

## EFFECTS OF SOIL POLLUTION ON GEOTECHNICAL BEHAVIOUR OF SOILS

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**ABSTRACT:** Ground pollution arises from the impact of past and current industrial activity and due to improper disposal of waste generated by society. Geoenvironmental engineering deals with the most important aspects: (a) Soil pollution processes and effect on geotechnical properties, and (b) Waste Management. Soil-pollutants interaction changes soil behaviour and also can lead to various geotechnical problems. Attempts to understand the soil response to various pollutants and available methods to control the same are presented. While the changes in the behaviour of soil contaminated with variety of pollutant in the absence of strong interaction, the behaviour of soil interacted with contaminants leading to mineralogical changes is only getting attention recently. The effect of sulphate on different fine grained soil in alkaline and acidic environment is presented.

### 1. SOIL POLLUTION PROCESSES

The environment can contaminate soil water by three basic mechanisms:

(i) Rainfall, such as acid rains falling onto a sanitary landfill, oil or chemical waste spilled into the ground (ii) Human activities (iii) Physico chemical alterations, which allow polluting substances to move within or between soil layers.

### 2. EFFECTS ON SOIL PROPERTIES

Soil response to environments depends on Soil structure, Geochemical parameters (Mineralogical and chemical characteristics), Soil-water interaction.

### 3. SOIL SENSITIVITY TO ENVIRONMENT

The sensitivity of soil to environment depends not only on the local environment but also influenced by mineral structure, such as particle size, bonding characteristics between particles, ion exchange capacity, etc. The smaller the soil particle greater is its ability to interact with the environment (Fig. 1). The weaker the bonding energy between particles or higher the cation exchange capacity, the higher the sensitivity of the particles to the environment. For, example, montmorillonite is potentially more sensitive to the environment than illite and kaolinite.

### 4. SENSITIVITY OF SOIL TO PHYSICO-CHEMICAL INTERACTIONS

Soil-waste interaction can affect almost all the properties of soils (Sivapullaiah & Sridharan 1987, Sridharan & Sivapullaiah 1987). Soil structure and mineralogy play very important role in understanding the effects of pollutants. Though the effects of pollutants on soils are complex, they

may be better understood if the various factors are isolated and considered independently. These factors are primarily due to ion exchange (cation and anion exchange) or nature of pore fluid (electrolyte concentration, dielectric constant, acidity and alkalinity). Strong acids and alkalis may dissolve and disintegrate clays and their effect is not considered here. The effects, which are different for different types of soils, are considered on the following geotechnical properties.

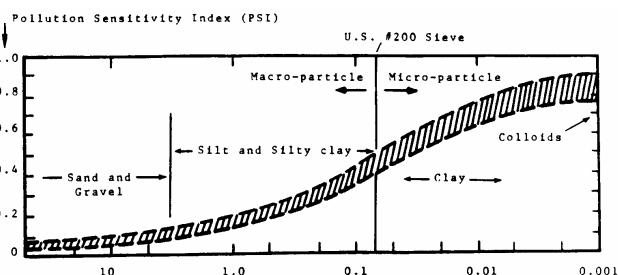


Fig. 1: Sensitive Index and Particle Size (after Fang 1976)

### 5. EFFECT OF SOIL-WASTE INTERACTION ON THE BEHAVIOUR OF SOIL

Soil-waste interaction can affect almost all the properties of soils. Though the effects of pollutants on soils are complex, they may be better understood if the various factors are isolated and considered independently. These factors are primarily due to ion exchange or nature of pore fluid. The effects may differ for different types of soils. The effects of exchangeable ions and the nature of pore fluids on the geotechnical properties can be summarized as follows:

#### 5.1 Index Properties of Polluted Soils

Clay particles are amphoteric in nature and have the capacity to attract cations and anions. The properties of soils

can vary significantly depending on the type of ions with which they are associated.

