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SOIL PROBLEMATIC

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Graduate students

CIVIL ENGINEERING DEPARTMENT

INTRODUCTION

problrmatic soil

Problematic soils are a group of soil materials that hinder the design and construction process. Therefore, investors and engineers usually decide to avoid making building investments in areas where problematic soils occur. Unfortunately, in densely populated areas, it is increasingly the only option to carry out construction on problematic soils.

Problematic soils, from a geotechnical point of view, are soils that have the potential to expand, collapse, disperse, undergo excessive settlement or even to fail under relatively low stress conditions. The above soil response phenomena are connected with the soil’s physical properties such as soil grain composition, saturation ratio, degree of compaction, mineralogy, and with its mechanical properties, for example, preconsolidation or soil strength parameters.

These problematic soils are creating a number of problems, including those that are related but not limited to bearing capacity, stability in excavation, stability in embankments, and long-term settlements.

In order to build on such soils, geotechnical engineers employ a wide range of improvement techniques, for example, physical and chemical stabilization, deep soil mixing, stone columns, etc.

For the successful utilization of problematic soil areas, scientific efforts need to be focused on the following activities:

- **(I) The physical, chemical and mechanical properties of problematic soil such as bearing capacity, stiffness and compressibility, etc.;**
- **(II) Laboratory and in situ testing techniques;**
- **(III) Design methods and numerical analysis.**

Contributions could address experimental investigations or mathematical descriptions. Case studies that propose a general procedure that could be applied in geotechnical engineering are also welcome.

This Special Issue is a call for geotechnical engineers, earthwork engineers, pavement engineers, and material researches as well as contractors. We would like to encourage them to contribute their research results and to report their experiences. We believe that these Special Issue contributions will significantly impact the problematic soils field of study.

causes problematic soil

Occurrence and Causes

Slow permeable soil is mainly due to very high clay content, infiltration rate < 6cm/day, so more runoff which eventually leads to soil erosion and nutrient removal. Since the capillary porosity is high it leads to impeded drainage, poor aeration and reduced conditions.

Problematic soil causes problems due to changes in climate or other components such as acidic soil, alkaline soil, sodic coil, and saline soil

Field observation and laboratory test can be useful to identify problematic soils. Some properties of soils such as dry density and liquid limit are helpful to estimate collapsibility potential of soils. In this regard, it was done a series laboratory tests to evaluate the collapsibility rate.

The problematic soils and their management

Soils that have serious constraints to cultivation and that need special management techniques are called problem soils. These limitations may be physical such as dryness, wetness, steepness, and extreme textures and chemical such as acidity, salinity, sodicity, and lack of fertility.

Types of problmatic soil

There are **three major types** of problematic soils. The types are:

1. **Acidic Soil**
2. **Alkaline Soil**
3. **Saline Soil.**

Problematic Soils: **Type # 1. Acid Soils:**

The soils with pH less than 6.5 and which respond to liming may be considered as acidic soils.

(a) Reasons for Acidity:

(i) Humus decomposition results in release of large amounts of acids. There by lowering the pH.

(ii) Rainfall: In areas with more than 100 cm rainfall associated with high R.H., Ca, Mg is dissolved in water and leached out due to this base saturation of soil decreases.

(iii) Application of elemental sulphur under goes reactions resulting in formation of H_2SO_4.

(iv) Continuous application of acid forming fertilizers like ammonium sulphates or ammonium chlorides results in depletion of Ca by CEC (cation exchange capacity) phenomenon.

(v) Parent Material: Generally rocks are considered as acidic, which contain large amount of silica (SiO_2) when this combined with water, acidity increases.

(b) Characteristics:

(i) pH is less than 6.5

(ii) These soils are open textured with high massive Structure.

(iii) Low in Ca, Mg with negligible amount of soluble salts.

(iv) These soils appear as brown or reddish brown, sandy loams or sands.

Problematic Soils: Type # 2. Alkaline Soils:

Alkali soils are formed due to concentration of exchangeable sodium and high pH. Because of high alkalinity resulting from sodium carbonate the surface soil is discoloured to black; hence the term black alkali is used.

(a) Reasons for Alkalinity:

The excessive irrigation of uplands containing Na salts results in the accumulation of salts in the valleys.

(i) In arid and semi arid areas salt formed during weathering are not fully leached.

(ii) In coastal areas if the soil contains carbonates the ingression of sea water leads to the formation of alkali soils due to formation of sodium carbonates.

(iii) Irrigated soils with poor drainage.

(b) Characteristics:

(i) Saline soil has soil pH of more than 8.5

(ii) Ec is less than 4.0 m.mhos/cm

(iii) ESP (exchangeable sodium per cent) is more than 15

(iv) It has black colour that why it is also called as Black alkali

Problematic Soils: Type # 3. Saline Soils:

The saline soils contain toxic concentration of soluble salts in the root zone. Soluble salts consist of chlorides and sulphates of sodium, calcium, magnesium. Because of the white encrustation formed due to salts, the saline soils are also called white alkali soils.

(a) Reasons for Salinity:

In arid and semi arid areas salts formed during weathering are not fully leached. During the periods of higher rainfall the soluble salts are leached from the more permeable high laying areas to low laying areas and where ever the drainage is restricted, salts accumulate on the soil surface, as water evaporates

(i) The excessive irrigation of uplands containing salts results in the accumulation of salts in the valleys.

(ii) In areas having salt layer at lower depths in the profile, seasonal irrigation may favour the upward movement of salts.

(iii) Salinity is also caused if the soils are irrigated with saline water.

(iv) In coastal areas the ingress of sea water induces salinity in the soil.

(b) Characteristics:

(i) Saline soil has soil pH of less than 8.5.

(ii) EC is more than 4.0 m.mhos/cm.

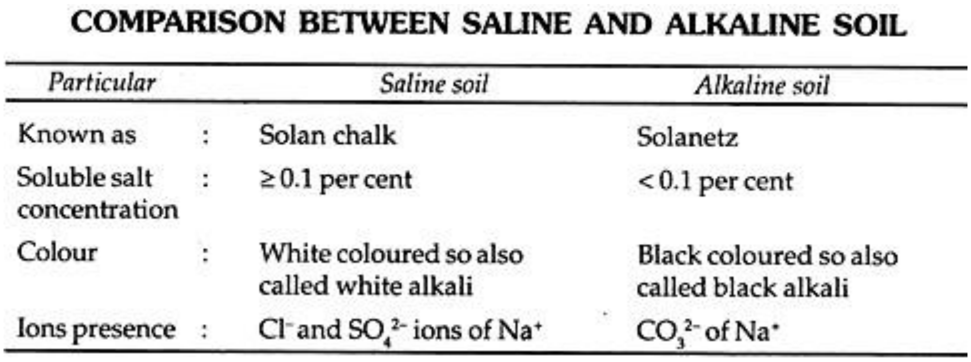
(iii) ESP (exchangeable sodium per cent) is less than 15.

(iv) Dominated by sulphate and chloride ions and low in exchangeable sodium.

(v) Flocculation due to excess soluble salts.

(vi) High osmotic pressure of soil solution.

(vii) Presence of white crust.



COMPARISON BETWEEN SALINE AND ALKALINE SOIL

Particular		*Saline soil*	*Alkaline soil*
Known as	:	Solan chalk	Solanetz
Soluble salt concentration	:	≥ 0.1 per cent	< 0.1 per cent
Colour	:	White coloured so also called white alkali	Black coloured so also called black alkali
Ions presence	:	Cl^- and SO_4^{2-} ions of Na^+	CO_3^{2-} of Na^+

Soil Quality indicators

Soils have chemical, biological and physical properties that interact in a complex way to give a soil its quality of capacity to function of performs. Thus, soil quality cannot be measured directly, but must be inferred from measuring changes in its attributes or attributes of the ecosystem, referred to as indicators.

A. Chemical

1) Soil organic carbon

2) soil pH

3) Cation exchange capacity (CEC)

4) Anion adsorption capacity

5) Base saturation

B. Biological

1) SOC (Soil organic carbon)

2) Microbial biomass carbon

3) Soil biomass

4) Microbial diversity index and enzyme assays

C. Physical

1) Integrated air capacity

2) Texture

3) Bulk density

4) Aggregation

5) Pore size distribution and continuity

6) Available water capacity

7) Non-limiting water range

8) Infiltration rate

9) Effective rooting depth

10) Soil temperature

D. Visual

1) Soil colour

2) Runoff

3) Plant response

4) Weed species

Problematic Soil in Geotechnical Engineering

Introduction

The earth’s crust is composed of soil and rock. Rock is often considered a consolidated material but soil is defined an unconsolidated sediment and deposits of solid particle that have resulted from the disintegration of rock.

