INVITED PAPER

Surprising Soil Behaviour: Is It Really!!!

P. V. Sivapullaiah

Abstract Several instances of unexpected soil behavior, which either conventional or advanced forms of soil mechanics could not be explained are termed as 'Surprising'. Several cases of unexpected behavior, more particularly heave in fine grained soils are due to contamination of foundation soil. An attempt is also made to understand and explain the mechanism of heave based on extensive laboratory and field studies on contamination of soils with strong acid and alkali solutions. Also the heave in lime stabilized soil in the presence of sulphate after long periods of interaction has been relooked with recent work. The mechanism and characteristics of occurrence of this type of heave in both swelling and non-swelling soils, which is different from conventional swell in expansive soil, is not understood. Conventional remedial approaches to control the heave would fail. Particular attention is paid to draw a special testing plan and analyzing the results from more fundamental principles. It was brought out that changes in the mineralogy of the soil which occur over geological ages (rock cycle) are triggered and occur in relatively shorter period due to interaction with strong acid or alkaline solutions. The associated changes in soil behaviour are explained based on mineralogical alterations, fabric and physic-chemical environment. Very often, more than formation of swelling minerals formed, the free energy released by mineral transformations controls the induced heave in soils. Some of these considerations are also important to overcome the problems in natural soils and initiate appropriate remedial measures.

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Introduction

The behavior of fine grained soils is much more complex and variable compared to coarse grained soils. The fine grained soil systems undergoes more volume changes, i.e. swell or shrink on wetting and drying, and is influenced by ionic concentration or composition. Very often fine grained soils exhibit unexpected properties/behavior. Four such cases—(1) The aging of quick clay after sampling, in which the remolded strength increased in samples maintained at constant water content; (2) time effects in freshly densified or deposited sand, in which natural sand deposits can lose strength if disturbed but regain strength over time periods of weeks to months; (3) apparently sound lime-stabilized soil that swells and disintegrates starting a few years after construction; and (4) the failure of excess pore pressures to dissipate as predicted during the consolidation of soft clays—are described by Mitchell (1976) and reinforced that soils are not inert materials and they can change with time and sensitive to environmental changes. Interactions with environment alter the behavior of the soils and, if not understood or explained, can be surprising, as highlighted by Eminent Professor J. K. Mitchell in his 20th Terzaghi's Lecture (ASCE 1986). To understand and also overcome the problems created by unexpected changes in soil behavior, it is necessary to consider the factors that influence their behavior, not only to deal with them and even forecast well in advance. It is necessary to present a brief account of formation of fine grained, particularly clay minerals, and factors controlling their behavior.

Fig. 1 A simplified version of the rock cycle (*Source* Eberl 1984)
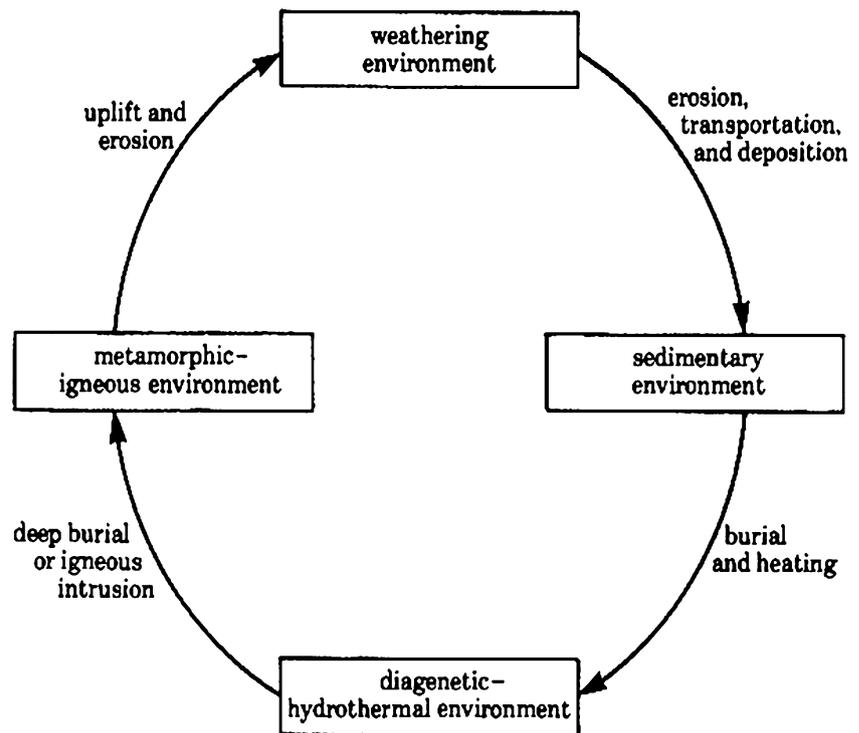
Coarse Grained Soils Versus Fine Grained Soils

Soil is a complex body composed of four major components inorganic mineral matters water, air or gases, and organic matter. According to its size, soil can be separated into various fractions—sand, silt and clay. Soils consisting of predominantly sand and silt are called coarse grained soils, whereas, fine grained soils contain only silt and clays. From a physical point of view soils are made up of solids and pore space which is occupied by varying proportions of air and water. Almost any mineral that exists may be found in some soil, somewhere. Mineralogically, sand and silt are just small particles of rock and are largely inert. In sands with little or no clay present the system consists of single-grain particles with only small contact area between particles and pore space which remains constant during saturation with water and also as water moves through the system. Particles in the system are not aggregated and remain as single-grain particles when the system is disturbed by external forces. There are no secondary compound particles (aggregates) and the structure depends only on the size, shape and packing of the solid nonporous particles. Thus soil mechanics which applies the laws of mechanics and hydraulics is generally adequate to explain the behavior of coarse grained soils. On contrary, the behavior of fine grained soils and clay minerals is dominated by physic chemical forces. It is, thus, important to make a great distinction in understanding the behavior of fine grained and coarse grained soils. An attempt is made to

present briefly the factors that control the behavior of fine grained soils more particularly those of the clays.

Clay Mineral

Three mechanisms for clay mineral formation (inheritance, neo-formation and transformation) operating in three geological environments (weathering, sedimentary, and diagenetic-hydrothermal) yield nine possibilities for the origin of clay minerals in nature. Several of these possibilities are discussed in terms of the rock cycle (Fig. 1) [1]. The mineralogy of clays neo formed in the weathering environment is a function of solution chemistry, with the most dilute solutions favoring formation of the least soluble clays. After erosion and transportation, these clays may be deposited on the ocean floor in a lateral sequence that depends on floccule size. Clays undergo little reaction in the ocean, except for ion exchange and the neo formation of smectite; therefore, most clay found on the ocean floor is inherited from adjacent continents. Upon burial and heating, however, dioctahedral smectite reacts in the diagenetic environment to yield mixed-layer illite–smectite, and finally illite. With uplift and weathering, the cycle begins again.

Formation of Different Clay Minerals

Clays and clay minerals occur under a fairly limited range of geologic conditions. The environments of formation

include soil horizons, continental and marine sediments, geothermal fields, volcanic deposits, and weathering rock formations. Most clay minerals form where rocks are in contact with water, air, or steam. Examples of these situations include weathering boulders on a hillside, sediments on sea or lake bottoms, deeply buried sediments containing pore water, and rocks in contact with water heated by magma (molten rock). All of these environments may cause the formation of clay minerals from preexisting minerals. Extensive alteration of rocks to clay minerals can produce relatively pure clay deposits. Precipitation from soil solution—products of weathering accumulates in the soil solution and may exceed the solubility product of certain minerals. The contact of rocks and water produces clays, either at or near the surface of the earth [2].

Rock + Water → Clay

For example, the CO_2 gas can dissolve in water and form carbonic acid, which will become hydrogen ions H^+ and bicarbonate ions, and make water slightly acidic.

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$$

The acidic water will react with the rock surfaces and tend to dissolve the K ion and silica from the feldspar. Finally, the feldspar is transformed into kaolinite.

Feldspar + hydrogen ions + water → clay (kaolinite) + cations, dissolved silica

$$2KAlSi_3O_8 + 2H^+ + H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 4SiO_2$$
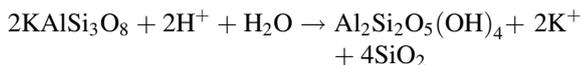
The alternation of feldspar into kaolinite is very common in the decomposed granite. The clay minerals are common in the filling materials of joints and faults (fault gouge, seam) in the rock mass weak plane. However the alterations in clays, when subjected intense chemical environment, are not well understood. A brief description of clay minerals structure is presented here as it plays an important role in these alterations.

Clay Mineral Structure

Clay minerals are layer silicates that are formed usually as products of chemical weathering of other silicate minerals at the earth's surface [3].

They are found most often in shales, the most common type of sedimentary rock. In cool, dry, or temperate climates, clay minerals are fairly stable and are an important component of soil. The role of annual precipitation on the formation of different types of clay minerals is shown in Fig. 2. There are many types of known clay minerals (Fig. 3) [4, 5].

Some of the more common types are:
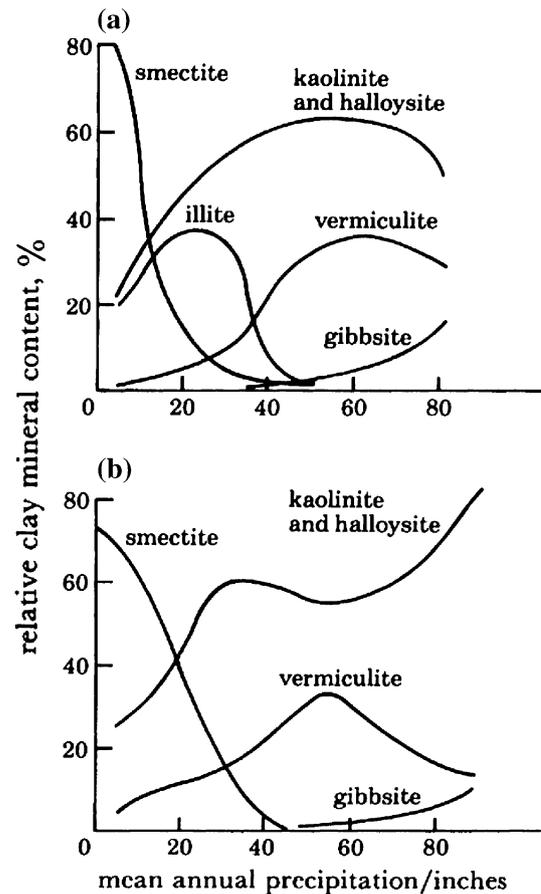
Fig. 2 The relative abundance of clay minerals with annual precipitation (Source Eberl 1984)

Kaolinite This clay mineral is the weathering product of feldspars. It has a white, powdery appearance. Because kaolinite is electrically balanced, its ability of adsorb ions is less than that of other clay minerals.

Illite Resembles muscovite in mineral composition, only finer-grained. It is the weathering product of feldspars and felsic silicates.

Chlorite This clay mineral is the weathering product of mafic silicates and is stable in cool, dry, or temperate climates. It occurs along with illite in mid-western soils. It is also found in some metamorphic rocks, such as chlorite schist.

Vermiculite This clay mineral has the ability to adsorb water, but not repeatedly.

Smectite This clay mineral is the weathering product of mafic silicates, and is stable in arid, semi-arid, or temperate climates. It was formerly known as montmorillonite. Smectite has the ability to adsorb large amounts of water, forming a water-tight barrier, and the chemical industry. There are two main varieties of Smectite, (a) sodium smectite (the high-swelling form of smectite, which can adsorb up to 18 layers of water molecules between layers
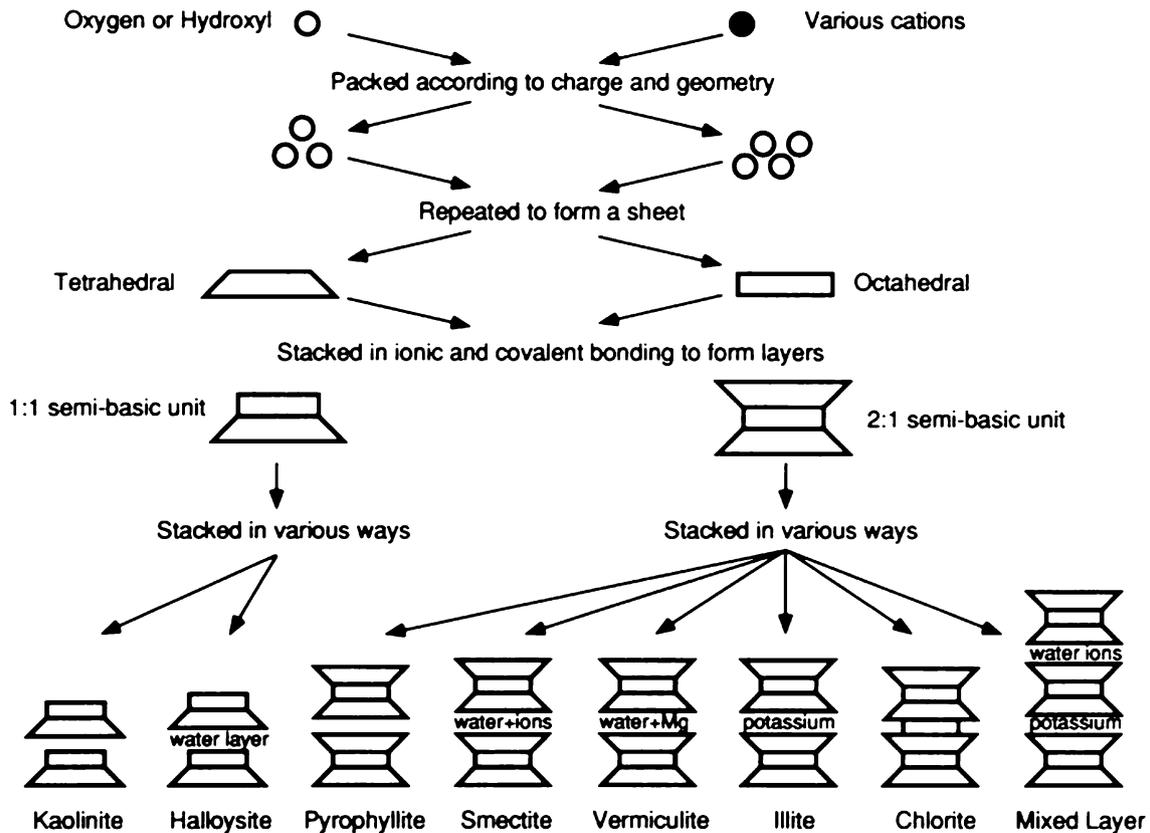
Fig. 3 Some common clay minerals (*Source* Mitchell 1993)

of clay) and (b) calcium smectite (the *low-swelling* form of smectite adsorbs less water than does sodium smectite). *Attapulgite* This mineral actually resembles the amphiboles more than it does clay minerals, but has a special property that smectite lacks—as a drilling fluid, it stable in salt water environments. When drilling for offshore oil, conventional drilling mud falls apart in the presence of salt water.

In humid tropical climates, clay minerals are unstable and break down under intense chemical weathering to become *hydrated oxides* of aluminum (bauxite) and iron (goethite).

Interstratification in Phyllosilicates (after [4])

The properties and compositions of some mineral colloids are intermediate between those of well-defined minerals such as kaolinite and smectite as described in above. Such minerals are referred to as mixed-layer or interstratified minerals. Most mixed-layer clays contain smectite or vermiculite as a swelling component [6]. Partial removal of interlayer potassium from micas or of interlayer hydroxide from chlorite is one way that interstratification minerals can form in soils [7]. Other possibilities include (i) fixation of adsorbed K^+ by some vermiculite layers to yield mica-

like layers, and (ii) the formation of hydroxide interlayers to produce chlorite-like layers. Interstratification of layers can be regular or random [8] as given below:

(1) A periodic alternation of layers of two types A and B refers to regular or ordered mixed-layers: ABA-BAB…. or AABAABAAB…

(2) A random alteration of each type of layer corresponds to irregular and randomly mixed-layered clays: AABABBBAAABAABA.

Illite–smectite is the most interesting mixed-layer clays (Fig. 4). They are quite ubiquitous, well known from a chemical standpoint and exhibit a mineralogical variation that responds to pressure–temperature variations during diagenesis.

Clay minerals act as "chemical sponges" which hold water and dissolved plant nutrients weathered from other minerals [9]. This results from the presence of unbalanced electrical charges on the surface of clay grains, such that some surfaces are positively charged (and thus attract negatively charged ions), while other surfaces are negatively charged (attract positively charged ions). Clay minerals also have the ability to attract water molecules. Because this attraction is a surface phenomenon, it is called adsorption (which is different from *absorption* because the
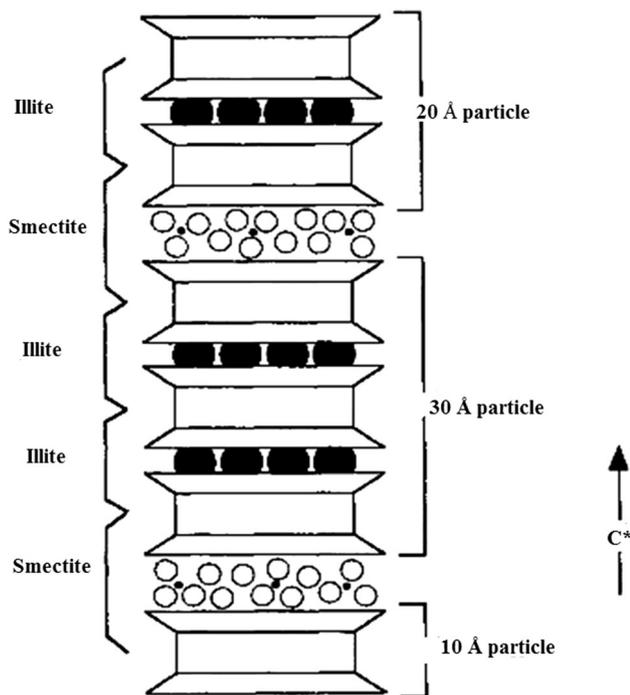
Fig. 4 Mixed layered illite–smectite (*Source* Mitchell 1993)

ions and water are not attracted deep inside the clay grains) [9]. Clay minerals resemble the micas in chemical composition, except they are very fine grained, usually microscopic. Like the micas, clay minerals are shaped like flakes with irregular edges and one smooth side. The amount and type of clays present in fine grained soils in nature varies considerably.

Behavior of Fine Grained Soils

Clay minerals form at or near earth's surface, in soil or in water. Most clays belong to a class of minerals called phyllosilicates, which have formed from the breakdown products of other minerals [10]. Like all phyllosilicates, clay minerals have a sheet-like structure, which is revealed when the crystals are observed through a scanning electron microscope. More familiar phyllosilicate minerals that are often large enough to be seen with the naked eye are the micas such as muscovite and biotite. It is commonly known that surface phenomena are important factors in controlling the behavior of fine-grained soils. Clay mineralogy, cation exchange capacity (CEC), specific surface area (SSA), and clay fraction are dominant factors in controlling the behavior of fine grained soils [11]. Specific surface area varies greatly between soils because of differences in mineralogy, organic composition, and particle-size distribution. Clays contribute the greatest amount of surface area of any of the mineral constituents of soil, but may also differ a great deal in specific surface area. For example, swelling clays such as montmorillonite have specific surface areas up to 810 m^2/g. Nonexpanding soils such as kaolinites typically have specific surface areas ranging from 10 to 40 m^2/g [11]. Consequently, the type of clay mineral present in soil is of major importance in determining the effect of specific surface area on soil properties. Since the surface area of a soil is controlled by the grain-size distribution and clay mineralogy, it can be considered as an "intrinsic" soil property. It is a constant related to the soil constituents and does not change with water content, time, etc. Therefore, SSA is much like the grain-size distribution of a soil, in that it is unaffected by external variables. There is strong evidence in the literature to indicate that specific surface area is the single most important factor in contributing the engineering behavior of fine grained soils [12].

Clay is involved in almost every reaction in soils which affects the geotechnical behavior. Both chemical and physical properties of soils are controlled to a very large degree by properties of clay. The geotechnical behavior of fine-grained soils is essentially controlled by soil mineral composition through their surface area, ion exchange capacity and through soil structure. Soil surface charges and their interaction with water play an important role in arriving at the structure and properties of fine-grained soils. Figure 5 shows the role of cations to change the behavior of soil.

Positive Charges

Anion exchange capacity (AEC) of clays arises by protonation of hydroxyl groups on the edges of silicate clays and on the surfaces of metal oxide clays Anion exchange is inversely related with pH is greatest in soils dominated by the sesquioxides. It is known that the edge and corners of the clay particles can carry a charge opposite to that of forces. The surface of the soil particle has a negative charge and the edge and corners have a positive charge. When electrostatic forces cause adsorption of anions, it is called nonspecific adsorption. Two types of adsorption of anions can be recognized as negative and positive adsorption. The repulsion of anions from colloidal surfaces possessing negative charges is called negative adsorption. Positive adsorption of anions is the adsorption and concentration of anions on the positively charged surfaces or edges of soil colloids. The anions Cl^-, NO_3^-, and SeO_4^{2-} and to some extent HS^- and SO_4^{2-}, HCO_3^-, and CO_3^- adsorb mainly by ion exchange. Borate, phosphate and carboxylate adsorb principally by specific adsorption mechanisms. In contrast to CEC, AEC is the degree to which a soil can adsorb and exchange anions. AEC increases as soil pH decreases. Thus clay particles have an amphoteric character, i.e. the power to bind both cations and anions. Anions function as counter ions and are

Fig. 5 The mechanism of
cations in influencing the
behavior of fine grained soils
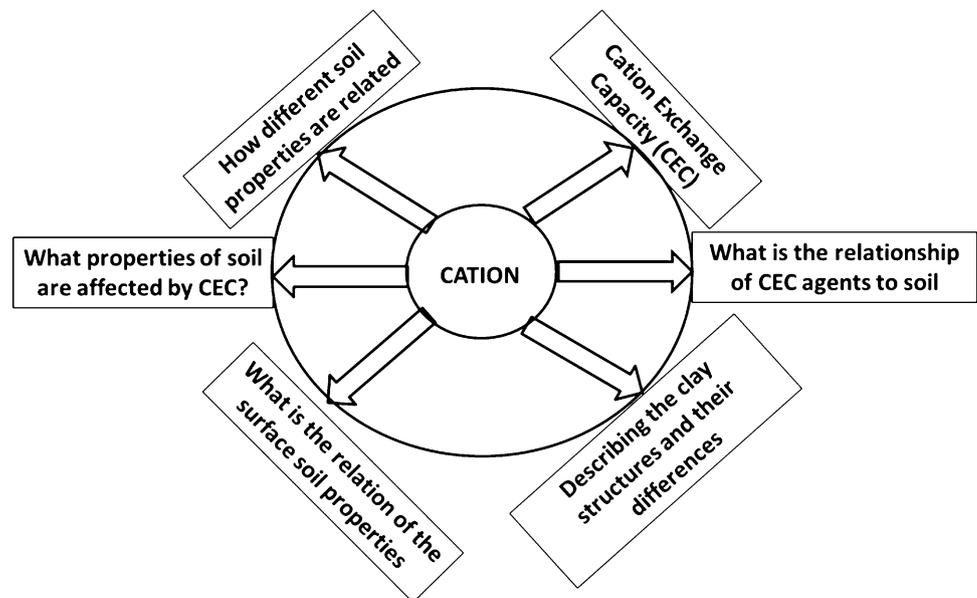
exchangeable with other anions in the same way as cations are exchanged.

Changes in the Behavior of Clays

Water logging and the reducing conditions created reduces iron in some clay mineral lattices leading to the formation of beidellite [13]. This reduction of iron creates more negative charge in the clay lattice which represents an increase in the CEC, greater selectivity for Ca and more particle–particle interaction. This will change the micro-structure of the clays and be reflected in the structure of the soil. Aggregation in soils is controlled by clay mineralogy, often modified and complicated by the addition of organic materials. Soils which contain clays with variable charge due to the presence of oxides of Al and Fe are generally porous and stable [13].

This characteristic is exhibited in volcanic ash soils where disordered aluminosilicates, ferrihydrite and organic materials interact to produce a structure stable to cultivation and manipulation in the laboratory, e.g. hydraulic conductivity of soil columns. Oxisols also exhibit structural stability due to a predominance of kaolinite and oxides—the variable charge

system typical of intense weathering in tropical regions. Care needs to be taken when liming such soils because it can decrease aggregation, at least in the short to medium term. In soils where the clays have a permanent negative charge structure and stability depend on the presence of Ca and/or organic materials. A range of presentations discuss positive correlations between clay, aggregation and organic matter including the composition of the organic matter. Studies range from field observations of soils to laboratory experiments using both extractions and additions of organic materials.

The role of clay minerals on geotechnical behavior is well understood. Changes in ion exchange are complex with respect to cations and anions can cause significant changes in soil water interactions and the soil structure. Thus, any change in the physico-chemical environment can significantly alter the behavior of fine grained soil. These effects can be understood from the considerations of diffuse double layer theory (Table 1) [14].

This may often result in progressive or sudden failure of structures when the foundation soil environment changes without any changes in applied stress. To exercise any control on changes in the behavior the chemical environment needs to be altered. However, the clay minerals once

Table 1 Properties of different prominent clay mineral (after Grunwald 2005)

Clay mineral	Type	CEC (cmol/kg)	Swelling potential	Specific surface area (m^2/g)	Basal spacing (nm)
Kaolinite	1:1 (non-expanding)	3–15	Almost none	5–20	0.72
Montmorillonite	2:1 (expanding)	80–150	High	700–800	0.98–1.8+
Vermiculite	2:1 (expanding)	100–150	High	500–700	1.0–1.5+
Hydrous Mica	2:1 (non-expanding)	10–40	Low	50–200	1.0
Chlorite	2:1:1 (non-expanding)	10–40	None	–	1.4

formed take a very long period (may be hundreds of years) and their influences persist in soils. The process of alterations of clay minerals in different environments during their formation and immediately after is not well understood. However strong change in the chemical environment can promote mineralogical changes inducing abnormal changes in the soil behavior which cannot be explained by soil water interaction process. The clay contaminant interaction can lead to formation of new minerals [15]. Little is known about the effect of alteration of clay minerals on the geotechnical behavior of soils.

Mineralogical Alterations

Influence of Structure or Fabric of Mineral Particles

The arrangement of particles will depend on how the particles repel or attract each other through the double layers. Because of the like nature of surface charges, the forces due to diffuse double layers are repulsive. The forces of interaction between charged surfaces in an electrolyte could be understood in terms of the increase in pressure as the two surfaces are brought together from infinity. The increase in pressure depends on the ion density at the mid plane.

Clay Fabric

The term 'soil fabric' describes the arrangement, shape, size, and size distribution of the mineral constituents in a soil. On a large scale, the soil macro fabric can influence the engineering behavior of the soil and should be noted in a soil description; for example, thin lenses of impermeable clay in a permeable sand would be significant, as would the inclusion of organic material, the presence of fissures or root holes within a clay, or the preferential growth of secondary minerals on soil laminations.

In non-cohesive soils, i.e. soils without a significant content of clay minerals, the principal characteristics of the fabric are the particle size distribution, particle shape, particle orientation, and the packing arrangement. For example, soils with well-rounded, equal grains have a more open structure than similar soils with angular grains, and soils with a range of particle sizes may be denser because smaller grains fit between bigger ones. A *grain-supported fabric* describes a soil where the larger particles touch, with finer sediment filling the spaces between; conversely where there is enough finer sediment for the larger particles to be separated, the fabric is described as *matrix supported*. *Locked sand* is a term used to describe sands that have undergone pressure solution and have interpenetrative point contacts, giving a much stronger fabric than might

otherwise be expected, although lost irreversibly upon disturbance [16].

In cohesive soils, the particular properties of clay minerals and the forces of repulsion and attraction acting between adjacent clay particles have important influences on the soil fabric. Clay mineral platelets carry a residual negative charge and attract cations present in the pore water to form a cloud around the particle, in what is termed the double layer. The cations are not held strongly and the equilibrium may be readily upset if the nature of the water changes and other cations are introduced, since some cation, depending on their valency and sizes have a greater affinity for the layer than others. Those with a greater affinity tend to replace those with less, by a process called *cation exchange*, resulting in a change in the thickness of the double layer.

Attraction between adjacent clay particles is due to short-range van der Waals forces, which decrease rapidly with increasing distance between particles. On the other hand, repulsion occurs between the like charges of the double layers. If the layer of cations is thin and the attractive van der Waals forces dominate over the repulsive forces between cations, then the particles will orientate themselves with edge-to-face orientation (positive to negative). This is termed *flocculation* and the soil is said to exhibit a flocculent structure [17]. In a marine depositional environment where there is a high concentration of cations, adsorbed layers are thin and the clay minerals tend to settle out of suspension with this structure. This is in contrast to lacustrine clays deposited in a freshwater environment which settle in a face-to-face orientation because of a net repulsion. This is termed a *dispersed structure*.

Natural clays invariably contain a mixture of various types of clay minerals and larger particles of more inert minerals such as quartz, leading to very complex structural arrangements.

Individual platelets generally form aggregations of particles with a face-to-face orientation which combine with other aggregations in a structure determined by the depositional environment (Fig. 6).

The property of cation exchange in clays is used whereby the dispersed mineral fabric of a heavy clay soil is flocculated by the additional of calcium (lime) to improve the workability. The clay minerals take up the calcium in preference to the existing sodium, and the rearrangement of the particles creates a more pervious, open structure.

The engineering significance of a soil fabric can be assessed by measuring the *sensitivity* of a soil. Thus the behavior of fine grained soils is highly sensitive to physico-chemical environment and often the changes are surprising if looked from mechanics point of view.

Monroy et al. [18] have showed important changes take place for weather London clay micro-fabric during
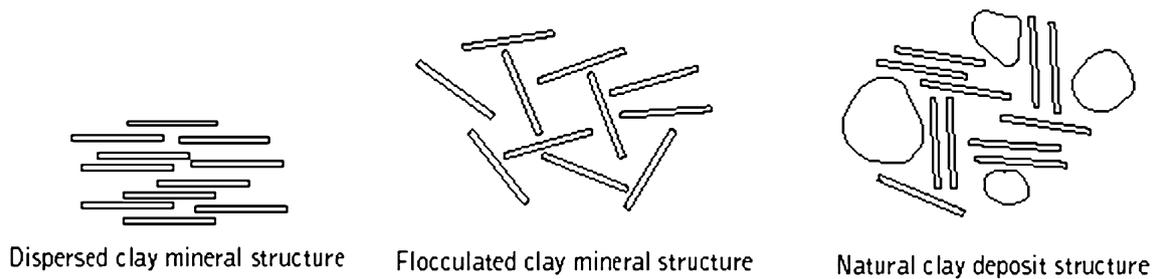
Fig. 6 Clay structures

Fig. 7 Schematic effects of change in the nature of pore fluid nature
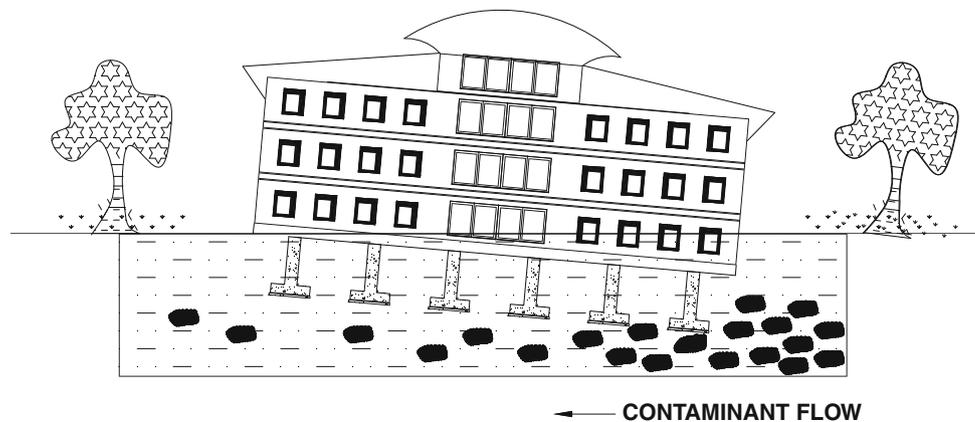
wetting, whereas the effect of loading was seen to be less severe.

Changes Soil Behavior due to Changes in Physico-Chemical Behavior Without Chemical Interaction

The change in properties of soil results from

(i)   alteration in the cation and anion exchange capacity and exchangeable ions of clay, and
(ii) change in the nature of pore fluid characterized by dielectric constant and electrolyte concentration.

The effects may be different for different types of soils. Their effects on the geotechnical properties such as index properties, volume change, strength and permeability of soils can generally be predicted based from considerations of changes in the thickness of diffusion double layer developed on clay surfaces [19, 20].

Hydraulic Conductivity

The permeability increases with decrease in the dielectric constant of the pore medium. Tests with organic fluids indicate that changes in hydraulic conductivity are in response to changes in fabric as well as pore fluid characteristics, interaction with the clay mineral, and confining stress.

Consequences

The volume change behavior is that high settlements can occur in the foundation soil at the same effective pressure, if there is a change in cation exchange complex of the clay in the soil/electrolyte concentration of pore fluid/dielectric constant of the pore fluid. These effects can be similar to what are shown in Fig. 7.

Some Abnormalities (Surprises) in the Relationships of Soil Properties

Swell Behavior of Different Types of Clays Mineralogy

The differential free swell of soils as determined by Indian Standard (IS) code suffers from the limitation in that the free swell of non-expansive kaolinite is higher in kerosene than in water. To overcome this limitation proposed to a method where the free swell is just measured as the sediment volume in water per gram of soil without comparing with any other fluid. This method also suffers from the problem when the specific gravity of soils differs considerably. To overcome both these limitations a new method is given by Sivapullaiah et al. [21] where modified free swell method is given as;

Fig. 8 Relationship between liquid limit and shrinkage limit in soils with and without lime treatment (Sivapullaiah et al. [25])
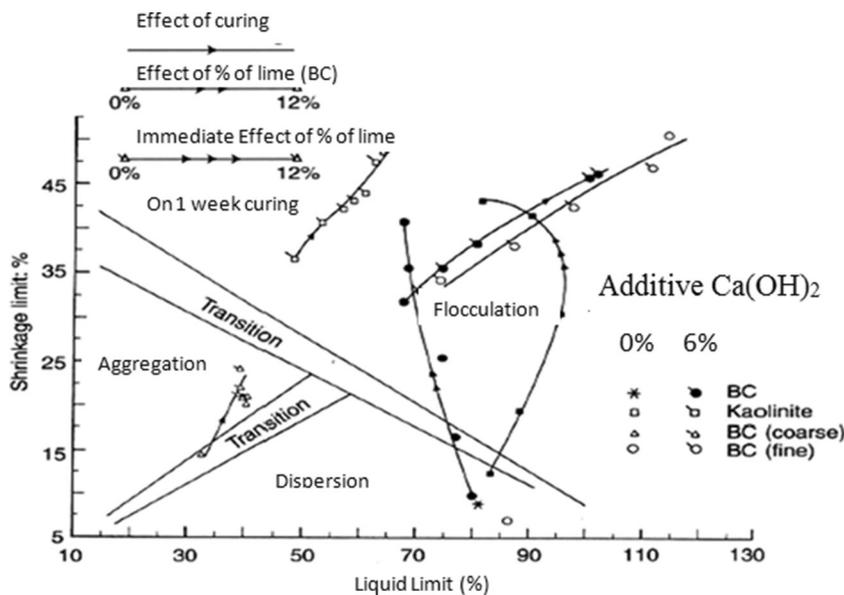
Modified free swell index $= (V - V_s)/V_s$

Liquid Limit Versus Plasticity Index

Attempts have been made to relate plasticity index and liquid limit. However many of these relationships are valid only for soils which lie on A-line in plasticity chart. It is often ignored that the relationship depends on the clay mineralogy of the soil and vary between A- line and U-line.

Shrinkage Limit Greater Than Plastic Limit

It is interesting that the plastic limit of soils would be higher than shrinkage limit. A literature review also reveals that, in some extreme cases, the shrinkage limit can be greater than the plastic limit [22–24]. This has been explained by Sridharan and Prakash [24] that in soils with low clay fraction such as in silty soils, which usually assume relatively poor gradation, cannot assume dense packing and the shrinkage limit assumes higher value than plastic limit as it will still be plastic stage.

Both Liquid Limit and Shrinkage Limit Increasing

Generally as the liquid limit of soils increase their shrinkage limit decreases. But for soil which are highly flocculated, as in the case of soils with many hydroxide including lime, the shrinkage limit also increases. Thus based on value of liquid limit and shrinkage, one can identify the fabric of the soils using the fabric chart (Fig. 8) [25].

### Maximum Dry Density Decreasing and Strength Increasing

For most soils as maximum density increases, the strength increases and vice versa. But for some soils the strength of soils increases even though the maximum dry density decreases as in the case of lime addition.

Behavior of Lime Stabilized Sulphatic Soils

Lime is often used to control the swell in soils with high cation exchange capacity and large specific surface. However the lime stabilized soils are known to exhibit delayed swelling and loss of strength in the presence of sulphate. This is attributed to the alteration of cementitious compound such as calcium silicate hydrate etc. into ettringite and thaumasite. Recent studies [26, 27] have revealed that these minerals may not have increased sizes. Thus the observed alterations in geotechnical properties in the lime stabilized soils may not be due to the formation of swelling type of compounds. An attempt has been made to explain the observed the changes based on free energy changes. The conversion of calcium silicate hydrate into ettringite (Fig. 9) can have two fold effects; firstly the loss of cementing nature of compounds and secondly the free energy released from the mineralogical alteration of cementitious compounds results in increase in volume at constant temperature and pressure, which in turn reduces the shear strength of soils.

Thus the mechanism of swell in lime stabilized sulphatic soils would be:

Fig. 9 Schematic Formation of Ettringite

(a)   (b)
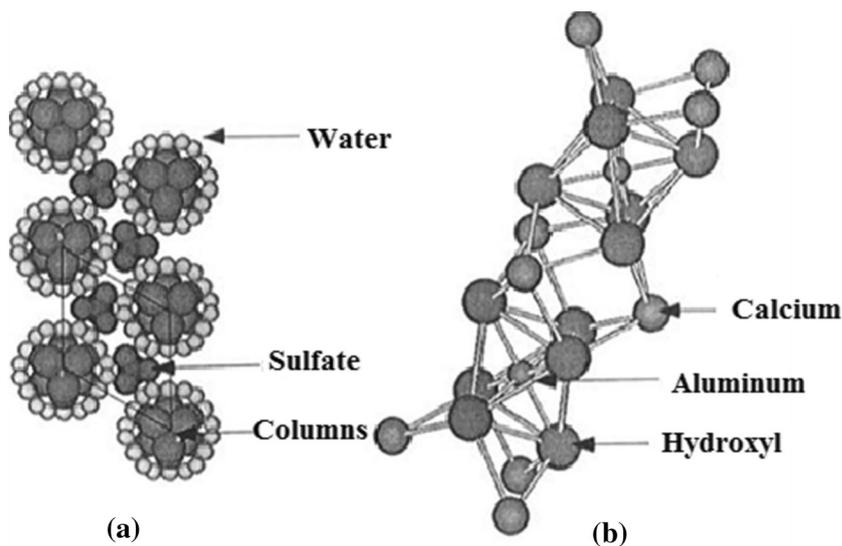
1. Increase in volume of new minerals formed
2. Free energy released
3. Upliftment of foundation soil
4. Any one or all of them.

Volume change = (molar volume products − molar volume reagents)/molar volume reagents

Volume change matrix water source = $(737.6 - 311.7 - 468.52)/780.22 = -0.05$ or 5 %, *shrinkage*

However, when water consumed in ettringite formation is considered to be from outside the matrix, the molar volume calculations, given below, indicates a volume increase and not shrinkage in the matrix

Volume change external water source = $(737.6 - 311.7)/311.7 = 1.37$ or 137 %, *expansion.*

The needlelike ettringite particles of ettringite (Fig. 10) can cause upliftment in the foundation soil.

Abnormal Behaviour Kuttanad Marine Soil

Soft clay deposits of Kuttanad area in Kerala, India extending to varying depths below the ground level, present a challenge as a foundation soil due to low bearing capacity and high settlement. Geologically Kuttanad is considered as a recent sedimentary formation. In the geological past, the entire area was a part of the Arabian Sea. Presently Kuttanad area covers an area of about 1,100 km^2. Many intriguing reports of distresses to structures founded on this soil are available. It is necessary to understand the role of components of soils such as organic substances, pyrite and sesquioxides for variations in its properties with change in water content. The high water holding capacity of the soil reflected in its liquid limit along with relatively low plasticity characteristics of the soil has been explained as due to the presence of minerals such as metahalloysite
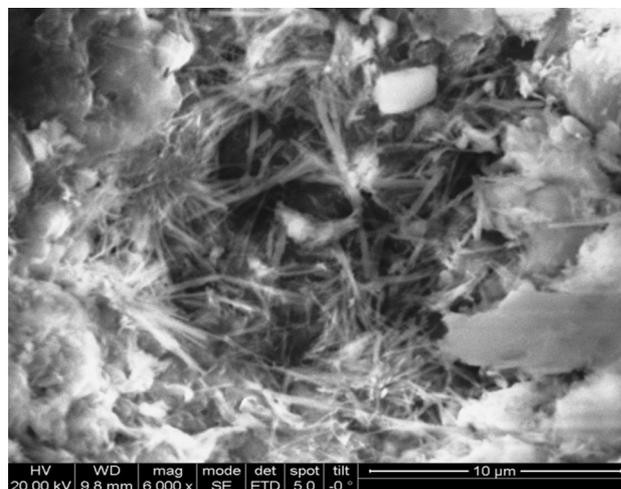
Fig. 10 Needle like particles of Ettringite

and gibbsite, the flocculated fabric, porous organic matter and water filled diatom frustules (amorphous silica).

Diatomics/frustules are made up of inorganic cell wall composed of hydrated SiO_2 diatoms are abundant where water is found—oceans, lakes, streams, mosses, soils, even the bark of trees. Diatoms grow as single cells, or form simple filaments or colonies. They form the base of aquatic food webs in marine and freshwater habitats. There are 20,000 to over 1–2 million number of species of diatoms present on earth. Diatoms are photosynthetic, gaining energy from the sun using chlorophylls a and c. Cells store energy from photosynthesis as Chrysolaminarin and lipids.

As an important global source of carbon fixation, diatoms already are an important "biofuel" for aquatic food webs. It is estimated that 40 % of the earth's oxygen (O_2) is produced through the photosynthetic activities of diatoms.

However the role of silica as diatomic on the geotechnical behavior of soils is not known.

It has been brought about that the organic content plays a dominant role in particle cementation and aggregation causing a substantial reduction in plasticity upon drying. Further, the presence of minerals such as pyrite and iron oxides also account for the plasticity changes. Presence of diatom frustules of varying sizes found to be responsible for its special characteristics and its response to various stabilization agents such as lime and cement. diatom frustules are forms of amorphous silica with opal-A structure [28]. Different forms of diatomic silica frustules are shown in Fig. 11. Detailed characterization has shown that Sodium Silicate (NS) along with cement can be successfully used to stabilize Kuttanad soil.

Contrasting Behavior of Bentonite and Organically Modified Bentonite

It is known that the swell potential of bentonite increases with increase in dielectric constant of the pore fluid. But when the bentonite is organically modified the swell decreased with increase in dielectric constant of the pore fluid (Fig. 12).

Thus, bentonite which is effective to reduce the hydraulic conductivity of soils is ineffective if it is modified with organic ions. But it is effective when the fluid is organic in nature or dielectric constant of the fluid is low. Also while bentonite is a good adsorbent for inorganic ions only organically modified bentonite is capable of retaining organic ions.

Heave in Field Contaminated Soils

A Case Study of Alkali Effect

Recently a case of heaving and distortion of roof and floor beams of industrial structures at an alumina extraction plant (Fig. 13) which was in operation for over 50 years has been reported.

It has been observed that the entire basement floor is inundated with high strength alkali solution (Fig. 14). Corrective measures such as increase of surcharge did not meet with any success. This has been suspected as due to the heaving of sub-soil due to prolonged leakage of the spent liquor consisting of concentrated alkali with extracted alumina into the sub-soil.

To plan remedial action based on thorough understanding of the reasons for heave in soil, the effects of sodium hydroxide solutions of varying concentration on the behavior of swelling and non-swelling soils have been studied. Soil samples were collected from locations where the sub soil has been contaminated and from the locations far away from the distorted structures. The leaking solution which contained suspended alumina has also been collected. Detailed laboratory investigations have been carried out.

Consolidation tests were conducted on field samples to bring out the effect of strength of alkali solutions and the effect of alkali solution along with suspended alumina which is present in the leaking fluid in the case referred above, While one series is compacted with water and inundated with alkali solution another series was compacted and inundated with same fluid. The following are the consolidation tests:

1. Compacted with water and inundated with1 N alkali containing alumina
2. Compacted and inundated with1 N alkali containing alumina
3. Compacted with water and inundated with 4 N alkali containing alumina
4. Compacted and inundated with 4 N alkali containing alumina

Figure 15 compares the consolidated behavior of samples compacted with water and 1 N alkali containing alumina and inundated with 1 N alkali containing alumina with samples compacted and inundated with 1 N alkali containing alumina. Alumina has been introduced into the soil by mixing the soil with alkali containing alumina. It can be noticed that swell at seating load is lower with samples compacted with water and inundated with alkali solution containing alumina compared to samples compacted with samples compacted and inundated with alkali solution containing alumina (Fig. 15). This alumina is inhibiting the soil-alkali interaction. Thus the field situation could have been worse if there is no alumina in leaking alkali solution.

Figure 16 shows that the rebound (delayed swell) is much higher in the samples compacted with water and inundated with 4 N alkali solution containing alumina. During unloading drastic increase in swell has occurred. Further the heaving during unloading appears to be higher in samples contaminated with 4 N alkali solution containing alumina compared to sample contaminated with 4 N alkali solution without alumina. The rebound is much higher when alkali concentration is higher even in the presence of alumina. This is due to the difference in the mineralogical changes, in both the cases, as confirmed by X-ray diffraction studies.

It is thus clear from the above results that the consolidation behavior varies significantly depending on the concentration of alkali and duration of interaction with the alkali.

Fig. 11 Forms of frustules present in Kuttanad Soil
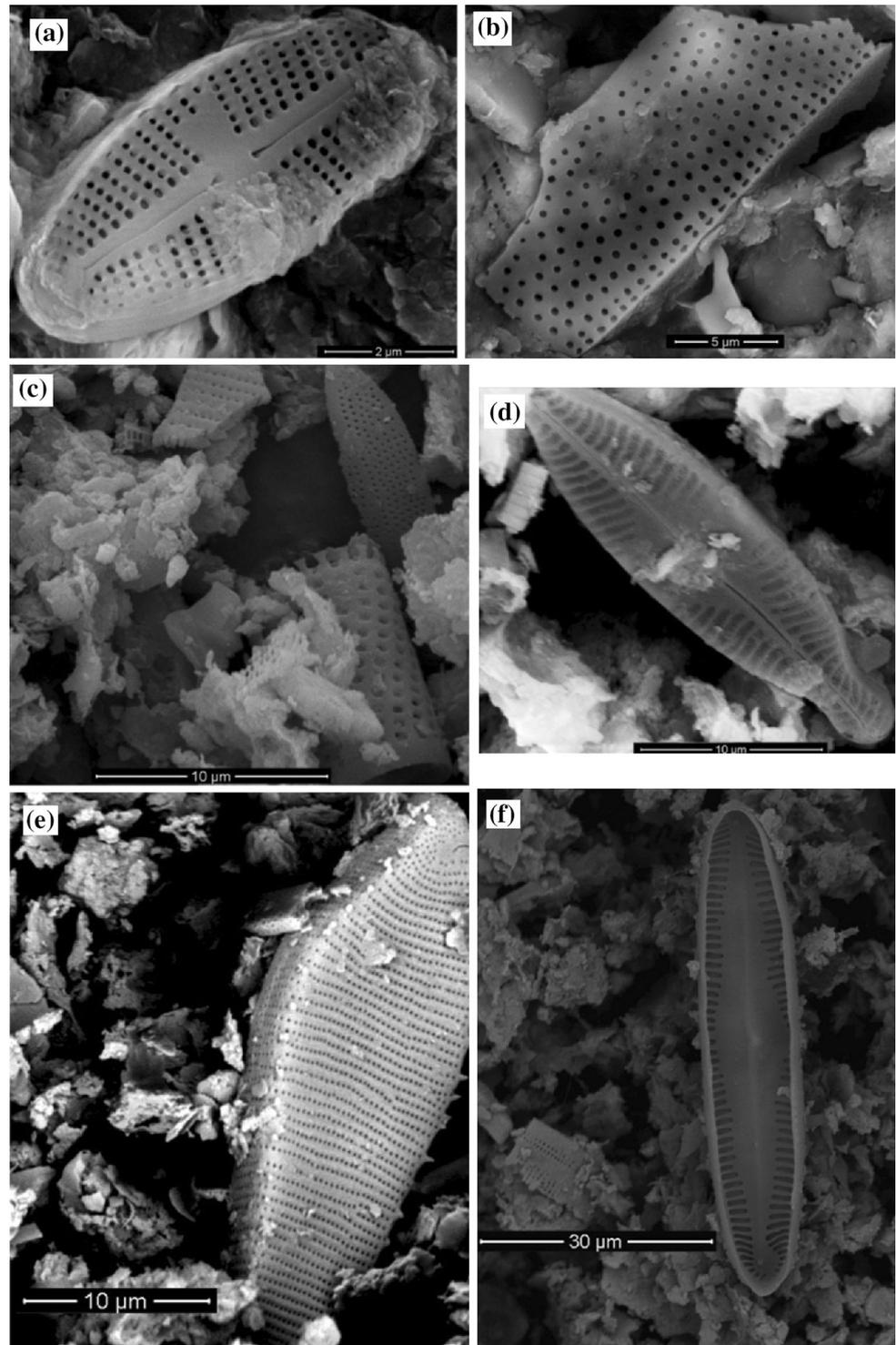
Swell in Soils Due to Contamination with Alkali Solution

One important pollutant that can have considerable effect is the alkali released from varies industries. The problem of spillage of liquid caustic soda solution during operation of the alumina plant is common and a particular case of foundation problem after 40 years of commissioning was reported by Sinha et al. [29]. A loss of about 33 % in safe bearing capacity was reported. The main remedial measure suggested was to neutralize the contaminated subsoil with 5 % ferric chloride solution, which is an acid solution. In
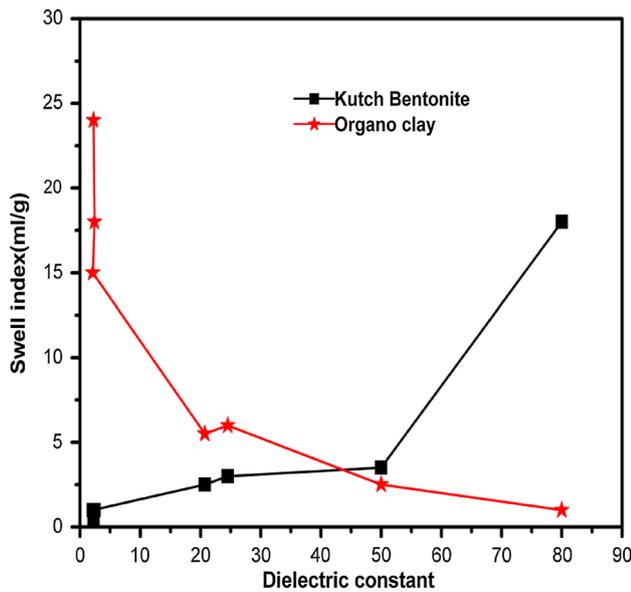
Fig. 12 Effect of dielectric constant on the swell behaviour of bentonite and organically modified Bentonite
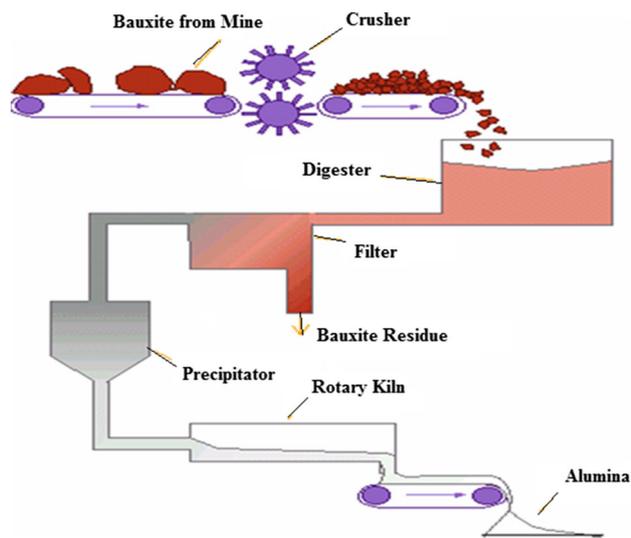

Fig. 13 Alumina extraction from Bauxite by Bayer's Process

yet another case, the heave in non-swelling foundation due to caustic solution has been attributed to loss of cementitious iron oxide from the soil [30].

Geotechnical Behavior of Kaolinitic Soils Interacted with Alkali Solution

Strength of Alkali Treated Kaolinitic Soils

The shear strength of both red earth and kaolinite increases on treatment with alkali solution. The increase is more due to increase in the cohesion rather than increase in the

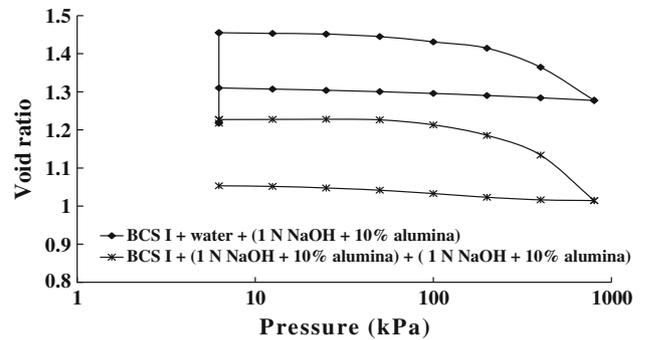Fig. 14 Leakage of alkali solution inundating floor

Fig. 15 Consolidation behaviour of black cotton soil remoulded with water or 1 N NaOH + 10 % alumina and inundated with 1 N NaOH + 10 % alumina
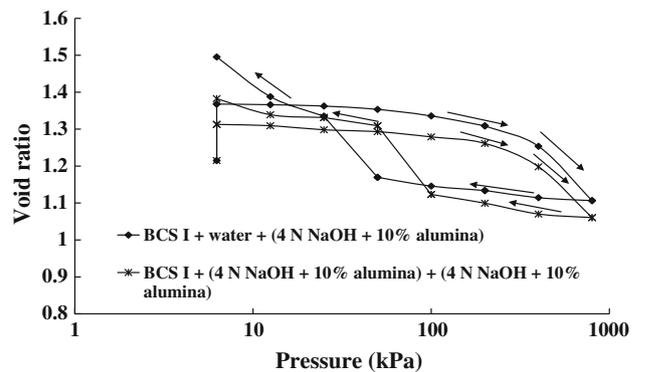

Fig. 16 Consolidation behaviour of black cotton soil remoulded with water or 4 N NaOH + 10 % alumina and inundated with 4 N NaOH + 10 % alumina

coefficient of friction angle. It is very interesting that heave is not associated with strength loss in this case. Thus the studies are directed more to understand the mechanism of volume change behavior of soils with alkali solutions.

Commercially pure kaolinite and kaolinitic red earth after treating with high caustic alkali concentrated solution (4 N or more has shown that soil alkali interaction leads to the formation of new mineral, zeolite (Sodium aluminum silicate hydrate). The presence of new mineral formed by soil alkali interaction, sodium aluminum silicate hydrate ($1.08Na_2O.Al_2O_3.1.68SiO_2.1.8H_2O$), has been confirmed by detailed x-ray diffraction, thermal and scanning electron microscope studies. The effect of formation of new mineral on the behavior of soils has been studied.

Volume Change Behavior of Soils with Alkali Solutions

To bring out the influence of alkali interaction on volume change behavior, Conventional Oedometer tests carried out on compacted soils with water or alkali solutions as inundating fluids. Surprisingly abnormal swell during unloading (rebound) has been observed with 4 N NaOH solutions (Figs. 17, 18). This has been attributed to formation of zeolites after interacting with alkali solutions. It is interesting to note that abnormal swell has occurred even at higher surcharge. To understand the mechanism, whether the swell is due interaction process or due to formation of new mineral consolidation tests were carried out after reaching full equilibrium at seating load. To confirm this, the samples were allowed to react with alkali solutions at nominal surcharge. After completion of swell at seating load, the specimen was then loaded gradually to find out the swelling pressure. Considerable differences in consolidation behavior have been observed when full swell was allowed at seating load. Both red earth and kaolinite had undergone compression during incremental loading in which full swell was not particularly allowed to complete at seating load.

In contrast, almost negligible amount of compression had taken place with increase of effective pressure up to 800 kPa when full swell were allowed at seating load. Consolidation tests were also performed on compaction of swell at nominal surcharge.

Effect of Concentration of Alkali

There is no abnormal swell in both red earth and kaolinite during unloading cycle in specimen inundated with 1 N NaOH solutions (Figs. 19, 20) when initial swell was not allowed for long time at nominal surcharge (seating pressure) as the conventional consolidation test are completed within one-month time. However, abnormal swelling during rebound has been observed with 4 N NaOH solution. This explains the observed swelling during unloading cycle in conventional consolidation test (Figs. 17, 18).

Now it is clear that red earth and kaolinitic soils swell with 4 N solution. The soils after completion of interaction
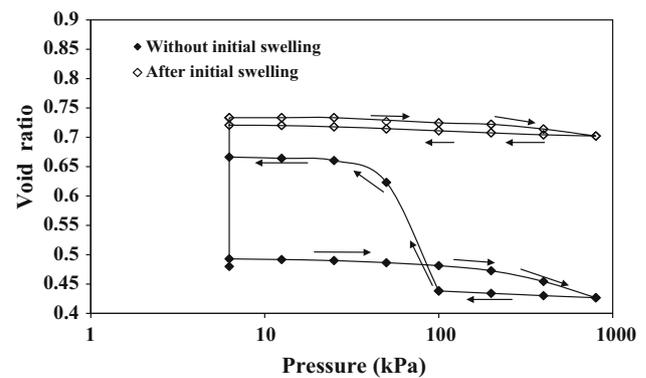
Fig. 17 Void ratio-pressure relationship of red earth remoulded with water and inundated with 4 N NaOH solutions, (1) without allowing full swelling at seating load; and (2) after allowing full swelling at seating load
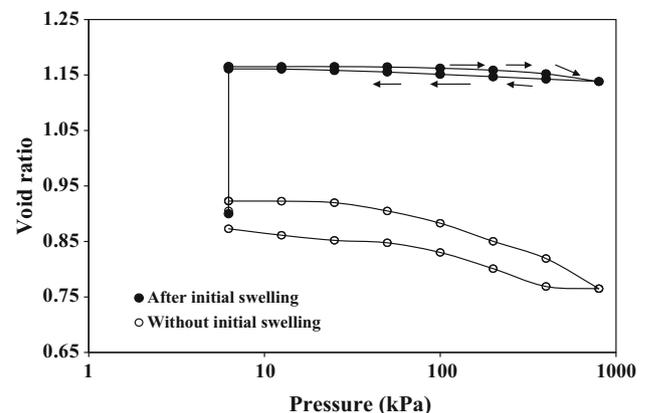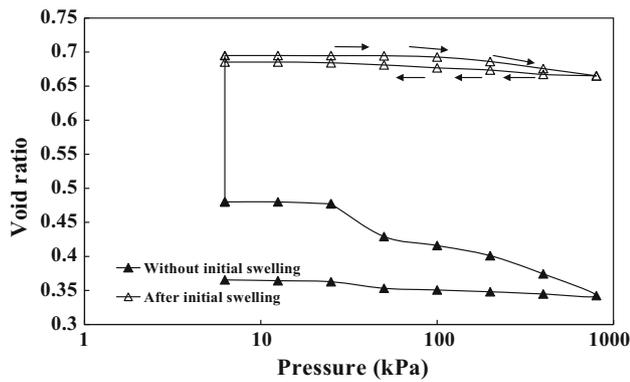

Fig. 18 Void ratio-pressure relationship of kaolinite remoulded with water and inundated with 4 N NaOH solutions, (1) without allowing full swelling at seating load; and (2) after allowing full swelling at seating load

with alkali solution for long duration undergoes very little volume changes either during loading or unloading cycles. This confirms that swell in specimen were due to zeolitization. Zeolites (Fig. 21) are microporous, alumino-silicate minerals commonly used as commercial adsorbents and catalysts.

Oedometer Free Swell Tests

To see the effect at lower concentrations of alkali, oedometer swell tests carried out with 1 N NaOH solutions as inundating fluid. The time required for swelling to occur at nominal surcharge and swelling during rebound to occur are comparable. There are three forms of zeolite of viz., natrolite, mesolite and scolecite [31].

Oedometer free swell tests at a nominal surcharge of 6.25 kPa for soils with 1 N and 4 N alkali solutions. It is observed even with 1 N alkali solution considerable swell

Fig. 19 Void ratio-pressure relationship of red earth remoulded with water and inundated with 1 N NaOH solution, (1) without allowing full swelling at seating load; (2) after allowing full swell at seating load
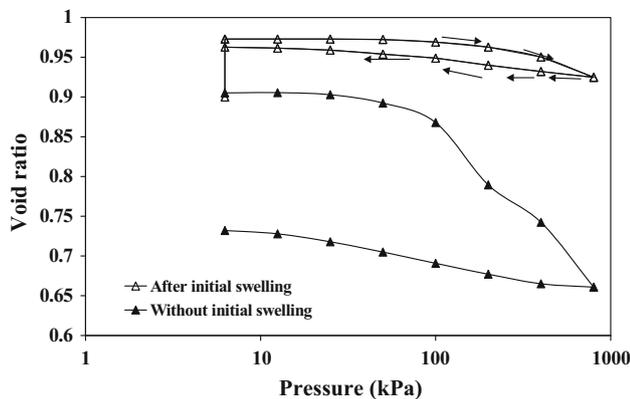

Fig. 20 Void ratio-pressure relationship of Kaolinite remoulded with water and inundated with 1 N NaOH solution, (1) without allowing full swelling at seating load; and (2) after allowing full swell at seating load

is observed for both kaolinite and red earth after 30 days of interaction time period (Fig. 22). The observed swell is about 13 % percentage of initial height in red earth and 4 % in kaolinite. Equilibrium is reached in about 45 days in red earth and 70 days in kaolinite. Thus, the percent swell increases for kaolinite and red earth with 4 N alkali solution and also equilibrium swell is reached relatively quickly (Fig. 23). With 4 N alkali solution the observed swell is seen after a lapse of about 15 days. However, the amount of maximum swell is about 15 % in both the soils. The alkali induced swell—time relationships does not follow rectangular hyperbolic relationship.

Effect of Alkali on Expansive Soils

It is clear from the above studied the non-expansive soils swell when alkali concentration is sufficiently high. The behavior of expansive soils with alkali solutions is also studied. Apart from montmorillonitic expansive soils, often
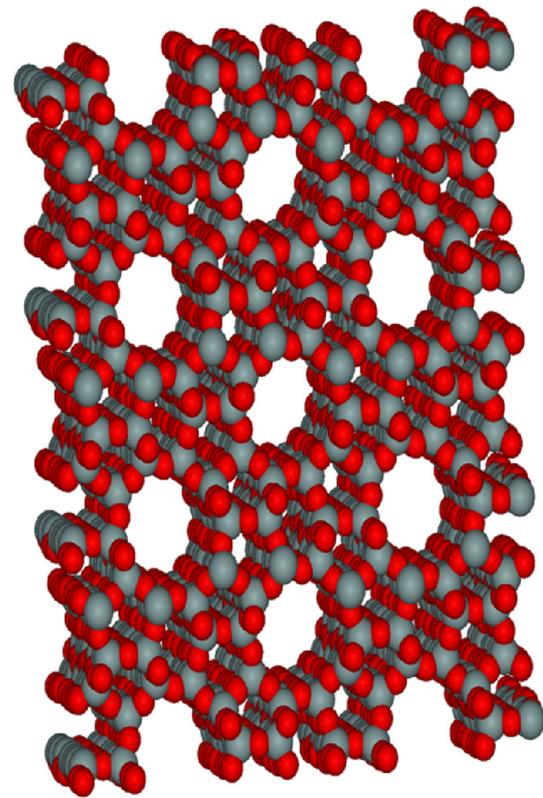
Fig. 21 Molecular Structure of micro porous Zeolite
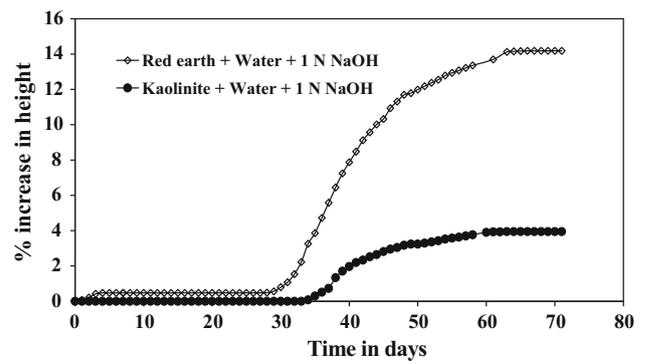
Fig. 22 Swell in non-swelling soils with 1 N alkali soils

expansive soils with illite–smectite mineral (rectorite) are encountered. Thus, the effect of alkali solutions of 1 N and 4 N concentrations on volume change behavior of expansive soils with rectorite mineral and on commercially available bentonite itself has been studied.

Oedometer Free Swell in Rectorite Soil Containing Inter Layer Mixed Mineral

The soil containing rectorite exhibited high swelling of about 36 % over a period of 3 months with 4 N solution.
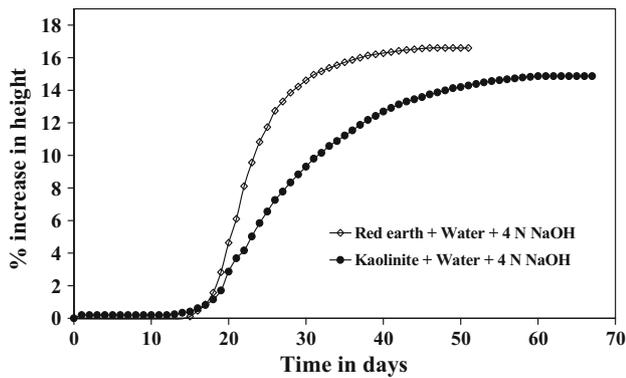
Fig. 23 Swell in non-swelling soils with 4 N alkali soils

Fig. 24 Swell in black soil with interstratified mineral with water and alkali solutions

The swell was about 18 % with 1 N alkali solution (Fig. 24).

Further the swell in soil with 4 N solution occurred in two phases—rapid initial swell followed by high but slow swell. The initial swell has been attributed to increase in negative charge on clay particle at high pH. The subsequent high swell has been attributed to mineralogical changes. The potassium linkages between alternate layers of illite–smectite in rectorite have been ruptured as confirmed microstructural studies. The interlayer potassium of illite is released and potassium hydroxide is formed in soil treated with 4 N NaOH. Since the abnormal swelling occurred with alkali solutions at seating load, two modes of consolidation tests were followed: (1) after completion of full swelling at seating load and (2) after completion of initial swelling as in the case of most consolidation tests, to bring out the effect of swelling on their compressibility,
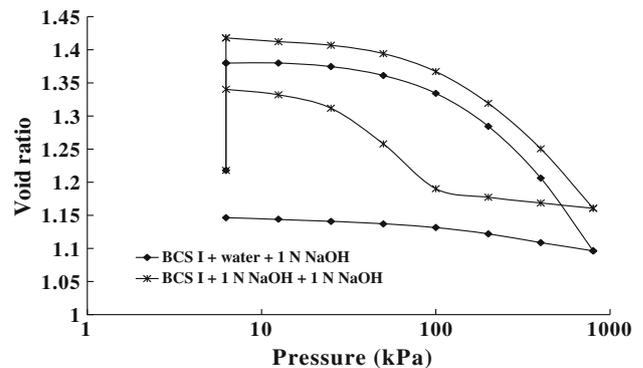
Consolidation Behaviour

Again consolidation behaviour of rectorite in 1 N and 4 N alkali solutions has been studied in two ways: (1) loading without waiting for the second stage of swelling to occur, as in standard consolidation procedure and (2) loading after completion of second stage of swelling which is occurring after considerable delay as explained earlier. As there is no second stage of swelling with 1 N solutions, these two types of consolidation tests produced the same results. Abnormal rebound is observed during unloading with 4 N solution in which loading cycle is initiated without waiting for second stage of swelling to complete.

Consolidation Behavior after Completion of Initial Swelling

Standard consolidation tests were conducted on samples compacted with water and 1 N alkali solution and inundated with 1 N alkali solution after completion of initial
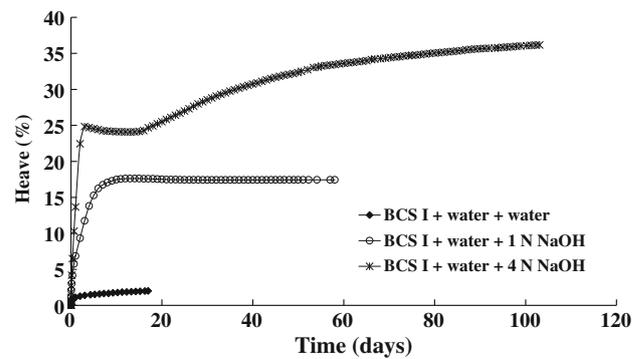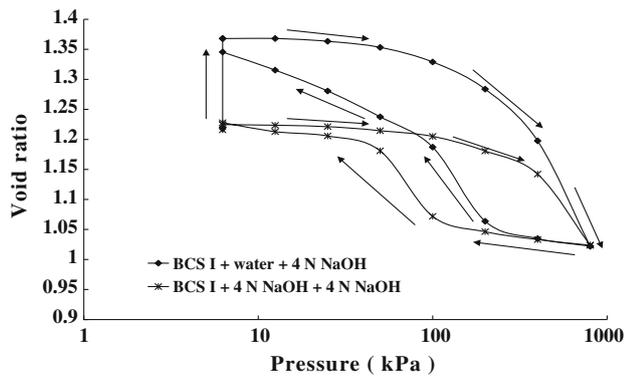

Fig. 25 Consolidation behavior of black cotton soil remoulded with water or 1 N NaOH and inundated with 1 N NaOH

swelling (Fig. 25). The samples exhibited higher compression during loading than in the case of samples loaded after completion of full swelling at seating load. However, the samples loaded after completion of initial swelling exhibited higher rebound during unloading. Thus it can be said that these samples exhibit delayed swelling.

The compressibility of sample compacted with water and inundated with 4 N solution exhibited abnormal rebound (Fig. 26). However in both the cases the consolidation tests conducted after completion of initial swell at seating load exhibited no such abnormal swell during rebound.

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 (Fe^{2+}) at the pH of acid sulphate

Fig. 26 Consolidation behaviour of black cotton soil remoulded with water or 4 N NaOH and inundated with 4 N NaOH

Fig. 27 Effect of lime on volume change behavior of alkali contaminated red earth

drainage than the pH of seawater. Sulphate present in the soil and in pozzolanic stabilization is also known to induce swell in soils.

Comparison of Effects of Field and Laboratory Contamination

Studies on the behavior of black soil containing mixed layer mineral contaminated in the field and laboratory by leaking Bayer's spent liquor in an alumina extraction plant has shown that swelling at seating load is higher in sample with liquor than in 4 N alkali solution. The mineralogical and micro structural changes in the soil samples that are contaminated by leaked spent liquor in the field are relatively more marked.

Remedial Measures to Control Alkali Induced Heave

Methods to control alkali induced swell are examined. Swelling in most soils can be control either by (a) converting the soil to a rigid or granular mass, the particles of which are sufficiently strongly bound to resist the internal swelling pressure of the clay, or by (b) retarding moisture movement within the soil. Ferric compounds are known to be cementing agents. The effect of addition of different amounts of ferric chloride salt and Fly ash on alkali-contaminated soil and its effect on volume change behavior have been studied [32, 33].

For red earth soil, treatment with ferric chloride salt has been considered. This study can establish the relative influences of the two factors on swelling of soil in the presence of alkali solution viz., due to the removal of iron oxide (cementing agent) and due to the formation of zeolitic minerals. Treatment with ferric chloride is not effective in controlling swelling indicating that removal of iron oxide is not the main reason for alkali induced heave. Lime is found to control the abnormal volume changes caused in
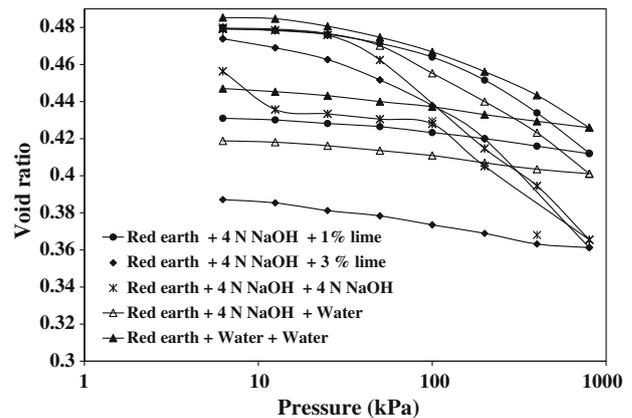
soils by presence high concentrated caustic solutions (Fig. 27) [34].

The other remedial measures explored include flushing with water to dilute the effect of alkali, neutralization with dilute hydrochloric acid, stabilization of soil with lime and calcium chloride and use of impervious membrane to separate the foundation soil from alkali solution. Though the swelling of contaminated soil can be controlled by passing dilute hydrochloric acid (1 N), the method is not advocated as it can lead to ground water contamination. Mixing the soil with solutions containing up to 5 % by weight of calcium compound in water could not prevent the alkali induced heave in the long run. This is due to dissolution of silica by the strong alkali solutions and formation of swelling compounds such as sodium aluminum silicate hydroxide hydrate (SASH). Replacing the foundation soil with soil thoroughly contaminated with 4 N alkali solutions and controlling the migration of contaminants into the foundation soil using high-density polyethylene (HDPE) geosynthetic membranes, can be an effective measure.

Effect of Acids on the Geotechnical Behaviour of Soils

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 Fig. 28.

When pyritic sediment falls dry, oxygen penetrates and pyrite is oxidized, by microbial intervention, to sulphuric acid and ferric hydroxide ($Fe(OH)_3$) [35]. 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. 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 oxidizing acid sulphate soils can cause rust-colored stains and slimes.
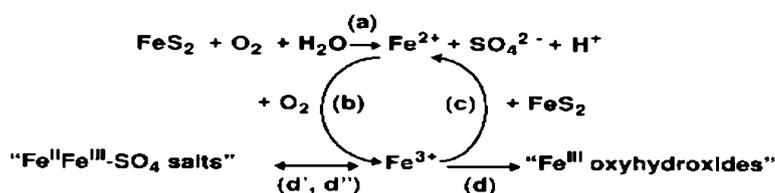
Heaving of Soil Due to Interaction with Acids

Assad [36] 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.

Sridharan et al. [37] 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. Detailed studies conducted have shown that while phosphate anion adsorption reduces the swell and increases the strength in montmorillonite soils it has opposite influence on kaolinitic soils. This is mainly due to phosphate retention in the soil altering the soil fabric. The hydrogen bonding between successive layers of kaolinite minerals is broken by phosphate adsorption whereas the results in binding of montmorillonite units by phosphate. Preventive measures such as closed conduits and drains with properly designed filter material where swell has been in kaolinitic soils.

Recently another case of acid induced heaving of floor sand pavement (Fig. 29) has been reported in Hindustan zinc limited at Chanderia, Chattisgarh where smelter is purified by acid treatment. This is similar to sulphate induced heave in stabilized soils. Studies are being conducted to assess the mechanism of this heave and to suggest remedial measures. An attempt has been to understand soil acid interaction mechanism and its effect on soil properties.

Induced Swell in Expansive Soils in Acidic Condition

As seen from Fig. 30, the black cotton soil shows considerably higher swell when it is saturated with 1 N H_2SO_4 at nominal surcharge of 6.25 kPa. 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 [38]. However, the sample compacted and inundated with water shows a swelling of about 2 % reached in about 10 days.

Fig. 29 Heave in road due to acid contamination
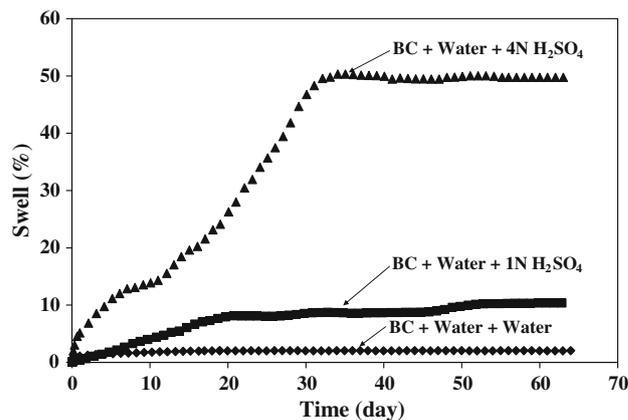
Fig. 30 Swell behavior of expansive soil with sulphuric acid solutions

Fig. 28 Oxidation of Pyrite (*Source* Rose and Cravotta 1998)

$$FeS_2 + O_2 + H_2O \xrightarrow{(a)} Fe^{2+} + SO_4^{2-} + H^+$$

$$\text{“Fe}^{II}\text{Fe}^{III}\text{-SO}_4 \text{ salts”} \xleftrightarrow{(d', d'')} Fe^{3+} \xrightarrow{(d)} \text{“Fe}^{III} \text{ oxyhydroxides”}$$

$$\text{OVERALL: } FeS_2 + 3.75\ O_2 + 3.5\ H_2O \rightarrow Fe(OH)_3 + 2\ SO_4^{2-} + 4\ H^+$$

The moderate swelling in black cotton 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 4 N H_2SO_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. 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.

Mineralogical Changes in Soil

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

$$H_2SO_4 + H_2O \leftrightarrow H_3O^+ + HSO_4^-$$

$$HSO_4^- + H_2O \leftrightarrow H_3O^+ + SO_2^{-4}$$
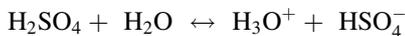
Initially the exchangeable cations of the soil sample are substituted by released H_3O^+ (hydronium). This is the reason for the release of exchangeable ions of soil on interaction with sulphuric acid. In addition to this, due to the ionic potential (electric charge of hydrated cation/smaller size) of hydronium it penetrates into the crystal of soil structure, leading to the displacement of structural ions. However, the anion, 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 H_3O^+ can cause changes in cation exchange complex of the clay particles, which lead to mineralogical and morphological changes.

Induced Swell in Non-Expansive soils in Acidic Condition

Figure 31 shows the percent swell of red earth compacted with water and inundated with water, 1 N and 4 N H_2SO_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 1 N sulphuric acid solution. This swell occurs over a period of 275 days. The swell further increased with 4 N 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
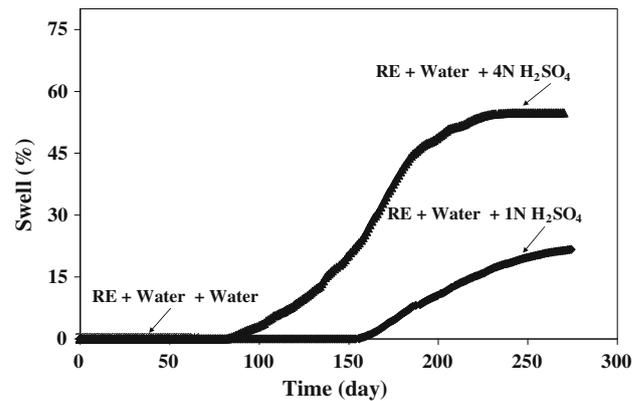

Fig. 31 Swell behavior of acid treated red earth

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, SO_4^{2-}.

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 1 N sulphuric acid, reduced to 85 days with 4 N 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 4 N sulphuric acid solutions as remoulding/inundating fluids have not shown hyperbolic relationships. Further, the non-occurrence of hyperbolic nature of curves show 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.

Consolidation Behaviour

The consolidation behavior of expansive and non-expansive soils with acids was similar to what has been observed in alkali solutions.

Mineralogical Alterations

X-ray diffraction patterns of treated and untreated red earth showed 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. 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—$(Al(H_2O)_6)_2(SO_4)_3(H_2O)_5$—showed pronounced peaks. The mereiterite which is potassium iron sulphate hydrate-$K_2Fe(SO_4)_2(H_2O)_4$ might have formed after the leaching of potassium from kalsilite.An indirect highlight of these studies is that knowing how sulfuric acid affects the common mineral particles helps to understand how they age in the atmosphere and the effect on climate from this aging. The important mineralogical alterations in the soil at various conditions are shown in Table 2.

Implications of Induced Heave in Foundation Soils Due to Strong Reaction with Acid/Alkali Solutions

The induced heave in soils due to interactions with strong chemical solutions throws more light on fundamental volume change behavior and shear strength behavior of soils. Generally the soils exhibiting higher compressibility show strength loss due to saturation but the induced does cause seems to cause any strength loss on the contrary increase in strength. The swell under high confining pressure shows strength gain.

Effects of Heave and Compressibility

While most research and field engineers concentrated on compressibility of soils under different surcharges the heave is given less importance. The total compressibility and rate of consolidation has been studied to assess the stability of structures. Also importance has been given differential settlement apart from total settlement. There are no detailed studies on allowable heave and rate of heave. But the unexpected heave can result in failures. The concept of differential heave as in case of differential settlement is not studied. The induced heave occurs only after prolonged periods of interaction and the chances of differential heave are rather remote. But if occurs it can damage structures built on these soils. It is known that Mexico City, the capital of Mexico and the second most populous city is sinking. It is estimated that during the 20th century, the city has sunk approximately 29–36 feet, about 8 inches per year.Many other cities around the world like Bangkok, Houston, Louisiana, Venice, Shanghai, New York are all sinking. Of course the reason are not all the exactly the same but Shaky foundations and encroaching seas are the major reasons. It creates serious problems that threaten infrastructure, water supplies and irreplaceable architecture if the problem is not fixed (Fig. 32). Similarly the irreversible induced heave can cause problems. It is very likely that in future we may see more Raising Places rather than Sinking Cities.

Volume Change Behavior of Soil and Strength Behavior of Soils

Fine grained soils undergo compressibility under surcharges more than their swell potential. Thus for fine grained soils geotechnical engineers concentrated only compressibility and the rate of compressibility and allowable settlements etc.

Fig. 32 Sinking Building in Mexico

Table 2 Important mineralogical alterations in soils

Soil/Mineral	Environment	Action	New mineral formed
Kaolinite	NaOH	Reaction between silica and alkali	Zeolites (aluminosilicates) $Na_{6.4}Al_{6.4}Si_{9.6}O_{32.4.6}H_2O$ and $NaAl_2(AlSiO_3)_{10}(OH)_2$, Sodium alumino silicates $1.08Na_2O.Al_2O_3.1.68SiO_2.1.8H_2O$
B C Soil	NaOH	Reactions between montmorillonite and alkali	$Mg_2Al(OH)_7$ -$NaFeO_{2.1}Si_{0.05}$ Lizardite $K_{1.25}Al_{1.25}Si_{0.75}O_4$
Red Earth	NaOH	Reaction between silica and alkali	Sodium aluminum silicate hydrate (NASH) $1.08Na_2O.Al_2O_3.1.68SiO_2.1.8H_2O$
Red Earth (kaolinite)	H_2SO_4	Hydrogen ions can leach out iron present in the lattices of kaolinite	Rozenite mineral(iron sulphate hydrate) $Fe^{2+}(SO_4)\cdot4(H_2O)$
B C Soil	H_2SO_4	Amesite leaching of potassium from kalsilite	Alunogen—an aqua aluminum sulphate hydrate—$(Al(H_2O)_6)_2(SO_4)_3(H_2O)_5$ Mereiterite $K_2Fe(SO_4)_2(H_2O)_4$

The strength of soils decreases with increase in volume. When, as brought out in the previous sections contaminated soils can undergo swell even at high effective pressures. It is time now geotechnical professional work out the rate of swelling and allowable swell. These soils need not possess low bearing capacity even after swelling. This is in fact confirmed in several cases.

Remedial Measures to Control Heave: Conventional Versus Induced Heave

Conventional heave in expansive soil is due to adsorption of water and is reduced with reduction in water content. The heave induced by mineralogical changes is not due to adsorption of water and cannot be controlled by reduction in water content and does not follow conventional hyperbolic nature with respect to time and is known to occur in both swelling and non-swelling soils. The swelling can at times be more in non-swelling soils. This type of swelling can also occur in inter stratified clays due to dissociation of minerals into their constituent minerals. The swelling can occur in soils when contaminated with alkali, acids and even salts. The swelling is known to occur in stabilized soil if sulphate is present. The swelling is generally irreversible and can only be stabilized by pozzolanic stabilizers. However the swelling cannot be observed if soil pollutant interactions have completed and mineralogical changes do not progress further. Thus, the behavior of fine grained soil in strong chemical environment cannot be explained by laws of mechanics alone.

Lime and Fly ash are found to be effective in controlling the induced heave in contaminated soils. This is mainly due to cementations of particles by pozzolanic compounds and the heave due to formation of new minerals (free energy released) is inhibited [32–34].

Induced Heave by Free Energy Change Due to Mineral Transformations

Changes in mineral structure due to physical or chemical environment respond to its free energy. The structure responds so that its free energy is always tends to a minimum value. Thus due to changes in physical or chemical changes in the system reactions may occur between mineral particles. Even cation interchange may alter their relative composition or new minerals assemblages may form. The energy released may vary widely from one alteration to another alteration. The standard free energies of formation of a number of zeolites from smectites were in the range of -500 to $-12, 1000$ kJ mol^{-1}. However, it does not give us any idea as how long it would take for the reactions to complete. The entropy changes for natrolite, scolecite and masonite at standard temperature and pressure are -5718.6, -6049.0 -5947 kJ mol^{-1} respectively.

Free energy released from formation of new clay minerals is in the form Gibbs free energy, increases the volume at constant temperature and pressure. When minerals are converted, the energy released might be responsible for swelling through particle rearrangement.

The differences in the two types of heave are as follows:

1. Conventional heave is restricted to expansive soils only. Induced/unexpected heave due to high alkali/acid contamination occurs in both swelling and non-swelling soils.
2. Conventional heave is due to increase in moisture content and can be effectively controlled by moisture control measures whereas the induced heave is not affected by change in water content.
3. Cation exchange plays important role in the swell behavior of conventional heave in expansive soils whereas its influence is not significant.
4. The heave in expansive soils and the unexpected heave in soils due to contamination are by different mechanisms. While the former is due to adsorption of water and occurs only when water content is increase, whereas induced heave is due to mineralogical changes, as seen in both types of soils. While alteration of kaolinite into zeolite is the major reason for swelling in kaolinitic soils, breakage of rectorite mineral is responsible for swelling in soils containing mixed mineral layer. Alterations in mineralogy of both expansive and non-expansive soils due to interaction with sulphuric acid have been confirmed.
5. The time swell relationship of induced heave does follow the conventional hyperbolic relationship as the induced heave occurs after considerable period of interaction.
6. The strength of soil is not significantly affected by induced swelling unlike in expansive soils.
7. Pozzolanic stabilization is however effective to control any form of swell. Separation of soil from alkali/acid solution is the most effective means of controlling the induced heave.

The differences are summarized in Table 3.

Impact of Heave on the Strength of Soils

Swell in non-swelling soils and increased swell in expansive soils due to interaction with alkali/acid solutions (different from swell due to increase in repulsive pressure) also indicates that there cannot be any associated reduction in bearing capacity of soils.

Table 3 Differences in the two types of Heave in soils

S. No.	Conventional Heave	Induced heave (Irreversible Heave)
1	Occurs in Soils containing expansive clay minerals	This heave can occur in any type of Soil
2	The heave is due to increase in Moisture Content	Change in moisture content has no effect on this type of Heave
3	Cation exchange capacity and exchangeable ions and repulsive pressure have influence	No influence of CEC and Repulsive pressure
4	Occurs relatively quickly	Occurs after considerable delay
5	Surcharge has significant effect	Surcharge has no effect
6	No mineralogical changes	Strong chemical interaction and Mineralogical changes are mainly responsible
7	Strength loss is associated with the heave	No Strength loss
8	Time-swell relationship follows hyperbolic relationship	Does not follow hyperbolic relationship
9	Moisture control measures and PozzolonicStabilistion is effective to control the heave	Neutralisation/reduction in of acidity/alkalinity and Pozzolanic stabilization are effective methods

Implications on Structures Built on Heaving Soil

The heave in foundation soil can distort structure built on them if this heave in soil is not uniform. But the heave in soils induced by mineralogical changes by soil pollutants interaction is delayed and there is every possibility the induced heave will be more uniform. Thus the effect is more in upliftment of the entire structure than in distortion and is usually go unnoticed.

Unexpected Benefits of Irreversible Heave

Impermeable Soil Liner

There is report where an acid lake at Armyansk (Crimea, Ukraine), where waste sulfuric acid is discharged in a ponded shallow bay, apparently, geochemical information on the local rock formations and pore waters has helped to produce self-sealing liners or plugs, and to break down harmful chemicals and immobilize pollutants. As every-man-made isolation will give way in a geologically speaking, short period, such 'natural' self-sealing isolations are much cheaper and safer. It is possible to engineer self-sealing liners by the juxtaposition of two reacting waste types.

This draws attention to another option that may greatly improve the environmental management of hazardous waste. This is the co-deposition of two or more types of hazardous waste that can react to a harmless substance. Although co-disposal is often prohibited as it is considered equal to indiscriminate dumping, it should certainly not be ruled out as a viable option in environmental management. As an example, one may consider the co-disposal of iron or manganese hydroxides and toxic organic sludge. Bacteria that use the oxygen from the metal hydroxides can break down the organics into harmless compounds. Also the co-disposal of organic sludge with soluble and toxic metal hydroxides may be a proper method, as reducing conditions are generated that lead to the immobilization of the metals as sulfides.

- No acid leaks to the groundwater as it reacts with carbonate in underlying clays.
- As a consequence of this reaction, an impermeable hardpan of gypsum and iron hydroxide is formed.
- Gypsum has a molar volume that is twice as large as that of the dissolved carbonate, and thus the pores of the clay are effectively sealed.

Another example is of a self-sealing layer formed within days if alkaline coal fly ash is brought in contact with acidic jarosite waste from the zinc industry.

An indirect benefit of the studies is to understand how the clays with age in the atmosphere and the effect on climate with aging.

Raise Land Above the Seas

Injecting sulfuric acid into coastal limestone at depths of some 500 m, the expanding gypsum would release continuous upward pressures, because after some initial horizontal expansion it would have no other place to go. Eventually, pressure forces spreading upward like an inverted cone would raise surface levels over a wide area.

Conclusions

Many of the unexpected cases of soil behavior is due lack of understanding of the changes in fine grained soils due to interaction with physic chemical changes and chemical interactions. One of the most reported cases is the heaving

of foundation soil observed after very long period of construction of super structure/building. Detailed microstructure and geotechnical evaluation of soil with different mineralogical composition after prolonged interaction with strong chemical fluids confirmed alterations in the soil including their mineralogy. This is not necessary due to formation of swelling type of minerals but may be more due to free energy released during transformation of clay minerals. Thus it is generally found that the soils after completion of interaction with chemicals/contaminants did not exhibit abnormal swell or heaving. Remedial measured to control the distress caused by chemical alterations vary from case to case.

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