#### 5.1.1 Cation Exchange

The influence of the exchangeable ions on the Atterberg limits of various clays has been well documented (Lambe 1969). In general, the influence of cations on soil properties increases with increasing activity of the clay. The most important characteristics of the cations are their valence and size. In soils containing expansive clay minerals, the type of exchangeable cation exerts a controlling influence over the amount of expansion that takes place in the presence of water. For example, sodium and lithium montmorillonite can exhibit almost unrestricted inter-layer swelling provided water is available, the conflicting pressure is small, and the excess electrolyte concentration is low. Di- and trivalent forms of montmorillonite do not expand beyond a basal spacing of about 18Å, regardless of the environment. In soils composed mainly of non-expansive clay mineral, the type of adsorbed cation is of greatest importance in influencing the behaviour. Monovalent cations, particularly sodium and lithium, promote deflocculation, whereas clay suspensions, ordinary flocculate in the presence of di- and trivalent cations.

#### 5.1.2 Anion Exchange

The effect of anion adsorption on Index chemical properties of clays is not well investigated, though some data has been available in recent years. Recently studies (Sreepada Rao 1982) are conducted on the effects of phosphate ions. Anion adsorption was caused by treating the clays with phosphate and acetates at low pHs. The treatment appreciably changed the physico-chemical properties of both kaolinite and montmorillonite clays, though by different mechanism.

Phosphoric acid increases stable aggregation leading to higher porosities and water holding capacities but lower bulk densities. Phosphate adsorption increases the liquid limit, the surface area and the free swell volumes of kaolinite significantly because of flocculation of clay particles. Because of aggregation, the liquid limit of Na-montmorillonite decreased on phosphate adsorption. In Ca-montmorillonite, initially these values decreased with treatment, but subsequently increased because of the exchange of divalent calcium by monovalent hydrogen.

#### 5.1.3 Nature of Pore Fluids

The effect of electrolyte upon the zeta potential or the electric charge of the clay minerals is an important feature in the case of the liquid limit of clays. Liquid limits of two clays have been determined after addition of low concentrations of sodium Pyrophosphate and sodium carbonate. At low concentrations of sodium carbonate, some sodium ions are adsorbed upon the clay minerals. This way the net negative charge of the clay mineral decreases. At higher concentrations some of the carbonate/phosphate ions combine with the clay mineral by chemical binds. This leads to an increase in the net negative charge. Such a chemical binding can continue

only until all possible bonds between anion and the clay minerals are established. Further addition of sodium carbonate will lead to an adsorption of the positively charged sodium ions and, hence, to a decrease in the net negative charge of the clay particle. These effects have influence on the liquid limit and hence the observed behaviour.

A number of polar organic molecules have been observed to form interlayer complexes with clays and to cause expansion of the clay lattice. Non-polar saturated organic molecules such as n-hexane and n-dodecane have also been reported to form inter-lamellar complexes with air-dried montmorillonite. The extent and case with which intercalation occurs with non-polar organics may depend upon the state of hydration of clay itself.

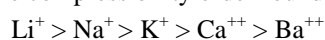
The interlayer spacing of montmorillonite in polar organic solvents will be very high particularly with solvents of high dipole moments and high dielectric constant such as formamide. Based on the effect of the various organic solvents on the liquid limit of clays, the effect of these solvents on other mechanical properties can be envisaged, since generalisation of soil behaviour through normalisation with liquid limits is possible.

It has been shown that good correlation exists between dielectric constant of pore fluid and shrinkage void ratio. For both these clays the shrinkage void ratio decreases as the dielectric constant of pore fluid increased. The studies also throw on the physical mechanisms involved in the shrinkage phenomena with the aid of modified effective stress concept

## 5.2 Volume Change Behaviour

Volume changes in soils are important because of their consequences in terms of settlement due to compression. In addition, changes in volume lead to changes in strength and deformation properties, which in turn influence stability. Compressibility of pure clays can be accounted for quantitatively by the consideration of double-layer repulsive forces. These forces between particles are due to the presence of exchangeable ions. It has been established that electrical double layer theory of Guoy-Chapman can be effectively used to describe the compressibility behaviour. The consolidation characteristics of montmorillonite depend upon the size of the cation present in the clay-water system. Variations in pore water electrolyte concentration have little effect on the void ratio-effective stress relationships for the Ca-montmorillonite in water, apparently because double-layer effects are smaller than predicted by classical theory and because of the formation of permanent domains. Even in the case of Na-montmorillonite there is evidence of domain formation during swelling at low values of effective stress though their consolidation curves are in qualitative confirmation of double-layer theory. Salas & Serratos (1953) did not find appreciable differences in the nature of cations in case of kaolinite because of its low exchange capacity.