Soils can be grouped into two categories depending on the method of deposition. **Residual soils** have formed from the weathering of rocks and remain at the location of their origin. Residual soils can include particles having a wide range of sizes, shapes and compositions depending on amount and type of weathering and the minerals of parent rock. Transported soils are those materials that have been moved from their place of origin. Transportation may have resulted from the effect of gravity, wind, water glaciers or human activities. Transported soil particles are often segregated according to size during the transportation process. The method of transportation and deposition has significant effect on the properties of the resulting soil mass Many large land areas have been formed with transported soils which deposited primarily by one of the transportation methods. The type and condition of soil deposits underlying proposed construction site must be recognized. Therefore engineers that engaged with construction has to be considered soil origin and properties of site especially problematic soils.

Problematic Soils

Problematic soils, from a geotechnical point of view as we mentioned priviously , are soils that have the potential to expand, collapse, disperse, undergo excessive settlement or even to fail under relatively low stress conditions.Many soils can prove problematic in geotechnical engineering, because they expand, collapse, disperse, undergo excessive settlement, have a distinct lake of strength or are soluble. Such characteristics may be attributable to their composition, the nature of their pore fluids, their mineralogy or their fabric. There are many types of problematic soils, some of the most noteworthy being swelling clay, dispersive soils and collapsible soils, soft and organic clay that discuss subsequently. In the following, briefly pay attention to expansive , depressive, collapsile soil, and finally soft soils have been explained.

1. Expansive Soils

Some soils undergo slow volume changes when change water content that occur independently of loading and are attributable to swelling or shrinkage. Expansive soils are those with excessive swelling clay minerals such as montmorillonite.

The presence of expansive clay minerals in soils can cause excessive swelling when the soil comes into contact with water and also shrinkage when it undergoes drying. These volume changes can give rise to ground movement which can cause damage to low-rise buildings that they don’t have sufficient weight to resist . These soils also represent a problem when they are encountered in road construction, and shrinkage settlement of embankments composed of such clays can lead to cracking and breakup of the roads they support. Construction damage is notable, especiallywhere expansive clay forms the surface cover in regions which experience alternating wet and dry seasons leading to swelling and shrinkage of these soils .

The principle cause of expansive soils is the presence of swelling clay minerals such as Montmorillonite. **The potential for volume change in soil is governed by its initial moisture content; void ratio and vertical stress as well as the amount and type of clay minerals . Cemented or undisturbed expansive soils have a high resistance to deformation**. Therefore, remolded expansive soils tent to swell more than undisturbed ones.

How to Treat The Expansive Soil

Soils which exhibit volumetric changes due to changes in their moisture content are referred to as expansive soils. They swell when wetted and shrink when dried, a phenomenon typically associated with seasonal moisture fluctuations. Such volume instability of expansive soils is influenced by several factors such as **their mineralogy, clay content, fabric structure, moisture content, density, pore water chemistry and loading conditions**. However, the primary reason is the presence of minerals like montmorillonite. In montmorillonite (2:1, silica/alumina unit), the tips of tetrahedra share oxygens and hydroxyls with the octahedral sheet, making it a single layer. Due to the charge deficiency in the structure and presence of weaker Van der Waals bond between two successive silica sheets, water and exchangeable cations can quickly enter in and thereby separate the primary layers. Therefore, the affinity to hold moisture makes a montmorillonite-rich soil more liable to swelling. Correspondingly, with the water evaporating out, it is prone to extensive contraction leading to visible settlement and shrinkage.

The volume instability, due to seasonal moisture fluctuation, induces stresses in the soil mass that tends to damage the superstructure, particularly the lightly-loaded ones, e.g. distortion of buildings; upheaval of floors and pavements; breakage of slab on grade members; damage of channel and reservoir linings; and distortion of irrigation systems, railways, canal, underground water supply networks.

Owing to such extensively high damaging potential, proper identification of the expansive soils in the preconstruction stage is an essential prerequisite. An expansive soil can be easily identified based on its physical, chemical and mineralogical properties. The physical properties consist of the Atterberg limits , free swell index , and volume change potential . In contrast, the chemical properties consist of cation exchange capacity (CEC) and specific surface area (SSA). Mineralogy can be identified through X-ray diffraction (XRD), scanning electron microscopy (SEM), differential thermal analysis (DTA), and dye adsorption test. However, the easiest way to recognize an expansive soil, in the field, is to determine its free swell index.

In general, when the soil at any particular site cannot provide stability to the proposed structure, the potential remedial measures the designer may consider are to:

(a) avoid the site;

(b) alter the foundation design;

(c) replace the problematic soil with a high strength non-swelling soil, such as murrum;

(d) modify the existing soil through ground improvement techniques so as to create a new material capable of meeting the desired requirements.

Although all the above methods have been tried but in case of expansive soil, choices (c) and (d) are widely adopted by the practising engineers. Choice (d), i.e. to improve the soil through ground improvement technique, is popularly known as **soil stabilization**. The replacement of problematic soil with a better quality of borrow soil may increase the construction cost significantly. In view of this, modification through soil stabilization is the alternate choice which is receiving engineer's attention over the years.

Soil stabilization essentially means unification of their particles leading to modified fabric and texture that enables it to achieve enhanced strength and durability. Over the years, many stabilization techniques have been evolved which can be broadly categorized into two groups, i.e**. mechanical and chemical .**

Mechanical or physical stabilization includes compaction, pre-wetting, reinforcement, and electro-kinetic treatment, whereas **chemical stabilization** is achieved by adding materials such as cement, lime, fly ash (FA) and salts. Petry and Little (2002) categorized these additives as traditional, by-product and non-traditional stabilizers. Cement, FA and lime are considered as traditional additives; Portland cement dust, lime kiln dust (LKD) and slags, as the by-product additives, along with sulfonated oils, polymers, salt and enzymes, as the non-traditional additives. In case of physical stabilization, soil performance is improved without altering the chemistry, whereas in case of chemical stabilization, reactions occur in the soil matrix leading to better bonding and stability (Abduljauwad, 1993).

Lime Treatment (Stabilization with Lime)

The most widely accepted chemical treatment is lime. The construction trade, according to Hinterkorn recognizes certain types of lime for use, these limes are listed in Table 2. The higher the magnesium content of the quick or hydrated lime the lesser is the water affinity and the heat developed in mixing with water. According to Tringale and Mitchell , the lime treatment of soils using both hydrated lime ($Ca(OH)2$) and quicklime (CaO) has been used extensively in conjunction with pavement construction, embankment lining and repair, and railroad subgrades.

The use of lime in soil stabilization started in the beginning of the 20th century. It was first introduced as a soil stabilizer in 1924 on a short extent of highway in USA (McCaustland, 1925). With the extension of highways and railways in modern days, stabilization of soils incorporating lime as additive has increased progressively. This is primarily due to its cost-effectiveness and prominent stability characteristics, both in the short and long run.

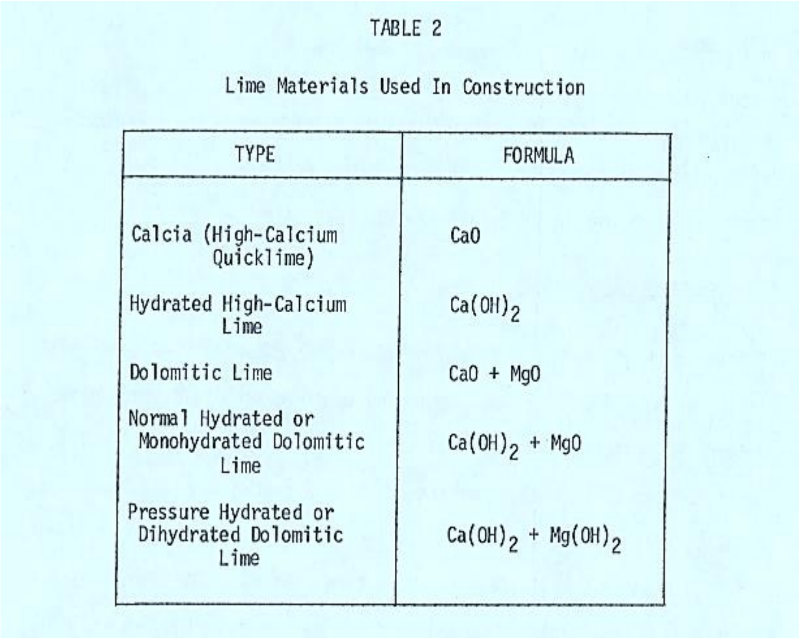


TABLE 2

Lime Materials Used In Construction

TYPE	FORMULA
Calcia (High-Calcium Quicklime)	CaO
Hydrated High-Calcium Lime	$Ca(OH)_2$
Dolomitic Lime	CaO + MgO
Normal Hydrated or Monohydrated Dolomitic Lime	$Ca(OH)_2$ + MgO
Pressure Hydrated or Dihydrated Dolomitic Lime	$Ca(OH)_2 + Mg(OH)_2$

The chemical theory involved in the reaction between lime and silicate, aluminate constituents of the expansive soils is complex. The primary factors include cation exchange, flocculation and agglomeration, pozzolanic reaction and carbonation. The reaction mechanisms can be further classified into two distinct groups: modification for plasticity reduction and solidification. Modification may be a reversible process but solidification results in irreversible changes in the soil characteristics (Deka, 2011). Modification results through flocculation and cation exchange activity, whereas solidification results through pozzolanic reaction. These reactions contribute to physical, chemical, mineralogical and microstructural changes in the treated soils.

Addition of water to lime results in an exothermic reaction that forms hydrated lime or Ca(OH)2. Generation of additional heat (15.6 kcal/mol) helps in cutting

$$\mathrm{CaO} + \mathrm{H_2O} \rightarrow \mathrm{Ca(OH)_2} + \mathrm{heat} \quad (15.6\ \mathrm{kcal/mol}) \qquad (1)$$

$$\mathrm{Ca(OH)_2} \rightarrow \mathrm{Ca^{2+}} + 2\mathrm{OH^-} \qquad (2)$$

down the natural water content of the soil. Further, when dissolving in water, Ca(OH)2 breaks into OH− and Ca2+ ions, as illustrated in the following equations:

The Ca2+ ions replace with the existing monovalent cations of soil minerals and cause an increase in inter-particular attractive force. As a result, the diffuse double layer (DDL) thickness of clay particles reduces considerably (Rogers and Glendinning, 2000). If the attraction is somewhat in excess of repulsion, the negative charge presented on the clay faces attracts the positive charges on their edges, thus resulting in flocculation/agglomeration. The change in DDL thickness and flocculation/agglomeration make the soil favorable for construction by reducing its plasticity and swelling characteristics (Elkady, 2016). In the second phase, OH− ions released from hydrated lime make the soil matrix alkaline leading to the dissolution of silica and alumina presented in it. Under a high pH environment (), silica and alumina from clay lattices become soluble and react with Ca2+ and OH− ions, and thereby form cementitious compounds such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH),. The associated reactions are called pozzolanic reaction as detailed below:

$$Ca^{2+} + 2OH^- + SiO_2 \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O \text{ or CSH} \quad (3)$$

$$Ca^{2+} + 2OH^- + Al_2O_3 \rightarrow 3CaO \cdot Al_2O_3 \cdot 3H_2O \text{ or CAH} \quad (4)$$

These cementitious compounds (e.g. CSH and CAH) bind clay particles strongly to obtain a long-term improvement in their shear strength, stability and bearing capacity.

In addition to the above, another reaction that takes place between lime and atmospheric carbon-dioxide is referred to as carbonation. It forms relatively weak cementing agents like calcium carbonate or calcite, but reduces lime availability for the pozzolanic reactions. This weak cementing compound contributes to a very small strength increase because of solidification or setting of lime. However, reduction in the availability of lime deters the pozzolanic reaction between silica, alumina and lime that tends to prevent long-term strength gain. Examination of relevant literature revealed that soil-lime stabilization depends on several factors such as soil type and mineralogy, lime content, pH of the soil matrix, curing period, curing temperature, freeze-thraw (F-T) and sulfate content.

1. Effect of soil mineralogy

Most of the clay minerals react with lime. The pozzolanic action of lime is controlled by cation exchange capacity, specific surface area and Si/Al molar ratio of the clay minerals In general, minerals having silica faces, on both sides, are relatively more susceptible to lime-induced reactions, than those having a single silica face. Accordingly, the amount of lime required for clay stabilization varies with the proportion of minerals presented in it. Addition of lime to kaolinite and illite leads to increase in liquid limit, whereas an opposite trend is observed in the case of montmorillonite. The deficient CEC (1–6 meq/(100 g)) of kaolinite causes insignificant reduction in the DDL and the change in liquid limit is mostly due to flocculation of the soil grains. Similarly, an increase in the plasticity index (PI) of kaolinite has been reported . Although illite has relatively higher CEC value (15–50 meq/(100 g)), it is inadequate enough to obviate the increase in flocculation-induced water content and thus the liquid limit increases. Moreover, higher CEC (80–150 meq/(100 g)) and higher Si/Al molar ratio usually make montmorillonite more reactive than illite and kaolinite, hence increases the lime requirement leading to reduction in the DDL thickness .

Apart from other variations, the pozzolanic reaction products that enhance the strength of the expansive soils tend to be different for different minerals. For example, in case of montmorillonite, it is the silica that is firmly attacked by lime producing CSH gel along with a small amount of CAH, C4AH13 or CAH10, wherein C represents CaO, A represents Al203 and H represents H2O. However, in case of kaolinite, lime preferentially reacts with alumina, producing CAH phases, e.g. C4AH13 and C3AH6 with a small proportion of calcium silicate aluminate hydrate phases, C2ASH8, where S is SiO2 (Bell, 1996; Eisazadeh and Eisazadeh, 2015). In addition, treating quartz with lime produces CSHs, C3S2H3 (Bell, 1996). Boardman et al. (2001) found that montmorillonite produces more reaction product, probably because of its greater surface area. Through unconfined compression tests, Bell (1996) observed that expansive clays such as montmorillonite show a relatively rapid gain in strength, in the presence of lime, than the kaolinite.While, it was found that kaolinite is more amenable to compaction and higher compaction density is obtained in lime-treated kaolinite than minerals with expandable lattices. It is also observed that, on addition of lime, the shrinkage limit of kaolinite increases slightly, wheras in case of montmorillonite, it is significantly high

2. Effect of soil type

Lime stabilization is not recommended for all types of soils. Addition of lime is beneficial when soil has a plasticity index (PI) more than 10% and at least 25% of its particles passing through 74 μm sieve (National Lime Association, 2004). Further, a soil that has at least 20% clay is preferably suitable for lime stabilization . Similarly, a sandy soil without any fines should never be considered as an active material for lime stabilization. In addition, lime is not efficient for silty soil having loam and granular soils, due to absence of adequate pozzolanas. High plastic expansive soils generally consist of almost 100% of clay particles and therefore, the lime requirement to alter their physicochemical properties is also high.

3. Effect of lime content

Upon adding lime to clay, first it tends to satisfy the soil's affinity. This affinity results from the adsorption of Ca2+ ions by clay minerals. Lime is not available for pozzolanic reactions until this affinity is satisfied. This limit of lime adsorption is referred to as **lime fixation point**. It was found that lime fixation point of soils normally varies between 1% and 3% by mass. In general, relatively low content of lime results only in modification of the soil. However, at higher lime content, both modification and solidification are possible . Further, a higher lime content provides better dispersion and hence better mixing of it in the soil matrix. This in turn tends to shorten the average distance between the reacting soil and lime particles, producing a more efficient molecular diffusion of Ca2+. Thus the degree of flocculation and concentration of cementitious pozzolanic reaction compounds tend to increase.

Chemical analyses indicated that when lime contents greater than 1% are used, pH increased significantly and the flocculation became more permanent and progressive. Further, 4% of lime has been found to produce maximum flocculation of dredged clay. A flocculated structure resists compaction effort and also occupies a larger space in the soil matrix which leads to a drop in the maximum dry density (MDD). In contrast, addition of lime raises the water requirement, due to its dissociation, and thereby the OMC increases . However, the reduction in MDD and increase in OMC continued up to about 3% of lime, beyond which the MDD increase and OMC decrease tended to be relatively slow . Consequently, the clay particles tend to move apart that the soil structure tends to become relatively dispersive, thereby allowing soil particles to slide over each other leading to ease of compaction giving rise to increase in the MDD.

Decrease in liquid limit of clayey soils with the addition of lime has been observed by many researchers. The decrease in liquid limit due to addition of lime is attributed to the reduction in thickness of the DDL and increase in shearing resistance at the particle. The reasons behind the increase or decrease in the liquid limit of the lime-treated soils have been reported and drew the following conclusions:

(1) An increase in the electrolyte concentration reduces the DDL thickness, leading to form clay clusters, which tend to decrease the liquid limit.

(2) If the available exchangeable cations in soil are monovalent, with the addition of lime, Ca2+ ions replace them leading to reduced DDL thickness, which in turn reduces the liquid limit.

(3) If the available exchangeable cations are divalent, cation exchange will have minimal effect on liquid limit. However, replacement with Ca2+ ions induces flocculation, which in turn increases water-holding capacity, and liquid limit increases accordingly.

(4) When the available exchangeable cations are more than divalent, partial replacement of higher-valence cations with Ca2+ ions increases the liquid limit.

(5) Addition of lime increases soil pH, which increases the CEC and thereby leads to an increase in the liquid limit.

The plastic limit of soils generally shows an increasing trend due to addition of lime. The greater the amount of clay, the larger the increase in the plastic limit, with the largest increase occurring in the case of montmorillonitic soils.

Irrespective of the liquid limit increasing or decreasing, the plasticity index is usually reduced with the addition of lime. This is due to the increase in the plastic limit and decrease in liquid limit of the clayey soils with addition of lime.

The shrinkage of clayey soils also can be reduced substantially by adding lime. The shrinkage limit upon drying is a measure of average particle orientation. Any soil with a parallel arrangement of particles undergoes more volume reduction upon drying than the same soil with its particles in a random/flocculent fabric. Also, a flocculated structure exhibits more resistance against capillary suction induced volumetric shrinkage (Dash and Hussain, 2015). Addition of lime to soil changes its fabric to the flocculated one. Hence, irrespective of soil plasticity, with an increase in the quantity of lime added the shrinkage limit of soil increases and the shrinkage void ratio decreases, indicating that the soils shrink less upon drying. However, the increase in shrinkage limit is more significant up to lime content of 5%, beyond which further improvement tends to be marginal . Additionally, with increase in lime content, workability, pH, yield stress, compressive strength, cohesion and California bearing ratio (CBR) of soils tend to increase nonlinearly up to a certain stage, typically referred to as the critical level .

Increase in lime content promotes stronger cementation bonds which tends to impart increased yield strength to the treated soil and minimizes the magnitude of deformations caused by the bond failure in the post yield. Additionally, a stronger cementation bond is found to have increased the resistance against compressibility of the soils; however, with lime content increasing beyond 4%, further improvement was marginal..

Optimum lime content can be determined in the laboratory by mixing different proportions of lime into the soil with a specific volume of distilled water. Total lime content required to obtain a pH of 12.4, referred to as the optimum lime content. The optimum lime content depends on various factors such as soil type, amount of clay presented, lime type and curing period. Hilt and Davidson (1960) proposed a linear relationship between optimum lime content and the proportion of clay as depicted in Eq. (5). However, the appropriate prescriptions are possible to make out through tests, as explained below:

$$\text{Optimum lime content (\%)} = \frac{\text{Clay content (\%)}}{35} + 1.25 \qquad (5)$$

4. Effect of type of lime

Among the ranges of parameters that affect lime stabilization, curing period is the one that plays an essential role. It tends to prolong the soil-lime pozzolanic reactions and thereby allow the soil-lime pozzolanic reaction products to grow. Consequently, as long as enough lime is presented and the pH remains above 10. However, the improvements are generally insignificant up to a curing period of about 24 h. It implies that pozzolanic reactions do not take place during the early curing stage (Sinha and Iyer, 2020). It is also observed that at about 10 d of curing period, the lime first results in a rapid exothermic hydration process and a simultaneous cation exchange which flocculates the soil into larger lumps. But, after 100 d, these lumps are once again cemented together by the subsequent pozzolanic reaction products such as calcium aluminate silicate hydrate (CASH), CAH and CSH. The resulting fabric tends to reduce the shrinkage and swell of the soil system.

Lime content also has a commanding influence on curing time. Extending the curing time by keeping the lime content low (e.g. 2%–4%) may not exhibit significant raise in strength due to the reduced availability of lime for pozzolanic reactions. With a higher amount of lime (e.g. 6%), availability of lime after short-term reactions (cation exchange and flocculation) is relatively more. As a result, pozzolanic reactions continue up to a longer duration. Consequently, to reach the peak strength, longer curing period, up to about 180 d, is required The strength increment is rapid during the first 7 d of curing, and then increases relatively slowly at a more or less constant rate for about 15 weeks. This is because the cementitious products, due to lime-clay reaction, form at an early stage of the process . Some studies have reported that strength improvement can rapidly increase up to 28 d, if the addition of lime is high. One of them observed that the time-dependent increase of the strength is approximately linear with the logarithm of time. While, the others have reported that the bonds between soil particles, which develop during curing, in the presence of lime and moisture, as a result of the development and growth of the newly formed cementitious compounds such as ettringite, gismondine, straetlingite and tobermorite, among others, are responsible for increased UCS of the soil mass . The strength gain may continue with curing age, even under severe environmental conditions, over years of service .

5. Effect of water content in soil

If a relatively small amount of water is added to fine-grained soils, due to inadequacy of the water, the clay particles share the available water mostly through adsorption, resulting in the formation of clusters. The rigidity of such clusters depends on the physicochemical properties of soils (expressed commonly by the liquid limit) and the mixing water content. The density achievable for a compactive effort is inversely proportional to the rigidity of the clusters. Since addition of lime changes the liquid limit of soil, it changes the rigidity of the clusters, ultimately changing the compaction behavior of the soil .

The maximum strength is obtained when molding water content of the soil-lime mixes is between 2% and 3% wet of OMC. Strength decreases with increase in water content. This is due to the fact that at higher water content, available lime per unit volume is less and the cementitious products are produced between more distant soil particles which cannot make the interparticle bonds any stronger. owever, for soils having very high natural water content (e.g. expansive soils), the percentage loss of water being too small, amount of lime required for adequate strength gain is also more .

When the added lime content is high and the sample is prepared at OMC and cured without adding any further water, the water content may become inadequate for complete lime hydrolysis. Therefore, all lime grains may not contribute to strength gain, but remain as it is, throughout the entire curing period. As lime exhibits relatively lower cohesion and friction than soil, its presence in unreacted form negatively affects the soil strength.

6. Effect of pH of soil matrix

The pH of a soil system is one of the crucial factors in lime stabilization. In general, soil exhibits good reactivity with lime, if it has a pH greater than 7. A higher pH has been proved to be efficacious for dissolution of silica and alumina, thereby, pozzolanic reaction increases, which contributes to achieving better flocculation. Also, a higher pH of the lime-mixed soil renders the clay particle edges more negative, which increases the CEC of the soil. Consequently, more Ca2+ ions get adsorbed at the clay particle edges, imparting them higher exchangeable calcium contents, thereby increasing the aggregation between particles. On the other hand, with reduced pH, silica and alumina of clay minerals do not dissolve effectively. Consequently, formation of less/negligible cementitious products, owing to the acidic environment, results in marginal improvement of soil strength. Moreover, in a highly acidic environment (pH ≤ 3), almost all freely available Ca2+ ions tend to get leached out, and therefore, lime often does not yield an acceptable performance . The acidic nature of soil also demands more lime for stabilization, since a part of the full amount dissipates to neutralize the pH. As a result, strength and stiffness of the soil tend to reduce significantly.

7. Effect of organic content in soil

Organic matters are often known for their poor engineering properties, including very high compressibility and low shear strength (Mitchell and Soga, 2005). Organic clay tends to hold water and thereby cuts down the free water for hydration of lime. With an increase in organic content, corresponding to a fixed lime content, OMC of soils increases and MDD decreases. The higher OMC is due to the higher water retention capacity of organic soil, whereas a drop in MDD is due to the decrease in the soil unit weight. Furthermore, the decomposition of biomass in an organic clay decreases the pH of the soil and restrains the formation of cementitious gel through coating the lime grains. Also, the higher water content in organic clay may induce increased spacing between aggregations, thereby reducing cementation bonding. In addition, organic soil has a very high CEC, i.e. 250-400 meq/g. Hence, when lime is added to organic clay, some of the Ca2+ ions are consumed by organic matter to satisfy its CEC, which in turn reduces the availability of Ca2+ ions. Thus, the presence of a relatively higher concentration of organic matter can have an adverse effect on the engineering behavior of lime-treated soils. In fact, it has been stated that the lime stabilization process becomes ineffective if the concentration of the organic compound exceeds 1.5%.

Cement Treatment (Stabilization with cement)

Other than lime, the most prominent chemical additive is ordinary Portland cement (OPC) which has been extensively used for somewhere about 100 years . It is a fine heterogeneous compound, consisting of four different oxides, such as tricalcium silicate (C3S), Di-calcium silicate (C2S), tricalcium aluminate (C3A), and tetra calcium alumino ferrate (C4AF), where, C is the CaO, S is the SiO2, A is the Al2O3, F is the Fe2O3, and H is the H2O. Although the stabilization mechanisms of lime and cement are almost identical , cement is extensively used for its easy availability, rapid strength gain (i.e. within a month), and relatively higher improvement in compressive strength. The stabilization mechanism consists of hydration, cation exchange, flocculation and pozzolanic reaction. When clay is blended with cement and water, hydration takes place immediately. C3S and C2S, presented in cement, react with water and release calcium ions into the clay mixture and thereby form cementitious compound such as CSH as shown in Eqs. (8), (9). Moreover, this cementitious hydration also forms calcium aluminium hydrate. These cementitious hydration products are gelatinous and contribute to the significant improvement of soil strength very fast. In general, OPC consists of a greater amount of C3S that reacts quickly with water and thereby contributes relatively more to the early strength gain than the C2S. The mechanism of strength gain due to cementitious hydration is depicted in Fig. 2.

$$2C_3S + 6H_2O \rightarrow CSH + Ca(OH)_2 \qquad (8)$$

$$2C_2S + 4H_2O \rightarrow CSH + Ca(OH)_2 \qquad (9)$$

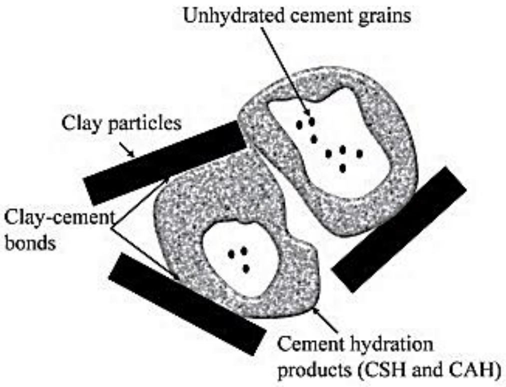


Fig. 2. Strength development mechanism due to cementitious hydration products (adapted from Prusinski and Bhattacharja, 1999).

Furthermore, the hydrated lime (Ca(OH)2), which forms during hydration of C3S and C2S, (Eqs. (8) and (9)), breaks into OH− and Ca2+ ions; subsequently, the Ca2+ ions contribute to soil flocculation. It also reacts with pozzolanic materials such as silica and alumina, present in the soil. Consequently, cementitious compounds i.e. CAH and CSH, are formed leading to strengthening of interparticle bonds, giving rise to enhanced performance of the soil mass. It was evident that, due to formation of additional cementitious gel, the cement-treated soil tends to exhibit higher resistance than lime-treated soil. The strength improvement mechanism due to cementitious compounds of pozzolanic reactions is shown in Fig. 3.

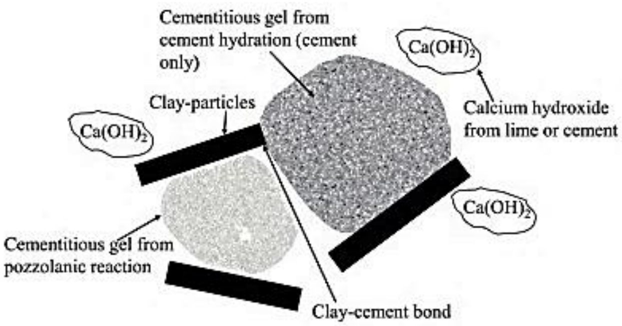


Fig. 3. Strength development mechanism due to pozzolanic reaction products (adapted from Prusinski and Bhattacharja, 1999).

It can be seen that initially, when the pozzolanic reactions were not significant, the soil grains were strengthened by cementitious products of hydration only. However, with the progress of time, when the pozzolanic reactions took place, the soil grains were further strengthened by the cementitious products. Consequently, bonding between the soil grains tends to become stronger with time, leading to a significant strength grain which is relatively larger than that of the lime-stabilized soil.

With the addition of cement, soil plasticity, liquid limit, as well as swelling potential, tend to reduce significantly, whereas shrinkage limit and strength gain tend to increase. Also, the addition of OPC in clay increases the concentration of multivalent cations (e.g. Ca2+). Therefore, monovalent cations (e.g. Na+ and K+) existing in the clay minerals tend to become replaced with the multivalent cations, leading to reduced DDL thickness and thereby reduced swelling capacity of the soil. Similar to lime, stabilization with cement is also influenced by several factors, such as water-cement ratio, cement content, curing period, and sulfate and organic content.

1. Effect of soil mineralogy

Kaolinite and well-crystallized illite have less SSA and are more resistant to penetration of interlayer cations. When kaolinite is blended with cement, the hydrated lime produced during cement hydration reacts with the clay minerals slowly. Therefore, in the early stage of curing, mineral contents have relatively less effect on the stability of cementitious hydration products. After a long curing period, the residual hydrated lime after the short-term hydration is consumed by secondary pozzolanic reaction and both the processes contribute to cementation. Moreover, the well-crystalized illite is considered as inert and the process of hydration and pozzolanic activity is ineffective as far as cement stabilization is concerned. In contrast, montmorillonite possesses higher SSA, poor crystallinity and it has a higher affinity for calcium ions. The lime or calcium ions liberated from cement during hydration lead to a decline in pH of the soil and due to the resulting deficiency of calcium ions, the cementitious products produced during the curing of the montmorillonite-cement matrixes are relatively inferior to the cement-stabilized non-expansive minerals. Therefore, the strength developed in montmorillonite-cement mix tends to be generally lower, unless the cement content is high . Thus, for a given content of cement, kaolinite seems to achieve higher strength and lower compression index, as compared to montmorillonitic clay. It is observed that minimum 2% of cement is essential for a considerable change in the strength of kaolinite. On the contrary, at least 5% of cement is required for montmorillonite .

2. Effect of soil type

All types of soils are amenable to treatment with cement. However, granular materials with enough fines and clay with low to medium plasticity are usually considered as suitable for cement stabilization. This is primarily because of ease of mixing. Gravel can also be treated with cement when the percentage retained on No. 4 sieve (4.75 mm size) is limited to 45%. American Coal Ash Association (2003) suggested that the use of cement is practical and economical if the soil plasticity index (PI) is less than 20%. Cement addition in expansive clay exhibits a significant decrease in the shrink-swell strain coupled with enhancement of strength and stiffness. Moreover, clay with relatively lower liquid limit tends to attain a compressive strength higher than that of clay with higher liquid limit.

$$PI \leq 20 + \frac{50\text{−fines content (percentage finer than 75 }\mu\text{m)}}{4} \tag{10}$$

Cement becomes hard to blend with highly plastic clay due to the formation of lumps and needs specific efficacy of mixing. In that case, a small amount of lime is added first to improve the workability. Sasanian and Newson (2014) recommended that as compared to low and medium activity (Ac), clay with higher activity reacts more readily with cement and thereby produces increased cementing bonds. A general guideline proposed by Terrel et al. (1979) for selecting cement as a stabilizer is given as follows:

3.Effect of cement content

Optimum amount of cement giving maximum performance improvement of soils is dependent on several factors. As the amount of clay increases, the requirement of cement content increases. This is primarily due to the rise in the SSA and particle to particle contacts. Depending on clay content, requirement of cement for significant modification of expansive soils can vary from 3% to 16%. Lower amount of cement is required for low plastic clay and higher amount for the high plastic one. It is observed that liquid limit of highly plastic clays continues to reduce until cement content as high as 6%, beyond which further changes were insignificant. In contrast, for low plastic clays, the liquid limit was found to have slightly increased up to cement content of about 3% and then decreased.

In general, the compressive strength of soils tends to increase with increase in cement content (khitam, 2014). For clayey soils with liquid limit in the range of about 40%–60%, it is observed that 4%–12% of cement can be sufficient to achieve the threshold compressive strength. But for liquid limit above 60%, the soil to achieve the desired strength needs cement content more than 12% by mass, which is generally uneconomical. The variation of strength development with cement, at certain water content, can be categorized into three different zones, i.e. active, inert and deterioration, as shown in Fig. 4.

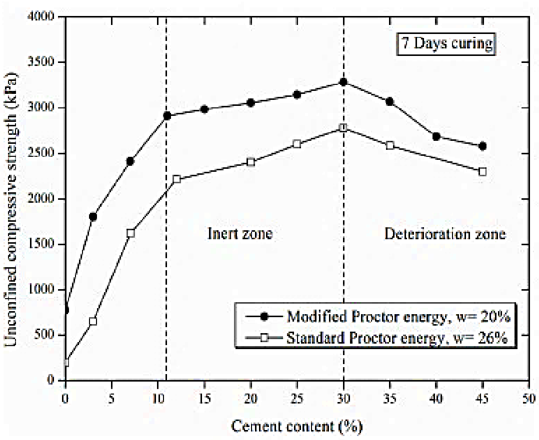


Fig. 4. Different strength development zones in cement-treated clay (sourced from Horpibulsuk et al., 2010).

In the active zone (cement content: 0%–11%), soil pore size decreases considerably due to an increase in the cementitious compounds formed, giving rise to enhanced strength. In the inert zone (cement content: 11%–30%), further reduction in pore size tends to be marginal, leading to reduced strength gain. In the deterioration zone (cement content: 30%–50%) due to lack of adequate amount of water, formation of cementitious compounds tend to get retarded. Consequently, with increase in cement content, the soil strength decreases. In addition, due to excessive amount of cement, shrinkage cracks tend to flourish, which may cause preferential seepage through the treated clay-layer. To avoid shrinkage cracking, cement content should preferably be less than 8% .

4. Effect of cement type

Though almost all types of cements available are beneficial for soil modification/stabilization, OPC referred to as the Type I cement is the most widely used one, because of its availability and cost-effectiveness. Two major factors which control the suitability of OPC are as follows: firstly, it can be appropriately mixed with clay, and secondly, after mixing and compaction, the soil-matrix produces sufficient strength and stiffness. Treated soil is better improved by Type III cement (rapid hardening cement), which provides higher order of early strength gain than Type I, OPC. Development of higher initial strength is associated with the higher surface area of cement grains and more upper C3S value. In the presence of water, fine-grained cement exposes more soil to water and also a higher C3S content leads to faster hydration. In contrast, Type V cement has a very low C3S and high C2S content. Owing to this, the strength development process continues over time, and the long-term strength gain due to the type V cement is found to be relatively higher than that for Type I. Blast-furnace slag cement induces a relatively lower heat of hydration, and compared to OPC, it shows better resistance against chemical agents such as chlorides, alkali metals, acidic water, heptane, methanol and trichloroethylene. Usually, C3A, i.e. 3CaO·Al2O3, presented in the OPC, imparts alumina which reacts with sulfate to produce ettringite. However, the lower concentration of C3A in Type V cement minimizes the possibility of ettringite formation; hence, Type V cement is more efficient for the treatment of sulfate-rich soils.

5. Effect of water-cement ratio

It is observed that for a given water content, there exists a maximum limit of cement content, beyond which cement grains cannot usually hydrate and thereby cannot contribute to the pozzolanic actions adequately. Typically, 1 mol of Portland cement, i.e. Type I cement, needs 4.2 mol of water for its complete hydration. Hence, water content and water-cement ratio (w/c) are two critical parameters for the engineering behavior of cement-treated clays. A specific water-cement ratio (w/c) can be achieved by varying the water content or proportion of cement, or both. If the water content is sufficient for hydration, a lower value of w/c ratio enables a better-cementing bond than that of higher w/c ratio (i.e. less amount of cement). Several investigations have reported that soil specimens prepared with the same w/c ratio (e.g. 7.5, 10 and 15) exhibit almost identical stress-strain relationship and deformation pattern. It is observed that UCS tends to decrease with increasing w/c ratio. However, for a fixed cement content and curing period, the soil sample prepared with initial water content at or above its liquid limit shows higher UCS than that of a sample molded at water content lower than its liquid limit. The resilient modulus was found to have decreased, and permanent deformation increased with increase in the w/c ratio.

6. Effect of curing period

It is observed that UCS tends to increase with elapsed curing time, irrespective of soil or cement types, and if the water content is adequate, the clay-cement reactions may run for months, or even years. The rate of strength development is found to be relatively quicker during the early stage of curing (0–7 days). This is due to the short-term cement hydration which tends to deaccelerate gradually to reach an asymptotic value at late curing age. Similarly, improvement of other engineering properties such as increase in elastic modulus, reduction of plasticity index, decrease in swelling potential, reduction in compression index, reduction in hydraulic conductivity, durability against wetting-drying (W-D), and dynamic shear modulus tend to continue with increase in the curing time. In addition, it was found that the effect of confining pressure on dynamic shear modulus (G) becomes ineffective at a higher curing period, i.e. about 90 d .

7. Effect of compaction delay

As cement hydration is quick, clay compaction must follow mixing, preferably within 2 h, and small clusters of cemented soil formed might not properly break up denying access to spread of water leading to unreacted cement in the soil matrix. Moreover, the time-lapse between compaction and mixing reduces the effectiveness of cement, which gives rise to much lower strength and density, unless the time gap is restricted to 2 h. Furthermore, higher compaction delay exhibited a lower secant modulus and higher compression index compared to the non-delayed ones. Although delayed compaction tends to be detrimental to the strength, plasticity and shrinkage limit of treated clay are not appreciably affected. If the permissible delay in compaction is not attainable due to some unfavorable environmental conditions in the field, addition of a set retarder with soil-cement mix can be a feasible solution, otherwise a higher compacting effort is recommendable to recoup the effect of lapse of time.

8. Effect of organic content in soil

Organic matters can be presented in soils in the form of proteins, resins, carbohydrates, fats and carbon (Mitchell and Soga, 2005). These organic compounds react with Ca(OH)2 to produce indissoluble products which get coated over the soil grains. Organic matter can adsorb Ca2+ ions and thereby leave an insufficient amount of Ca2+ for pozzolanic activity. Furthermore, the presence of organic matter causes soil pH to fall. Thus, organic matter affects adversely on the cement hydration and cementation, particularly when the organic content exceeds 3%–4%. Consequently, strength loss in soil increases with organic content, however, the strength loss is more obvious in highly expansive soil containing organic content. It was observed that strength loss is around 15%–30% when organic content is increased by 1%. Furthermore, the high water-holding capacity of organic matter is believed to cause a rise in OMC and liquid limit of cement-treated clay. However, if a soil-cement mix produces a pH of 12 or more, organic matter possibly does not affect the cement hydration; otherwise, the soil needs a higher amount of cement to neutralize the negative effect of the organic content.

9. Effect of sulfate content in soil

Similar to lime, the presence of sulfate adversely affects the strength and stability of cement-stabilized soils. The reaction mechanisms related to the formation of ettringite in a sulfate-rich cement-stabilized soil is similar to that of lime-stabilized soil. The formation of swelling minerals (e.g. ettringite and thaumasite) leads to heave as well as cracks in the treated soils. The presence of sulfate leads to reduction of the pH of the soil that tends to hinder the pozzolanic activity. It is also observed that addition of sulfate results in increased permeability and reduced shear modulus. Further, ettringite holds moisture, causing to rise of the liquid limit of sulfate contaminant soils. It was reported that temperature rise in summer accelerates the rate of ettringite formation.

10. Effect of nano-silica

Nano-silica has the efficacy to improve physicochemical properties of cement-treated clay due to its high reactivity with cement. In general, the higher purity of silica and high SSA of nano-silica accelerate cement hydration, and thus the requirement of cement content gets reduced. Inclusion of nano-silica in cement paste increases the heat of hydration. Further, higher silica content increases the rate of pozzolanic action, so does the cementation. In addition, the pore voids get filled with nanoscaled particles, leading to a denser microstructure. When cement is blended with nano-silica and water, both cement and nano-silica break into

$$\begin{aligned}&\text{Cement} + H_2O + \text{nano-silica} \rightarrow Ca^{2+} + H_2SO_4{}^{2-}\ (\text{from cement}) \\ &+ H_2SO_4{}^{2-}\left(\text{from nano-silica}\right) + OH^{-}\end{aligned} \tag{11}$$

H2SiO42− along with Ca2+ and OH−, as shown in Eqs. (11). These H2SiO42− further reacts with Ca2+ during hydration leading to increased pozzolanic effect, giving rise to formation of additional CSH gel. Addition of nano-

silica in cement-treated clay, even in a small quantity (i.e. 0.5%, 1% and 1.5%) can improve the strength and reduce the hydraulic conductivity significantly.

Stabilization with FA

FA is a non-expansive finely graded material produced from the burning of coal in a thermal power plant . FA is generally finer than OPC and consists of aluminous silicious glassy spheres. FA particles are spherical (diameter of about 1–50 µm), non-plastic, have a higher SSA (2000–10,000 cm2/g), and can be regarded as ‘silt’ according to the United Soil Classification System. Major constituents of FA are silica and alumina but some other trace of oxides such as CaO, Fe2O3, TiO2, K2O, MnO, Na2O and SO3 may also be presented (Phanikumar and Sharma, 2007). Depending on the chemical composition and nature of burned coal, it has been categorized into Class-F and Class-C types (ASTM C618-17, 2017). Calcination of anthracite or bituminous coal produces Class-F FA (FFA), whereas Class-C FA (CFA) can be produced by burning fresh lignite or sub-bituminous coal. CFA contains a higher proportion of lime, CaO (>20%), higher alkali and sulfate contents. The total sum of Al2O3, SiO2 and Fe2O3 presented in this type of FA is in the range of about 50%–70%. On the other hand, FFA generally contains less lime (<10%), and the amount of Al2O3 + SiO2 + Fe2O3 exceeds 70% (ASTM C618-15, 2015). In the presence of water, CFA forms cementitious compounds which help in gaining strength with time. In contrast, FFA exhibits cementation in the vicinity of an activator such as lime or cement. In view of this, CFA is preferred over FFA. Some studies have shown that high-calcium CFA is a more economical and environmentally sustainable substitute, for stabilizing expansive soils, as compared to other active additives. Several other studies have been conducted towards the use of FA as an alternative to chemical additives such as cement and lime. Ferguson (1993) classified the benefits of CFA into three categories: (1) Drying agent: as substantial amount of water is consumed by the FA in the hydration process, it can be used as a drying agent for damp soils, particularly when rapid drying is desirable; (2) Control of volume instability: it can reduce the volume instability of soils through reduced shrinkage and swelling; and (3) Strength improvement: cementitious compounds from the pozzolanic reaction of the FA provides a cementing bond in soil that enhances its strength. Several other factors affecting the treatment process of the FA are discussed below.

1. Effect of soil type

In general, FA is used to make a weak soil worthy of construction; however, its incorporation at times cannot improve soil properties to the desired levels. Since a highly plastic clay has a higher sensitiveness towards calcium, addition of substantial amount of FA can cause significant reductions in the liquid limit and swelling potential, but the addition of FA alone might not suffice for the complete elimination of the swelling potential of expansive clay. In contrast, the inclusion of FA in lean clays causes the clay particle to behave as fines and thus swelling potential and liquid limit increase. CBR and resilient modulus values tend to increase, irrespective of the soil type; still, the most significant improvements were observed with highly plastic clay and the smallest with a silty clay. Furthermore, on increasing the clay content in a soil-FA mix, strength continued to increase due to the enhanced pozzolanic reactions caused by the alumina and silica presented in the soil. The addition of FA in highly expansive clay reduces the cohesion (c) and increases the friction angle (ϕ), but for lean clay, both c and ϕ values increase with added FA. With FA alone, the ϕ value of residual soil was also found to reduce when it was tested under undrained condition.

2. Effect of FA content

In general, with the increase in FA content, MDD of the treated soil increases and OMC decreases. The rise in the dry density may be associated with the filling up of larger inter-particle voids with the finer FA during compaction, whereas the reduction in OMC is attributed to the increased consumption of water by the fine particles as the SSA of grains increases with the addition of FA. Additionally, with increase in FA content, plasticity, swelling pressure, swell potential and shrinkage of soils tend to reduce significantly. The hydraulic conductivity (k) decreases and undrained cohesion (cu) increases with increase in the FA content. The angle of internal friction and CBR value are also found to be increasing nonlinearly with the FA content. FA brings down the volume change in the secondary consolidation stage due to creep and slippage of particles. Moreover, an increase in the FA content shortens the duration of primary consolidation of soil and thereby reduces settlement of the supported structures. The drainage property of clay also improves with the increase in the CFA content.

With FA content increasing, resilient modulus increases and permanent deformation, at a given confinement pressure or number of loading cycles, decreases. Moreover, small-strain shear modulus (Gmax) increases and damping ratio decreases with increase in the FA content. At higher confining pressure, the stabilized soil stiffness increases due to increase in the particle to particle contacts (Mitchell and Soga, 2005). Also, cementation effect of FA provides a better confinement effect at the soil particle interfaces, which causes increased rigidity of the soil mass, leading to increased value of Gmax .

Overall, it is observed that the optimum FA content for maximum performance improvement primarily depends on the types of soil and FA. It has been reported that for soils with different plasticity indices, the effective dosage of CFA for improving the physicochemical properties of soils ranges between 15% and 20%. However, optimum dosage of FFA is higher than that of CFA which can be as high as 25%–60%.

3. Effect of FA type

Not all of the silica presented in a FA participate in the pozzolanic activity. The reactive silica is non-crystalline and amorphous and tends to react more readily with lime to form the cementitious compounds. The remaining silica presented in the FA being crystalline in nature can hardly react with the lime. Consequently, FA with higher reactive silica gives better cementation. CFA is having major constituents of non-crystalline silica which are more responsive to lime and exhibits higher pozzolanic activity than FFA. Furthermore, the reactivity of FA varies with its fineness, chemical and phase composition, morphology and loss on ignition. Particles finer than 10 μm tend to exhibit better pozzolanic reactivity . Also, a clay sample stabilized with FA having higher CaO/SiO_2, CaO/Al_2O_3 and $CaO/(SiO_2 + Al_2O_3)$ ratios experiences higher pozzolanic activity as well as better improvement in engineering properties. FFA does not often yield acceptable performance in stabilized soils, and therefore, should be mixed along with lime or cement; else, the requirement of FFA will be high. It was observed that 10% of CFA is good enough to minimize the swelling potential, whereas, to achieve the same effect, soil requires 40% of FFA. Off-specification (off-spec) FA is a particular type of FA that contains a higher amount of SO_3 (>5%), carbon (loss on ignition >6%), as well as lime, and thereby exhibits superior performance, in soil stabilization, as compared to CFA and FFA.

4. Effect of curing period

Two major factors which control the pozzolanic reactions are lime content and amount of pozzolana. Presence of relatively higher silica and alumina contents in the FA can extend the pozzolanic activity, which can be as long as 180 d. However, expansive clay treated with FA exhibits significant improvement during the first 28 d of curing; beyond that age, the improvement is insignificant. It is observed that for FA content up to about 5%, neither FA content nor curing age notably affects the strength of soil. However, the effect of curing period tends to be significantly more when the FA content exceeds 10%. FA-stabilized soil has enhanced strength and stiffness with curing, resulting in increased CBR, dynamic shear modulus, and resilience modulus, over time. Some reserchers found that the gain in UCS of FA-treated soil with time can be assumed to be nonlinear. The variation of UCS with curing period is shown in Fig. 5. It is shown that irrespective of the FA content, UCS of soil increases nonlinearly with curing time; however, rate of improvement is marginal when the curing period is beyond 28 d.

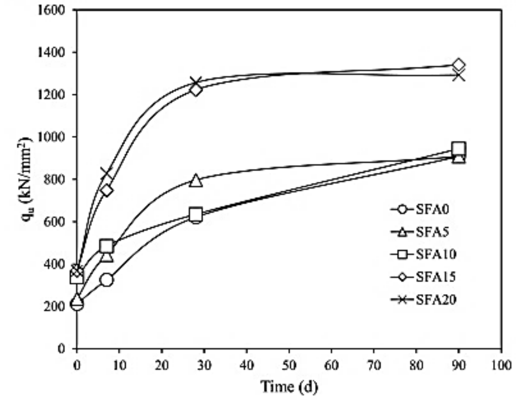


Fig. 5. Variation of UCS (q_u) with time (SFA0, SFA5, SFA10, SFA15 and SFA20 denote soil with 0%, 5%, 10%, 15% and 20% FA, respectively) (sourced from Sezer et al., 2006).

5. Effect of compaction delay

Similar to lime and cement, in case of FA admixed soil too, it is preferable to keep compaction delay as low as possible. Even though the FA hydration is a lengthy process, the major portion of the cementation process seems to occur during the first few hours. On exposure to water, hydration products start bonding soil grains during the delay, and a major part of the compactive energy is usually lost in surpassing the cementation bonds. If the primary concern is to achieve the maximum strength, a maximum 1-h delay in compaction is recommended. Otherwise, a maximum of 2-h delay in compaction can be employed . In general, delay in compaction reduces soil density. It is observed that, depending upon the chemical composition of FA, 1-h delay may reduce the MDD value by about 1.6 kN/m3. Such reduction in MDD can cause a detrimental effect on the maximum compressive strength of the treated soil.

6. Effect of water content

Molding water content also plays a vital role in the performance improvement of the FA-treated soils. As the strength and durability of treated soil are highly dependent on the molding water content, strict water control is required during compaction. The general trend is that, regardless of FA content, strength and stability tend to decrease with an increase in the molding water content. A clay-FA mix achieves the maximum strength, if the sample is molded with water content about 4%–8% lower than the OMC. On the other hand, sample compacted at a water content equivalent to OMC generally gives higher CBR value than the sample prepared at 7% wetter than the OMC. Moreover, a clay-FA mix prepared with 10% of CFA and water content 7% higher than OMC can reduce the resilient modulus (Mr) lower than that of the soil compacted at OMC. However, at CFA content greater than 18%, the Mr value was found to be higher than that of the unstabilized soil compacted at OMC.

7. Effect of organic content in soil

Presence of organic matter in an expansive soil adsorbs calcium ions and thereby limits their concentration in the admixed soil. Further reduction in the calcium ions leads to reduced pozzolanic activity. Therefore, to compensate the loss, a relatively large amount of lime should be presented in the FA. As the amount of lime presented in FA is generally less, its application in treatment of an expansive soil containing organic matter is not desirable (American Coal Ash Association, 2003). It was found that an organic clay treated with FA increases both liquid limit and plastic limit and also causes detrimental effect on its strength). Increase in the concentration of organic matter exponentially decreases the strength of clay-FA mix. Also, addition of FA (either F type or C type) has almost negligible effect on CBR and resilient modulus of organic clay, even though the FA content is high. However, a modest degree of stabilization can be attained by applying off-spec FA due to the high CaO/SiO2 content.

8. Effect of sulfate content in FA

Apart from calcium, silica and alumina, the CFA generally contains a considerable amount of sulfate. Therefore, in an alkaline environment, it acts as a potential source of ettringite. Although CFA can form a significant amount of ettringite, partial replacement of cement with FA forms relatively less ettringite than the primary soil-cement mix. Similarly, addition of FA in lime-treated clay reduces the ettringite-induced swelling to an allowable limit, i.e. <5%. The presence of silica in FA reacts with Ca2+ ions of lime and thereby decreases Ca2+ concentration. As ettringite requires more Ca2+ ions to form, the reduction in the Ca2+ concentration tends to reduce the chance of ettringite formation. Thus, sulfate-induced swelling reduces. In addition, FA is effective in reducing the plasticity of both untreated and lime-treated sulfate bearing expansive clays. FA with high sulfate contents may contribute to the total potential sulfate of the lime-treated clay, which can exacerbate the formation of ettringite as well as swelling. Thus, FA can also be a crucial factor concerning the selection of materials to restrict sulfate-induced swelling in the lime-treated expansive soils.

Stabilization with non-traditional additives

1. Salt

The effects of inorganic salts (e.g. NaCl, KCl, CaCl2, MgCl2, AlCl3) have a significant role in soil modification. When expansive clay comes in contact with a salt solution, the hydrous cations (Na+, K+, Mg2+, Ca2+, Al3+) presented in the clay matrix tend to move into the solution, wherein the multivalence cations (e.g. Ca2+, Al3+) are capable of replacing comparatively weaker cations (e.g. Na+, K+) through the process of cation exchange, as shown in Fig. 6.

The effectiveness of lime treatment and the various methods of application are summarized in Table 4

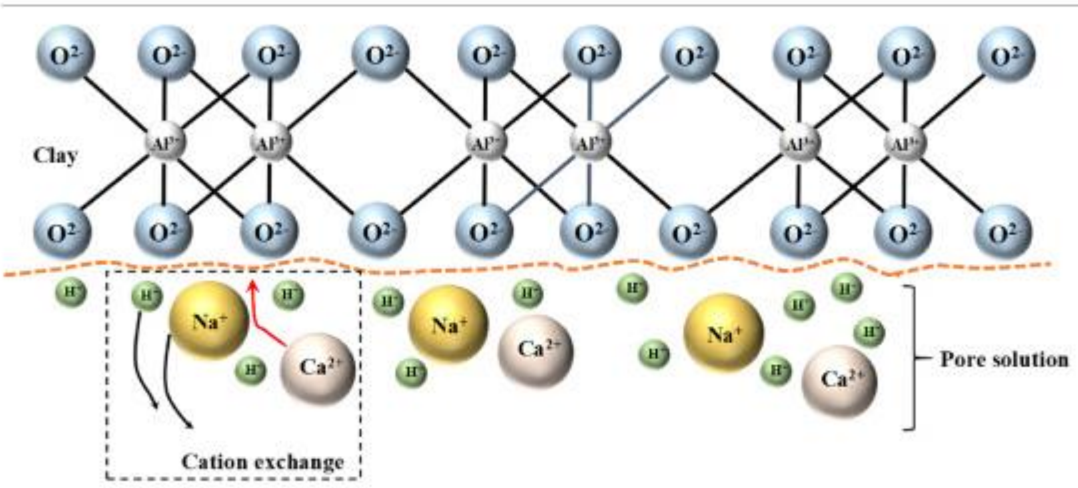


Fig. 6. Mechanism of cation exchange (adapted from Shon et al., 2010).

Moreover, with the increase in salt content, the salt concentration in the pores increases, enabling the particles to flocculate rapidly and thereby increasing the effective particle size. However, the amount of adsorbed water decreases as the flocculating particle size increases. Also, an increase in cation concentration decreases the inter-particle repulsion, resulting in a reduction in the DDL thickness. Studies have been reported that reduction of absorbed water and DDL thickness further results in reduction of liquid limit, plasticity, swelling potential and swelling pressure of clay soils. Usually, for any type of salt, a concentration of 1 mol/L is enough to decrease the liquid limit and swelling potential to the minimal level. The performance of CaCl2 is relatively superior to other salts. Treatment of expansive soil with CaCl2 leads to an increase in MDD and decrease in OMC, which contributes to an increase in both initial and long-term strengths of native soil. The strength improvement is probably due to the cation exchange and formation of CSH and CASH gels . Salts can also cause a rise in pore water surface tension, which increases the apparent cohesion of the soil and thereby improves the soil strength. Moreover, the strength improvement also increases with increase in curing period .

2. Geopolymers

Geopolymer, an inorganic material, has been introduced as an innovative and eco-friendly binder for stabilization of soft soils. It is a network of alumino-silicates made up of alumina (AlO4) and silica (SiO4), connected alternatively by sharing the O2− atoms. Its simplified molecular formula can be written as {Mn-(SiO2)z-AlO2-}n, where M is the alkali cations (e.g. Na+ and K+), n is the degree of polymerization and z represents the Si/Al molar ratio. When , a stiff three-dimensional structure is formed, but when the geopolymers have more linearly linked structures which exhibit adhesive properties and thereby favor soil stabilization (MacKenzie et al., 2006). Geopolymers synthesized at higher temperature achieve higher strength gain at early stage; however, formation of relatively weaker polymeric chain at higher temperature tends to reduce the long-term durability of the stabilized soil. In addition, the presence of an inferior amount of Ca2+ ions in the polymer significantly reduces the risk of ettringite formation in sulfate-rich soils. A specimen with a substantial amount of geopolymer (20%) produces an appreciable amount of artificial bonds, which has been shown to improve dynamic shear modulus and reduce shear modulus of degradation. Thus, a geopolymer-treated clay can be suitable in supporting dynamic loading systems like highways and railways.

3. Enzymes

Enzymes such as Renolith, PermaZyme, TerraZyme and Fujibeton are organic, non-toxic and biodegradable liquid catalyst which has been proven to be efficacious and economical for stabilizing fine-grained soils, especially the expansive ones. Upon adding enzyme, the negative charge on clay surfaces is neutralized by enzyme cations and reduces the clay's affinity for water. Furthermore, enzymes produce cementitious products as explained in the following equation:

$$\mathrm{H_2O} + \text{enzyme-stabilized clay} \rightarrow \mathrm{CSH} \tag{12}$$

On the other hand, enzyme coats the soil particles, which prevent any further adsorption of water, leading to reduced swelling. Also, the coating creates a physical bond between the soil grains making a more stable clay structure, leading to improved soil strength and CBR value. Furthermore, enzyme-stabilized clay exhibited a reduced distribution of voids in the soil matrix. Lessening in the pore spaces connecting the soil grains leads to an increase in the soil compactness and reduces its permeability.

Enzyme in expansive soils limits the strength losses and crack propagation due to W-D cycles, sustaining strength and durability of the stabilized soil. Additionaly, enzyme stabilization reduces the stresses and strains experienced on the soil subgrade. Thus, enzyme addition limits the permanent deformation. Enzyme contributes to enhance the tensile strength of expansive soils and thereby tends to alleviate the effects of desiccation cracks. The stabilizing soil performances increase with curing period, but the impact of curing beyond 30 d is minimal. Clay content plays an important role in the effectiveness of enzyme activity, and a commendable improvement can be assured only when the soil contains an adequate amount of clay. Enzyme performs well at temperatures below 40 °C, but a higher temperature limits the enzyme activity. As enzymes are not devoured in their reactions with clay, a low concentration of enzyme is enough for a commendable improvement in the soil performance. It was found that depending on the clay fraction presented in soil, the enzyme's optimum dosage varies between 0.002% and 0.1%.

Other Chemical Treatments

Acidic Phosphates - mixing acidic phosphates with montmorillonite clay, insoluble iron and aluminum precipitates were formed. The precipitates act as cementing agents and were found to increase the remolded shear strength of the clay, at water contents below 60 percent.

PDC - This product of the Product Development Company is a mixture of portland cement, hydrated lime and casein. During its development and evaluation, the proportions of the ingredients were repeatedly adjusted by the company, and various types of milk casein and soybean casein were tried. The company's test .results showed PDC to be an effective stabilizer for clay soils. However, FHWA tests did not show PDC to be significantly more effective than the same cement-lime mixture without casein. A number of successful field sections using this product were constructed on secondary roads through the company's efforts, but the additional cost of the seemingly unnecessary ingredient, casein, could not be economically justified, hence no practical use of the product has re - sulted.

Terbec - Dow Chemical Company developed a rapid, inexpensive test for evaluating their products and experimental chemicals as stabilizers, and applied the test to thousands of compounds. Although they have not revealed the details of the test, the test results or the identity of the tested chemicals, they advanced Terbec (chemical name -- 4-tertbutylpyrocatechol) for further consideration. In FHWA tests, Terbec was an effective waterproofer, but it did not permanently strengthen or otherwise improve clayey soils, and full attainment of its limited effects required some drying back of originally moist soil mixtures. In cooperation with the Minnesota Department of Highways, Iowa State University , the Iowa State Highway Commission, and various county highway departments, the company installed 25 test projects in six States.

Phosphoric Acid - Monsanto Chemical Company found that phosphoric acid reacted with soils to increase their strength and water resistance. Tennessee Corporation also did considerable experimentation with phosphoric acid . Field test sections were constructed in Georgia and Missouri. Although the acid was fairly effective with soils in eastern United States, the cost was too high for successful competition with lime and cement, and the treated soil was difficult to compact . Test results in the FHWA soils laboratory were encouraging. However, a severe limitation was found with calcareous soils, the acid being consumed by the soil without roducing adequate strength . Although the acid could be treated to eliminate the corrosion of road building equipment, its probable effects on workmen discouraged further attempts at its use.

The University of Wyoming evaluated approximately 17 different addi - tives for stabilizing an expansive clay on I-80 west of Laramie . Effectiveness was evaluated by volume expansion tests using a CBR mold and swell pressure tests using a 4-in .-diam Proctor mold . