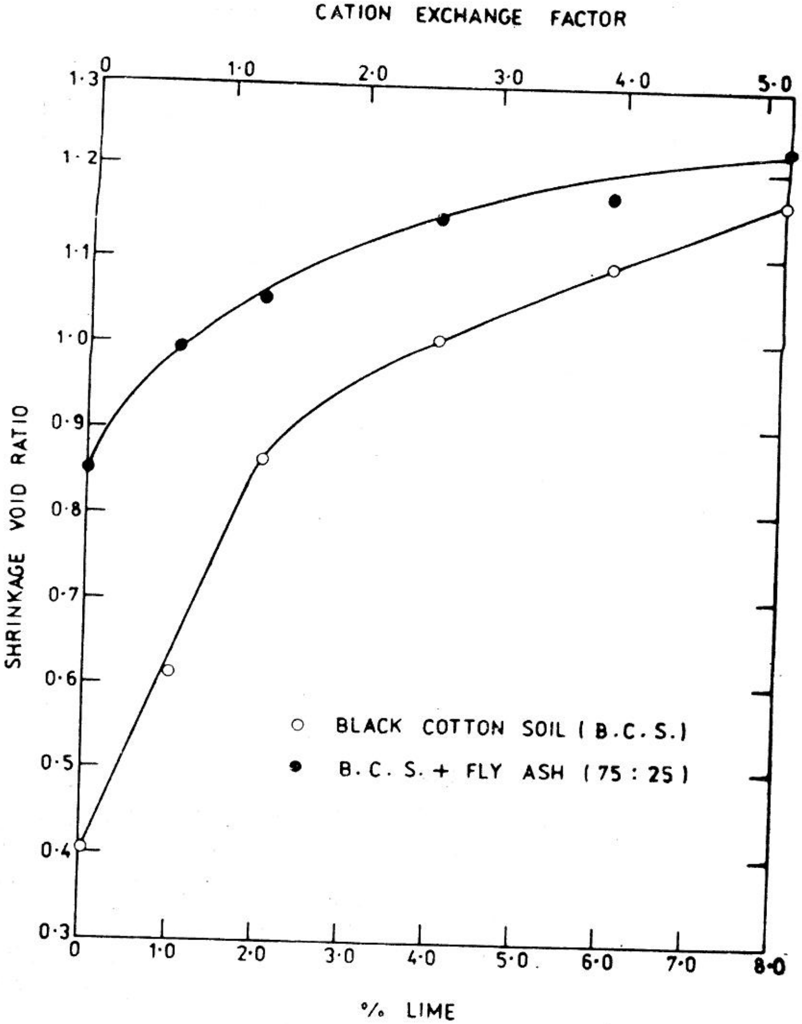

FIGURE 5. Effect of lime on shrinkage void ratio of black cotton soil and fly ash admixtures

fly ash content leads to increase in shrinkage void ratio at any lime content for both the soils. This of course follows Figures 2 and 3 which clearly show that addition of fly ash without any chemical increases the shrinkage void ratio. Figures 4 and 5 confirm only that this is true for any given lime content also.

Effect of chemicals:—Figure 7 presents the effect of lime, $CaCl_2$ and NaCl on the shrinkage void ratio of silt. Figure 8 presents similar results for black cotton soil. From Figure 7 it may be observed that for silt the effect of addition of lime is to increase the shrinkage void ratio in general, whereas initial addition upto 2 per cent of $CaCl_2$ and NaCl tend to decrease the shrinkage void ratio and later tend to increase the same. At any given percen-

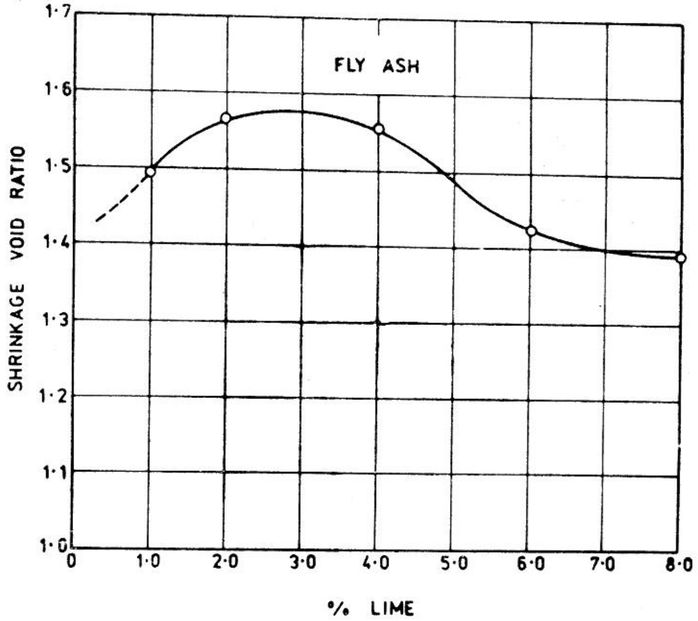

FIGURE 6. Effect of lime on shrinkage void ratio of fly ash

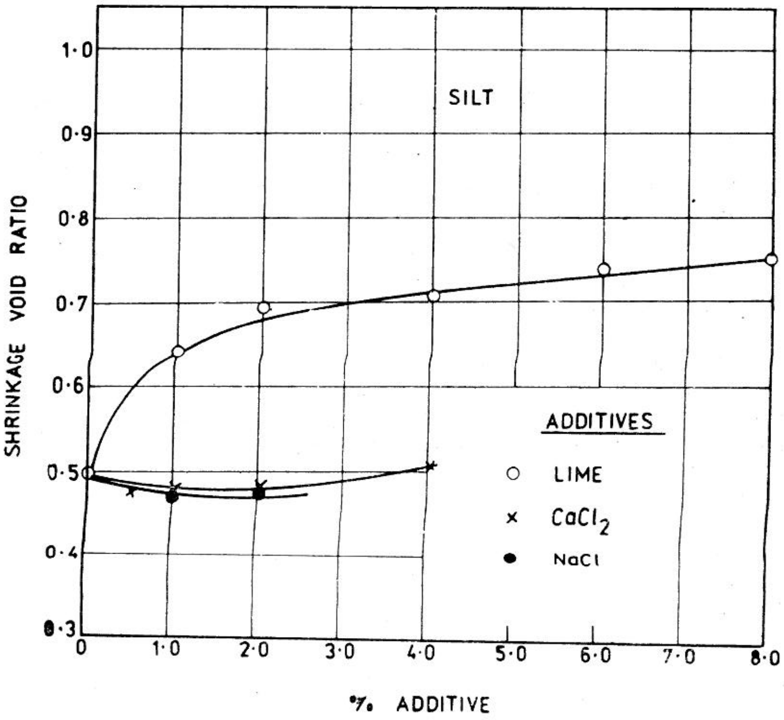

FIGURE 7. Effect of different chemicals on shrinkage void ratio of silt

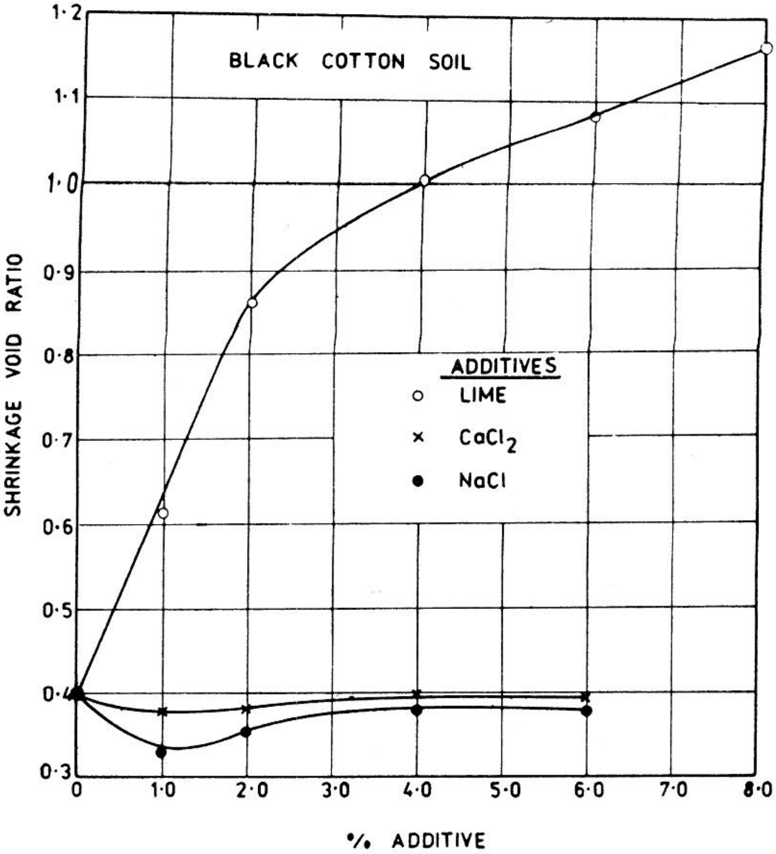

FIGURE 8. Effect of different chemicals on shrinkage void ratio of black cotton soil

tage, lime gives the highest shrinkage void ratio followed by $CaCl_2$ and then NaCl. Black cotton soil shows a very similar trend as seen from Figure 8. The results obtained by Nagaraj and Somashekhar (1969) for montmorrillonite and kaolinite also show similar trands. The force of repulsion due to the diffuse double layer decreases with increasing distance between the clay particles, with increasing electrolyte concentration and with increasing valence of exchangeable ion (Verwey and Overbeek, 1948; Bolt, 1956). Hence it could be postulated that for the same type of clay soil and the same ion concentration, the interparticle repulsive force is higher when sodium is exchangeable cation than for calcium. According to Warkentin and Yong (1961), "Increasing the salt concentration and the valence of exchangeable ion decreases the interparticle repulsion, and either increases or leaves unchanged force of attraction." The electrostatic force of attraction of positive edge to negative surface also increases as the salt concentration increases. Hence it follows from Equation (1) that the effective contact stress is higher for calcium system than for sodium system other things remaining the same. Thus shrinkage void ratios of $CaCl_2$ and $Ca(OH)_2$ are expected to be higher than NaCl. Comparing $Ca(OH)_2$, and $CaCl_2$, it is well known that addition of lime not only leads to the above said physico-chemical changes but also has cementitious properties. This cementitious property of lime gives the soil a higher shearing resistance than $CaCl_2$ and obviously leads to higher shrinkage void ratio.

From the above it may be concluded that the results presented are in consistence with the mechanism that the shearing resistance at interparticle level governs the shrinkage of a system.

Liquid limit

Effect of fly-ash:—Figure 9*a* shows the effect of addition of fly ash on the liquid limit of silt and Figure 10*a* on black cotton soil. From these it may

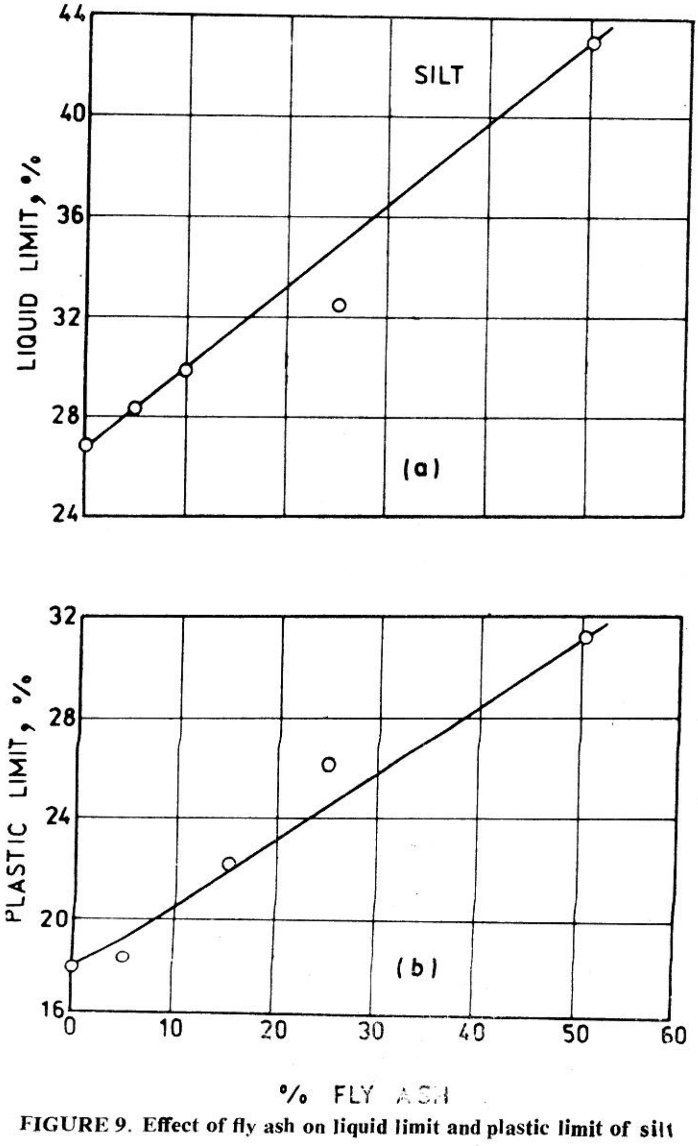

FIGURE 9. Effect of fly ash on liquid limit and plastic limit of silt

be seen that addition of fly ash increases the liquid limit of silt whereas it decreases that of black cotton soil. Addition of fly ash to a soil has twin effects:

(*i*) In brings up the average shearing resistance between particles (as shown earlier), thus increasing the liquid limit, as per the mechanisms proposed earlier.

(*ii*) As it does not possess any diffuse double layer, it brings down the overall affinity to water of the admixture, thus decreasing the liquid limit.

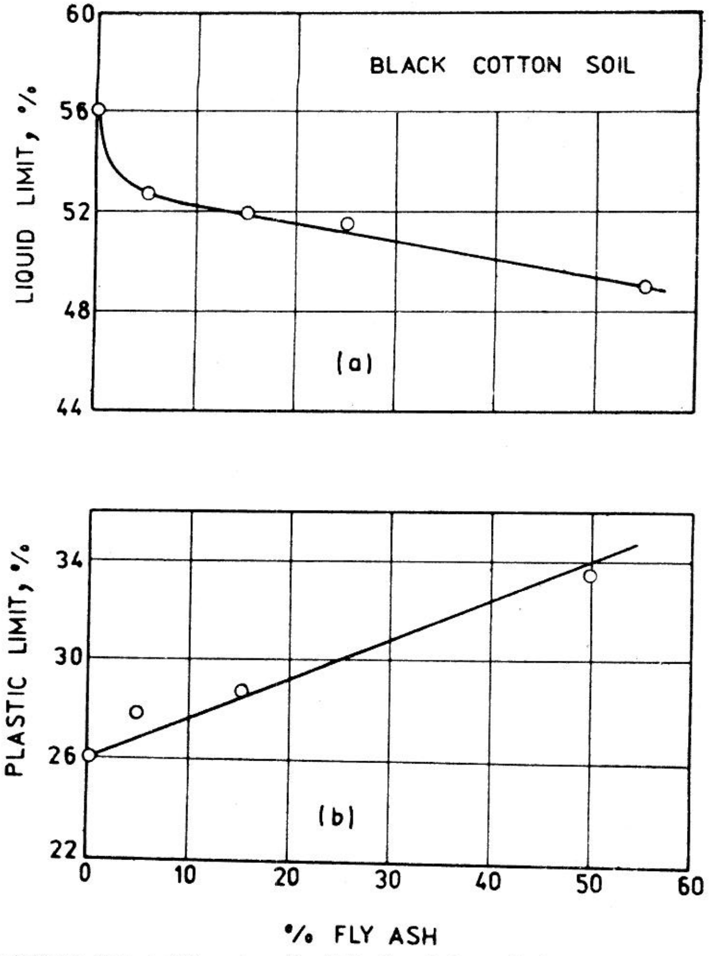

FIGURE 10. Effect of fly ash on liquid limit and plastic limit of black cotton soil

These two effects are obviously opposite in nature and the liquid limit behaviour of a particular soil depends upon the predominating influence of the two. With the help of the foregoing, the liquid limit behaviour of the two soils can be satisfactorily explained as follows:

For silt, addition of fly ash does not bring in appreciable changes in average diffuse double layer, as silt by itself does not possess thick double layer (in comparison to black cotton soil etc.) and fly ash does not have any. Thus, increase in fly ash content is reflected only as a significant change in shearing resistance showing increased liquid limit.

The effect of addition of fly ash to black cotton soil is primarily to bring down the overall affinity to water of the admixture and its influence on the shearing resistance at particle level may be comparatively lower. Although the liquid limit for the black cotton soil also should be governed by the shearing resistance, the contribution due to the diffuse double layer overrides this and hence, the behaviour is governed by the changes in the same. Thus an addition of fly ash causes lowering of liquid limit of black cotton soil.

Effect of chemicals:—Figures 11*a* and 12*a* present the liquid limit behaviour of silt and black cotton soil respectively with additions of lime, $CaCl_2$ and NaCl. It is seen from these figures that the addition of lime generally increases the liquid limit of silt whereas it decreases that of black cotton

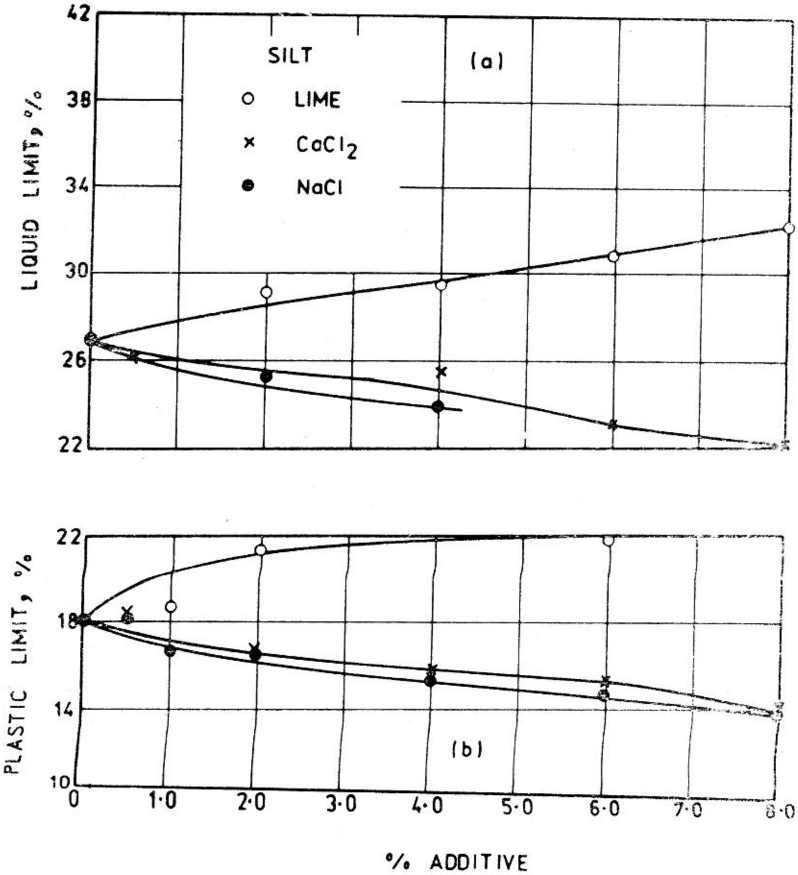

FIGURE 11: Effect of different chemicals on liquid limit and plastic limit of silt

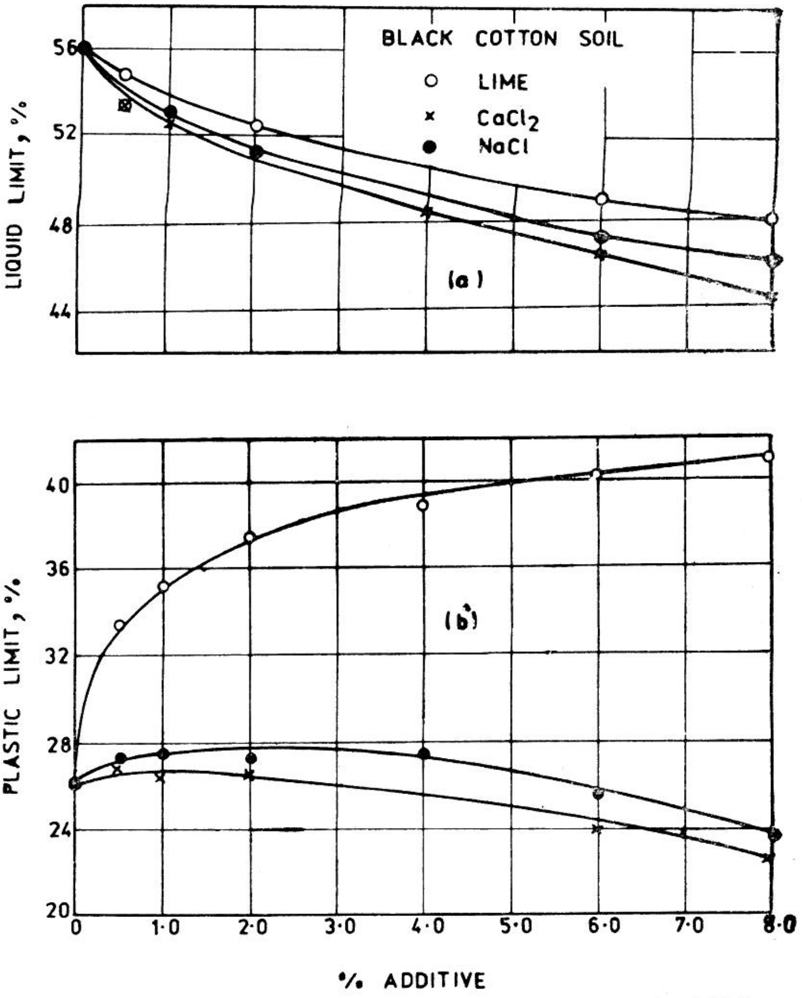

FIGURE 12: Effect of different chemicals on liquid limit and plastic limit of black cotton soil

soil. Similar results on black cotton soil are reported by Katti *et al*, (1966). The addition of divalent calcium has two effects (Sridharan *et al*, 1971):

(*i*) the thickness of the diffuse double layer decreases because of divalency and this brings down the liquid limit,

(*ii*) attractive force is increased and hence flocculation tends to take place, which leads to higher liquid limit.

It can be seen that these two effects are opposite in trend. For a swelling soil like black cotton soil, the first effect is predominant and for non-swelling silt, the second effect is predominant.

Although both $CaCl_2$ and NaCl bring down the liquid limit of both the soils, the net effect is not the same in the two. Whereas the curve for

$CaCl_2$ is above that of NaCl for silt (Figure 11*a*), the reverse is the case for black cotton soil (Figure 12*a*). As is already discussed in the above, the effect of addition of divalent calcium is not only to decrease the thickness of diffuse double layer, but also to increase the shearing resistance between particles. Thus in the expansive black cotton soil, the effect of the diffuse double layer prevails over the increase in shearing resistance resulting in higher liquid limit for $CaCl_2$ than for NaCl. The reverse is true for silt as in this case, the diffuse double layer effect being relatively insignificant.

When the effect of addition of lime and $CaCl_2$ is compared, it is seen (From Figures 11*a* and 12*a*) that for both the soils, lime gives higher liquid limit than $CaCl_2$. This is understandable because, as both the additives are of calcium, they are likely to yield the same order of diffuse double layer thickness, hence the one giving higher shearing resistance, *viz*; lime is the one likely to predominate, as is clearly observed.

Thus the results obtained are easily explicable on the basis of the mechanisms brought forth earlier by Sridharan and Venkatappa Rao (1975). Thus the mechanisms originally hypothesized for pure clay minerals like kaolinite and montmorrillonite using organic fluids, have been found to be valid for two widely different natural soils, using salts (which are also likely to be present in natural soils). It may also be noted that the result of Warkentin (1960) on Na- and Ca- montmorillonites, and Na and Ca- kaolinites using Ca-and Na-salts, as also those of White (1949) are in tune with the mechanisms proposed.

Plastic limit

Effect of chemicals:—Figures 11*b* and 12*b* present the variation of plastic limit with different chemicals for silt and black cottonsoil respectively. For both the soils it is seen that addition of lime increases the plastic limit and increasing the percentage of lime increases the plastic limit. For black cotton soil similar results are reported by Katti *et al* (1966). It has been stated earlier that two factors are responsible for controlling the plastic limit: the shearing resistance at particle level and diffuse double layer. Though the same factors have been stated and proved to be controlling the liquid limit of soils, these factors have to be viewed from the point that, the plastic limit represents the lower limit at which "plasticity" is observed. That is to say that, the shearing resistance in the case of plastic limit is bound to be higher than in the case of the liquid limit and the diffuse double layer thickness is much lower. These two things are in retrospect brought out by lowering interparticle distance and changes in ion concentration etc. Thus though the mechanisms responsible for liquid and plastic limit appear to be same, it should be stated that they are only similar. Thus, in case of addition of lime, it may be that the increase in shear resistance at particle level is more significant, that it overrides the influence of the double layer and controls plastic limit, hence any increase in lime content is to bring out increase in plastic limit for both the soils.

It is further seen from Figures 11*b* and 12*b* that for both the soils variations in plastic limit behaviour with addition of $CaCl_2$ and NaCl of different concentrations is similar to that of liquid limit in the sense that, for silt the addition of Ca Cl_2 causes higher plastic limit than NaCl, whereas for black cotton soil the reverse is the case. It is obvious that in the case of silt the necessary shearing resistance is developed at a high water content for calcium system than that of sodium, hence the plastic limit being higher in the case of the former. Whereas, for black cotton soil, the diffuse double layer comes into picture when comparing $CaCl_2$ and NaCl, so that the additive giving thicker double layer viz., NaCl gives rise to higher plastic limit. For the black cotton soil, when comparsion is to be made between $CaCl_2$ and lime both being divalentt are likely to poessss the same order of double layer thickness, with the result, shearing resistance controls plastic limit, and hence lime system being stronger of the two yields higher plastic limit.

Effect of fly ash:—From Figures 9*b* and 10*b*, it may be noticed that the plastic limit increases with percentage fly ash added for both the soils. As fly ash does not posess any diffuse double layer it is possible that addition of fly ash affects the average shearing resistance more significantly, resulting in increasing plastic limit with increase in fly ash content.

From the foregoing it may be concluded that two factors significantly influence the plastic limit behaviour of the soils *viz*;

(*i*) shearing resistance at interparticle level

(*ii*) diffuse double layer thickness.

Though both the factors act simultaneously, for a given system, one of the factors dominates apparently.

Plasticity index

Figures 13 and 14 show the variation of plasticity index with the different chemicals for silt and black cotton soil respectively. Considering the effect of lime it is seen that it decreases the plasticity index cosiderably for black cotton soil, whereas its effect on silt is nominal. (In fact other chemicals also yield same result with silt). This is in consistence with the results published earlier (Katti *et al*, 1966). The $CaCl_2$ and NaCl also reduce the plasticity index of the black cotton soil, though less significantly when compared to lime.

Figures 15 and 16, depict the effect of addition of fly ash on the plasticity index of silt and black cotton soil respectively. Here again, the influence

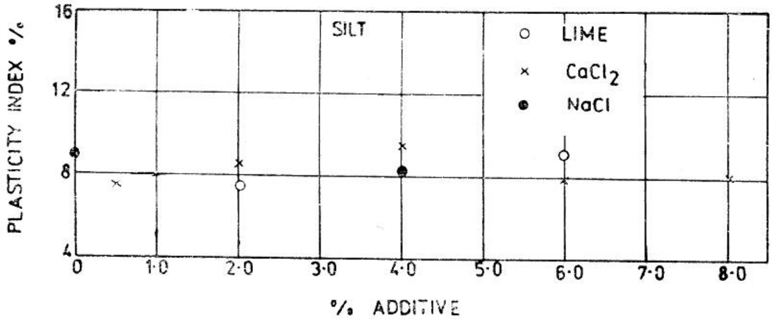

FIGURE 13: Effect of different chemicals on plasticity index of silt

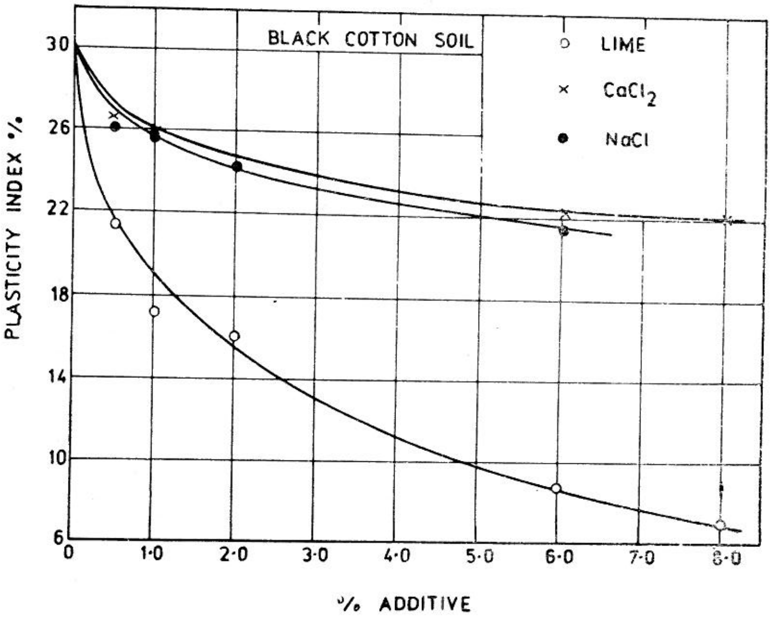

FIGURE 14: Effect of different chemicals on plasticity index of black cotton soil

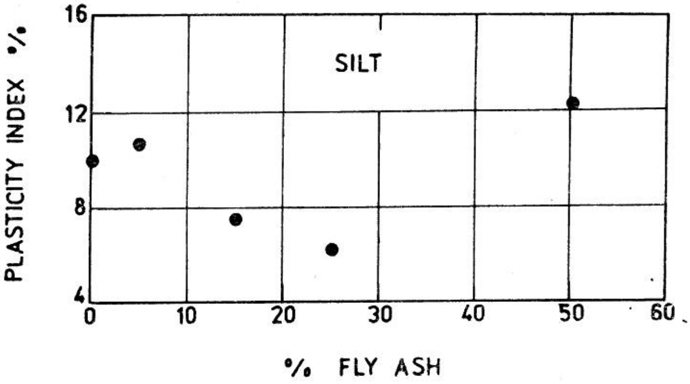

FIGURE 15: Effect of fly ash on plasticity index of silt

is very marked in the case of black cotton soil, with plasticity index reducing with increase in percentage of fly ash.

Thus it may be concluded that either with fly ash and/or lime, it is possible to bring down the plasticity index of a swelling soil black cotton soil, and thus make it more workable or friable. This is a major side benefit which is obtained by lime—fly ash addition apart from stabilization.

Summary and Conclusions

The investigations reported in this paper bring out in detail the physico-chemical mechanisms involved in the plasticity behaviour of two natural

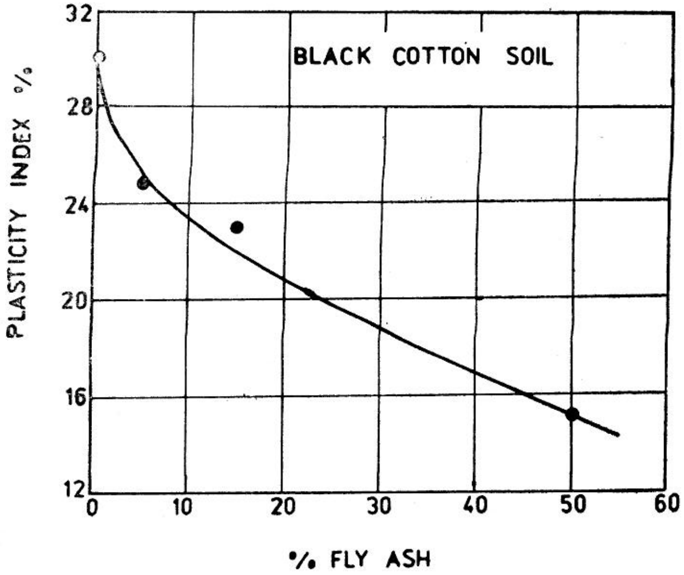

FIGURE 16: Effect of fly ash on plasticity index of black cotton soil

soils. Lime, calcium and sodium chlorides in varying percentages and fly ash in different proportions have been used as additives to silt and black cotton soil, to vary widely the interparticle electrical attractive and repulsive forces and bring out the various phenomena involved.

It has been clearly shown that the shearing resistance at interparticle level controls the shrinkage behaviour of a system for both silt and black cotton soil. The study confirms the earlier finding that the liquid limit behaviour is controlled by shearing resistance at interparticle level as also the thickness of diffuse double layer. Though both act simultaneously, usually one of them predominate. It has been hypothesized that the plastic limit is also controlled by the interparticle shearing resistance and diffuse double layer thickness. It has been shown that this hypothesis is valid.

Further, the following conclusions may be drawn from this study:

1. Shrinkage limit increases with addition of fly ash for both silt and black cotton soil.
2. Shrinkage limit increases with percentage lime for silt-fly ash and black cotton soil—fly ash admixtures.
3. Shrinkage limit is highest for lime as additive, followed by $CaCl_2$ and NaCl for both the soils.
4. Liquid limit of silt increases whereas that of black cotton soil decreases with addition of fly ash.
5. Liquid limit increases for silt with addition of fly ash, whereas reverse is true for black cotton soil.

6. For silt, the liquid limit is highest for lime followed by $CaCl_2$ and NaCl; whereas for black cotton soil, though it is highest for lime, it is followed by Na Cl and then Ca Cl_2.
7. Plastic limit increases when lime is added both in case of silt as well as black cotton soil.
8. For silt, plastic limit is highest for lime, followed by $CaCl_2$ and then NaCl, whereas for black cotton soil, though plastic lilmit is highest for lime it is followed by NaCl and then $CaCl_2$.
9. For black cotton soil, the plasticity index decreases significantly due to the addition of lime as well as fly ash, whereas the effect on silt is insignificant. This property of reducing the plasticity of black cotton soil has great potential in lime-fly ash stabilizatiou.

All the above phenomena are clearly explicable by the mechanisms presented.

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References

BOLT, G.H. (1956), "Physico-chemical Analysis of Pure Clays", *Geotechnique* 6:2:86-93.

DAS, A.K., ANANDA KRISHNAN, M. and GOKHALE, K.V.G.K. (1969), "Shrinkage Behaviour in Clay-Sand Systems", *Proc. International Clay Conference, Tokyo*, Vol. 1, pp. 829-833.

De JONG, E., WARKENTIN, B.P. (1965), "Shrinkage of Soil Samples with Varying Clay Concentration", *Canadian Geotch. J.* 2. pp. 16-23.

KATTI, R.K., KULKARNI, K.R. and RADHAKRISHNAN, N. (1966), "Research on Black Cotton Soils Without and with Inorganic Additives", *Road Research Bulletin No. 10, Indian Roads Congress, New Delhi.*

KENNEY, T.C., MOUM J. and BERREE, T. (1967), "An Experimental Study of Bonds in a Natural Clay", *Proc. Geotch. Conf. Oslo*, I:65-69.

KINGERY, W.D., and FRACL, J. (1954), "Fundamental Study of Clay: Drying Behaviour and Plastic Properties", *Journal of American Ceramic Society*, Vol. 37, pp. 596-602.

LAMBE, T.W. (1958), "The Structure of Compacted Clay", *Proc. ASCE*, Vol. 84, SM2, pp. 1-34.

LAMBE, T.W. (1960 *a*), "A Mechanistic Picture of Shear Strength in Clay", *Proc. Research Conf. on Shear Strength of Cohesive Soils, ASCE, Boulder, Colorado*, pp. 555-580.

LAMBE, T.W. (1960 *b*), "Discussion on Factors Controlling the Strength of Partly Saturated Cohesive Soils", *Proc. Research Conf. on Shear Strength of Cohesive Soils, ASCE, Boulder, Colorado*, pp. 1094-1095.

NAGARAJ, T.S., and SOMASHEKAR, B.V. (1969), "Influence of Clay Composition and Exchangeable Cations on Inferential Testing", *Soils and Foundations*, Vol. IX, No. 1.

ROSENQVIST, I. T.H. (1955), "Investigations in the Clay-Electrolyte-Water Systems", *Publication No. 9, Norwegian Geotechnical Institute*, pp. 31-53.

SCOTT, R.F. (1963), "*Principles of Soil Mechanics*", Addison-Wesley Publishing Co., Inc.

SEED, H.B., MITCHELL, J.K., and CHAN, C.K. (1960), "The Strength of Compacted Cohesive Soils", *Proc. Research Conf. on Shear Strength of Cohesive Soils, ASCE, Boulder, Colorado*, pp. 727-745.

SRIDHARAN, A., NARASIMHA RAO, S. and VENKATAPPA RAO, G. (1971), "Shear Strength Characteristics of Saturated Montmorillonite and Kaolinite Clays", *Soils and Foundations*, Vol. 11, No. 3, pp. 1-22.

SRIDHARAN, A., and VENKATAPPA RAO, G. (1971), "Effective Stress Theory of Shrinkage Phenomena", *Can. Geotech. J.* 8:4: 501-513.

SRIDHARAN, A., and VENKATAPPA RAO, G. (1975), "Mechanisms Controlling the Liquid Limit of Clays", *Proc. Istanbul Conf. Soil Mech. and Foundation Engg., Turkey*. I:65-74.

VENKATAPPA RAO, G. (1972), "*Physico-chemical Mechanisms Controlling Volume Change and Shear Behaviour of Clays*", Ph.D. Thesis, Indian Institute of Science, Bangalore.

VENKATAPPA RAO, G., and MOONDRA, H.S. (1976), "Strength Behaviour of Pilani Soil", *Indian Geotechnical J.* Vol. No. 2, pp. 120-127.

VERWEY, E.J.W. and OVERBEEK, J.T. (1948), "*Theory of the Stability of Lyophobic Colloids*", Elsevier Publishing Co., New York.

WARKENTIN, B.P. (1960), "Interpretation of the Upper Plastic Limit of Clays", *Nature*, Vol. 190 pp. 287-288.

WARKENTIN, B.P. and YONG, R,N. (1961), "Shear Strength of Montmorillonite and Kaolinite Related to Interparticle Forces", *Clay and Clay Minerals*, 9:210-218.

WARKENTIN, B.P. (1964), "Measurement of Shear Strength, Plasticity and Water Retention of Clays Related to Interparticle Forces", *Proc. 16th Conference of Soil Mechanics*, NRC, Memo 82, Ottawa.

WHITE, W.A. (1949), "Atterberg Plastic Limits of Clay Minerals", *American Mineralogist*, Vol. 34, pp. 508-512.

YONG, R.N., and WARKENTIN, B.P. (1966), "*Introdution to Soil Behaviour*" Macmillan, New York

YONG, R.N., and WARKENTIN, B.P. (1975), "*Soil Properties and Behaviour*" Elsevier Publishing Co., New York.

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