The compressibility order found for bentonite is,



in accordance with the characteristics of these ions. However, special notice should be taken of the particular position occupied by the K-bentonite. This different behaviour is due to particle fixation of potassium in a non-exchangeable manner (on drying the sample) and becoming colloiddally inactive.

### 5.2.1 Anion Adsorption

The compressibility characteristics of various phosphate and acetate adsorbed clays were studied by Sreepada Rao (1982). It has been shown that phosphate adsorption significantly influences the volume change behaviour of clays. Phosphate adsorbed Na—and kaolinites have shown increased volume on saturation at seating pressure and reduced compressions upon subsequent loading. The quantum of swelling at the seating pressure increases with duration (or degree) of phosphate adsorption, and resistance to compression increase on further loading. The increase in volume at seating pressure has been attributed to the change in the fabric towards a higher flocculation (or random fabric) and increase in volume of individual particles because of phosphate adsorption. An increase in resistance offered by the treated clays has also been attributed to the above changes in fabric and to the reduced plasticity characteristics of the treated clays. Phosphate treated Ca-kaolinite swells more than treated Na-kaolinite at seating pressure, although the difference is small. The compression for subsequent loading is less for treated Ca-kaolinite than for treated Na-kaolinite than for treated Na-kaolinite. The effect of the associated cation is small for treated kaolinite clays. Treatment of Na-montmorillonite with phosphoric acid results in reduced swelling at seating pressure and resistance to external loading increases for Ca-montmorillonite. For Ca-montmorillonite treatment causes the clay to swell but the compressibility reduced. The difference between behaviour of Na- and Ca- montmorillonites is due to the cation effect. While the replacement of  $\text{Na}^+$  by  $\text{H}^+$  causes less swelling, that of  $\text{Ca}^{++}$  by  $\text{H}^+$  causes increased swelling because of changes in the thickness of the diffuse double layer. This is further confirmed by the essentially similar behaviour of 1000h treated  $\text{Na}^-$  and  $\text{Ca}^-$  montmorillonite, where both the clays become in essence H—montmorillonites. Treatment causes aggregation of particles and, possibly a change in the fabric towards a greater flocculence. The combined effect is for the soil skeleton to resist the external loading with reduced compressions. The results on H- clays (both treated and untreated) confirm the conclusions drawn for treated N- and Ca—clays. For all the different homoionic kaolinite and montmorillonite clays, phosphate adsorption causes reduction in compression index values. The reduction is marked for montmorillonite clays.

### 5.3 Effect of Dielectric Constant

The volume change behaviour of clays can be significantly affected by the nature of the pore fluid. It has been found by several investigators that both swelling and compression can take place with changes in the nature of pore fluid but without any change in the external load. The two important

aspects of the nature of pore fluid which have been studied in detail and reported in the literature are the dielectric constant and the ionic concentration. In the presence of different organic pore fluids, the effect of dielectric constant is diametrically opposite for kaolinite and montmorillonite clays in their compression behaviour. While montmorillonite clay shows significant swelling with increase in dielectric constant (at constant external load), kaolinite clay showed a decrease in volume. This behaviour has been explained by two different mechanisms: mechanism 1, where the volume change is governed by the shearing resistance at interparticle level and mechanism 2, where the volume change is governed primarily by the diffuse double-layer repulsive forces. Although these two mechanisms operate simultaneously, the results reveal that mechanism 1 primarily controls the volume change behaviour in non-expanding type clays like kaolinite, whereas mechanism 2 operates in the case of expanding lattice type clays like montmorillonite.

Secondary compression, which can form a significant portion of total compression, is also greatly influenced by the type of pore fluid using several organic fluids. It has been shown that the secondary compression per unit of log (time) to the final thickness of the sample for any pressure increment is directly related to the strength of the soil skeleton at particle level. The secondary compression coefficient decreases with increase in the strength of soil skeleton at particle level, which is governed by the dielectric constant of the pore fluid.

### 5.4 Effect of Electrolyte Concentration

The compression behaviour of a clayey soil is significantly influenced by the concentration of ions in the pore fluid. The effect of the concentration of ions in the pore fluid is different for different types of ions. According to double-layer theory, as ion concentration increases the equilibrium void ratio decreases because the double layer is compressed. The effect of ion concentration is strong at low consolidation pressures when the concentration is greater than  $10^{-4}\text{M}$ . When the ion concentration is less than  $10^{-4}\text{M}$  its effect on the equilibrium void ratio is negligible at all pressures.

## 6. SHEAR STRENGTH

Sridharan & Rao (1979) conducted triaxial tests on Ca- and Na- kaolinites and montmorillonites. Friction angles of  $28.4^\circ$  and  $24.4^\circ$  for Ca- and Na- kaolinites and  $21.7^\circ$  and  $11.2^\circ$  for Ca- and Na- montmorillonites were reported. Zero cohesion intercepts were obtained for all the cases. Thus it is seen that both kaolinite and montmorillonite given higher friction angles when saturated with calcium

### 6.1 Anion Adsorption

Lutz & Haque (1975) reported that phosphorous adsorption reduced modulus of rupture of montmorillonite and montmorillonite-kaolinite mixtures. Shroff (1970) finds that the physico-chemical effect of phosphates improves the strength and durability characteristics of clays. Sreepada Rao

(1982) confirmed by studying various homoionized saturated clays treated with phosphates, that anion adsorption improves the strength.

The phenomenal increase in strength, in the case of kaolinite in spite of reduction in dry density at failure, has been attributed to phosphate adsorption. In case of montmorillonite, the differences in dry densities at failure between treated and untreated soils are small and the increase in strength is only due to phosphate adsorption. The strength behaviour is significantly influenced by the nature of pore fluid. The shear strength of soil which is controlled by modified effective stress is affected by changes in electrical attractive and repulsive pressures. From several investigations it has been concluded that the primary forces responsible for repulsion between two clay particles are due to the interaction of diffuse double layers, which is directly proportional to the dielectric constant. A number of phenomena are responsible for the existence of electrical attractive forces among clay particles and these forces are inversely proportional to the dielectric constant of the pore fluid. Sridharan & Rao (1979) demonstrated that the shear strength increases with decrease in dielectric constant for both kaolinite and montmorillonite clays which is in accordance with the modified effective stress concept. The effect of ion concentration is not significant on the shear strength of saturated sodium and calcium montmorillonite. However, this aspect needs further investigation with other clays and clayey soils.

## 6.2 Permeability

Permeability,  $k$  of clay liner is one of the most important parameter required for calculating the thickness of the liner to attain a particular quantity of seepage. In many sites, leakage rates above the designed level occur due to change in the permeability of the liner due to interaction between the fluid and the clay. While designing the liner, hydraulic conductivity values obtained on samples prepared in the laboratory and tested with pure water are taken. This problem, to some extent, can be solved by testing the clay samples with the actual waste fluid that it will be used for. But, sometimes the characteristics of waste fluid may change while servicing. It is this desirable to understand the parameters that influence the permeability characteristics of different types of contaminants on them. The variables which influence the permeability of soils apart from molding water content, compaction method and compactive effort are: i) associated exchangeable cations; ii) adsorbed anions, and iii) nature of permeating fluid. The effects can be summarized as follows:

- (a) Complex changes in the permeability of clay soil occur with exchangeable cation type, adsorbed anions and the nature of pore fluid. An attempt is made to generalize these changes.
- (b) Increase in the electrolyte concentration of pore fluid increases the permeability of liners. At low and relatively low electrolyte concentrations, the permeability increases with increase in the concentration. At high electrolyte concentrations, the type of cation or anion of the electrolyte plays less important role.

- (c) Acidic solutions generally decrease the permeability of clays initially due to plugging of pores by precipitates formed by reactions between clays and acids. But the long-term effects increase the permeability. The clay becomes saturated with aluminium ion and/or degradation of clay by reactions with acids takes place. Clay saturated with water is impervious to immiscible organic solvents.
- (d) The effect of mixtures of organic fluid and water on the permeability is negligible until the organic liquid content of the fluid is about 70%.
- (e) The permeability increases with decrease in the dielectric constant of the pore medium.
- (f) In the presence of organic fluids of low dielectric constant or electrolyte solutions of high concentration (like brine solution), the clay may shrink and crack causing hydraulic fracturing. But if the confining stress is high this phenomenon may not occur.
- (g) Abnormal increase in the permeability of montmorillonite clays occurs in the presence of potassium salts due to potassium linkages between clay liners.

Thus the behaviour of polluted soil, on the absence of strong interaction can be explained based on changes in double layer development and fabric changes.

## 7. SOIL-POLLUTANT INTERACTION EFFECTS

### 7.1 Salt Contamination Effects

Horta (1985) indicated that when salt water is available in the capillary voids of the pavement and evaporation is allowed, salt crystallization starts and crystals grow in size. Salt crystallization pressure increases with temperature and aridity and decreases with the permeability of the base course material. This pressure causes the heaving in soils.

The influence of clay-brine interactions on the index properties, mechanical properties and hydraulic properties has been described by Barbour & Yang (1993). Decrease in plasticity, increase in shear strength, reduction in volume and alteration of hydraulic conductivity has been reported.

#### 7.1.1 Heave due to Alkali Contamination

Rao & Rao (1994) have reported heave in kaolinite due to loss of cementitious iron oxide coatings by the seepage of the caustic soda solution. Sinha *et al.* (2003) reported that safe bearing capacity of contaminated site is lower by about 33% compared to uncontaminated location.

Recently it is reported that high alkali solutions induce unexpected swelling in both swelling and non swelling soils (Sivapullaiah & Manju 2005; Sivapullaiah *et al.* 2009). Sivapullaiah *et al.* (2004) have studied the structural distortion due to heaving of foundation soil induced by prolonged alkali contamination in an alumina extraction plant, Karnataka, India. They have recommended the use of geo-membrane below the flooring to isolate the footings and to prevent further contamination of sub soil.

### 7.1.2 Acid Induced Heave

Sridharan *et al.* (1981) reported the heaving of a non-swelling soil in a fertilizer plant due to phosphoric acid leakage into the foundation soil from the damaged open drains with joints. This is mainly due to phosphate retention in the soil altering the soil fabric. Preventive measures such as closed conduits and drains with properly designed filter material were suggested.

Assad (1998) reported the tilting of phosphoric acid storage tank of chemical fertilizer factory on the sub grade soil, Aqaba, Jordan. The amount of tilt continued to increase beyond the allowable limit and threatened to hinder the operation of the factory. Laboratory studies revealed that the tilt was due to a differential upheaval of the foundation soil resulting from the chemical reaction taking place between the phosphoric acid that had leaked over the sub grade soil.

Schuling & Van Gaans, (1997), reported that the waste sulphuric acid from ammonium-phosphate fertilizer plant at Armyansk, Crimea, Ukraine, on disposal in to the lake resulted in the natrojarosite formation, which acted as a perfect sealant and restricted the seepage.

Stephenson, *et al.* (1989) reported the upward movement of portions of Kerr-McGee Electrolysis Plant in Henderson, Nevada, in excess of 18 inches, due to the formation of gypsum in the presence of sulphuric acid.

## 8. SULPHATE IN SOILS

The effect of sulphate in soils on geotechnical properties assumes great importance. Sulphates of sodium (thenardite,  $\text{NaSO}_4 \cdot 10\text{H}_2\text{O}$ ), potassium (arcanite,  $\text{K}_2\text{SO}_4$ ), calcium (gypsum or selenite,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and magnesium (epsomite,  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ) are commonly present in the surface sediments, especially in regions of limited rainfall (Grim 1968; Wild *et al.* 1999). Most metal sulphates are readily soluble in water, but calcium and mercuric sulphates are slightly soluble. Sulphates present in pore water or in mixing water can interact with soil. They can induce unexpected cation exchange reactions by removing higher valency ions from ion exchange complex of clay due to formation of insoluble salts with them. Sulphates can also alter pozzolanic reactions of cement and lime treated soil systems. The nature of above reactions depends on the type and concentration of metal ions present, and the availability of alumina and silica that can influence the engineering behaviour of soil with time.

## 9. SOIL-LIME-SULPHATE REACTIONS

There are several factors that influence the lime treated soil properties such as cations, concentration of sulphates and clay minerals composition (available alumina and silica). The anions of sulphates combine with the available calcium and alumina, and form insoluble ettringite in the soil system. The formation of ettringite increases the porosity and simultaneously decreases the free moisture content available

during ettringite nucleation and its subsequent growth. Kota *et al.* (1996) reported that, the presence of sulphate poses problem with calcium-based stabilisation.

Hunter (1988) has reported induced heave in lime-treated soil containing sulphate. Sivapullaiah *et al.* (1993), Sridharan *et al.* (1995, 1997), Puppala *et al.* (1999) have shown that the presence of sulphate increases the compressibility of lime-treated black cotton soil after curing for prolonged periods. Burkart *et al.* (1999) showed that the presence of sulphate as gypsum induces deformation in lime treated soils. However, very little information is available regarding its effects on sulphate in acidic environment.

## 9.1 Volume Change Behaviour of Expansive Soil with Acid Solution

Acid sulphate soils are soils containing highly acidic soil horizons affected by the oxidation of iron sulfides. Acidic drainage results from the interactions of sulphide minerals particularly pyrite with oxygen, water, and Acidithiobacillus bacteria. The mechanism of pyrite oxidation is given in Figure 2.

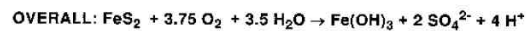
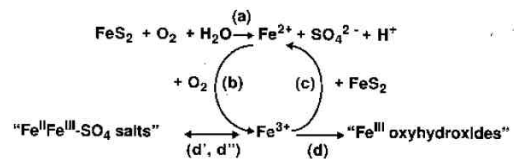


Fig. 2: Oxidation of Pyrite (Rose & Cravotta 1998)

When pyritic sediment falls dry, oxygen penetrates and pyrite is oxidized, by microbial intervention, to sulphuric acid and ferric hydroxide ( $\text{Fe}(\text{OH})_3$ ). Potential acid sulphate soils contain sulphidic soil material that contains pyrite but has not oxidized to the extent that the soil-pH dropped to a value below 3. Sulphuric acid is a widely-used industrial chemical. Spills from the storage tanks and extensive use of sulphuric acid are some of the common sources of soil contamination.

## 10. PROBLEMS DUE TO ACID SULPHATE SOILS

When the acid sulphate wetland soils are drained, their gel-like iron sulphide layer dries out and the soils shrink and subside. This may make farmland more prone to flooding and water logging. Acid water leached from oxidising acid sulphate soils can cause rust-coloured stains and slimes.

## 11. ACID-IRON OXIDE-REACTIONS

Considerable information is available on the effect of strong acids on iron oxides, which is present in both the octahedral and tetrahedral sheets of 1:1 and 2:1 clay minerals. In natural soils, iron oxides are commonly precipitated or adsorbed to the clay surfaces or admixed as a separate phase. The acid

sulphate when interacts with iron compounds, the stability to form compounds depends on the pH of solution. It is interesting to note that most of the iron is in dissolved form ( $\text{Fe}^{2+}$ ) at the pH of acid sulphate drainage than the pH of seawater. Sulphate present in the soil and in pozzolanic stabilization is also known to induce swell in soils.

### 11.1 Swell-Compression Relationship of Polluted Soils

Interaction of clay minerals and soils with chemical solutions can cause alteration of the diffuse double layer; can have pronounced effect on the tightly bound water, hydration and exchange of ions and alteration of the minerals and hence change the swelling behaviour. It is generally observed that in natural environment, soil that swell more undergo high compression and vice versa. When the soil interacts with different pore fluids, swell and compression behaviour changes that take place are not known.

Different investigators brought out the time-swell relationship pattern as hyperbolic nature in the natural soils (Dakshanamurthy 1978). The nature of time swell relationship and the applicability of the hyperbolic relationship for contaminated soils in general and acid contaminated soils in particular are not known.

### 11.2 Acid Sulphate Induced Swell

As seen from Figure 3 the soil shows considerably higher swell when it is saturated with 1N  $\text{H}_2\text{SO}_4$  at nominal surcharge of 6.25 kPa.

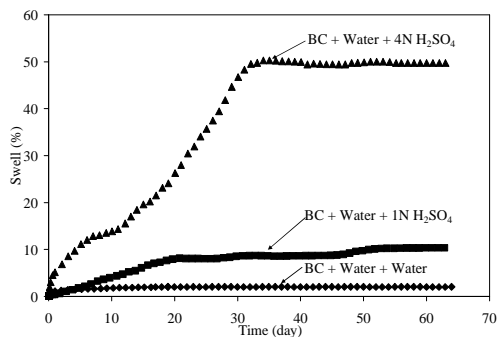


Fig. 3: Swell Behaviour of Expansive Soil with Sulphuric Acid Solutions

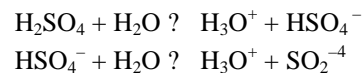
This might be due to disassociation of hydrated hydrogen ion in sulphuric acid which replaces the exchangeable cations in the interlayer of minerals initially with hydrogen. However, the sample compacted and inundated with water shows a swelling of about 2% reached in about 10 days. The moderate swelling in BC soil alone is due to the presence of divalent or trivalent iron cation, though the soil is rich in montmorillonite. The soil shows abnormally high swelling when the soil is saturated with 4N  $\text{H}_2\text{SO}_4$  solution in the consolidation cell under nominal surcharge. This could be due to attack on the lattice structure of soil mineral by the dissociated hydrogen ions.

### 11.3 Time Swell Relationship

It has been observed that the time-swell relationship of soil alone with water strictly follows hyperbolic pattern. However, the swell patterns observed for soil with 1 or 4N sulphuric acid solutions as remoulding/inundating fluids have not shown the hyperbolic relationships. Further the non-occurrence of hyperbolic nature of curves shows the change in mineralogy, which may be due to very long period of interaction with acid solution to complete the mineralogical changes. Thus the start of swell is delayed.

### 11.4 Mineralogical Changes in Soil

When sulphuric acid is diluted with water, its dissociation occurs in the following two stages:



Initially the exchangeable cations of the soil sample are substituted by released  $\text{H}_3\text{O}^+$  (hydronium). This is the reason for the release of exchangeable ions of soil on interaction with sulphuric acid. In addition to this, due to the ionic potential (electric charge of hydrated cation/smaller size) of hydronium it penetrates into the crystal of soil structure, leading to the displacement of structural ions. However, the anion,  $\text{SO}_4^{2-}$ , remains mobile and acts as the counter-ion for the cations. Thus these reactions cause considerable changes in the mineralogy of soil. The released  $\text{H}_3\text{O}^+$  can cause changes in cation exchange complex of the clay particles, which lead to mineralogical and morphological changes.

The original black cotton soil having amesite and kalsilite minerals interacted with sulphuric acid solutions formed alunogen and mereiterite. The alunogen (an aqua aluminum sulphate hydrate— $(\text{Al}(\text{H}_2\text{O})_6)_2(\text{SO}_4)_3(\text{H}_2\text{O})_5$ )—showed pronounced peaks. The mereiterite which is potassium iron sulphate hydrate-  $\text{K}_2\text{Fe}(\text{SO}_4)_2(\text{H}_2\text{O})_4$  might have formed after the leaching of potassium from kalsilite.

### 11.5 Volume Change Behaviour of Non-Expansive Soil with Acid Solution

Figure 4 shows the percent swell of red earth compacted with water and inundated with water, 1 and 4N  $\text{H}_2\text{SO}_4$  solutions at nominal seating load. With water as inundating fluid, only 0.36% of swell is observed. The low swell is due to mineralogy, lower clay content and the lower cation exchange capacity. It is very interesting that abnormal swell of 22% is observed in the same soil when the inundating fluid is 1N sulphuric acid solution. This swell occurs over a period of 275 days. The swell further increased with 4N sulphuric acid as inundating fluid. An incredibly high swell of 55% is noticed when it reaches equilibrium in about 230 days.

The induced swell by sulphuric acid can be explained as the Sulphuric acid dissociates into hydronium and sulphate ion in water. Initially, the hydronium ion, due to its smaller size and/or ionic potential, penetrates into the crystal of mineral

structure leading to the reduction in H-bonding between successive basic units of kaolinite. Hydrogen ions can leach out iron present in the lattices of kaolinite and can form a new mineral by association with dissociated anion,  $\text{SO}_4^{2-}$ .

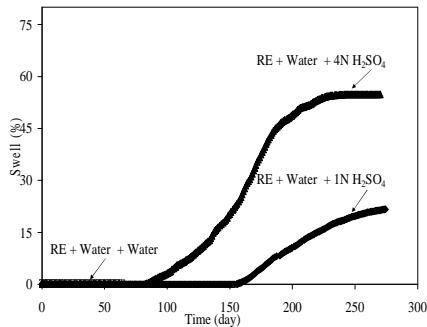


Fig. 4: Swell Behaviour of Acid Treated Red Earth

Further it can be observed that the delay in starting of swell process decreases with increase in concentration of inundating fluid. A lag period of 160 days which was observed in soil inundated with 1N sulphuric acid, reduced to 85 days with 4N sulphuric acid. It has been observed that the time–swell relationship of soil alone with water strictly follows hyperbolic pattern. However, the swell patterns observed for soil with 1 or 4N sulphuric acid solutions as remoulding/inundating fluids have not shown hyperbolic relationships. Further the non-occurrence of hyperbolic nature of curves shows the changes in mineralogy, which may be due to very long period of interaction with acid solution to complete the mineralogical changes, hence leading to delayed start of swell.

X-ray diffraction patterns of treated and untreated red earth shows the peaks due to kaolinite mineral. After the completion of consolidation in red earth inundated with acid solutions, formation of rozenite mineral has occurred, which is an iron sulphate hydrate. In addition, the peak of corundum–aluminum oxide is also observed in the soils inundated with acid solutions.

## 12. MEASURES TO CONTROL THE SWELL

Understanding the mechanisms of contaminated induced heave helps to control and/or arrest the swell by adopting various conventional or modified approaches.

The following are the common methodologies help to control the heave reported in soils.

**Addition of Potassium Chloride:** Potassium chloride which improves the properties of expansive soil is found to control the ill effects of alkali solution.

### 12.1 Pozzolanic Stabilization

**Cement Stabilization**—In this technique Portland cement and soil mixed at the proper moisture content has been used increasingly in recent years, in special situations.

**Lime Stabilization**—Lime stabilization has been extensively used to decrease swelling potential and swelling pressure in

clays. The addition of lime produces a high concentration of calcium ions in the double layer around the clay particles, hence decreasing the attraction of water. Also the pozzolanic compounds bind soil particle to improve the strength and decrease swelling.

**Lime-Fly Ash and Lime-cement fly ash**—One way to improve the given soil is to blend it with other natural materials. The use of lime (L) or cement (C) and fly ash (F) is common to improve the properties of expansive soils. Fly ash can be successfully used to control the alkali induced heave in soils (Sivapullaiah & Reddy 2009).

**Injection and Grouting**—Grouting has been extensively used to control the ground water flow. Since the process fills soil voids with some type of stabilizing material, grouting is also used to increase soil strength and prevent excessive settlements.

**Moisture Control Measures**—Cutoff walls, which limit inflow into the excavation, or lower the ground water levels to reduce the hydraulic head, act as impermeable membranes.

**Stabilization by Geotextile and Fabrics**—Geotextiles are versatile in use, adaptable to different circumstances, and can be combined with many traditional materials. Geotextiles usually fulfill one or more criteria such as drainage, filtration, separation and reinforcement are made to control the acid induced effects.

## 13. SUMMARY

- Changes in Fine Grained soil behaviour due to contaminants in the absence of strong interaction leading to mineralogical changes can be explained based changes in diffuse double layer theory and fabric changes.
- Unexpected heave can occur in swelling and non swelling soils due to contamination. With Acid contamination induces swelling soils due to gradual changes in the mineralogy of soils.
- The amount of swell depends up on the type of mineral present in the soil and concentration of the acid solutions.
- The conventional hyperbolic relationship for swell—compression is not valid for the contaminated soil.
- Innovative measures are needed to control undesirable changes in the soil behaviour.

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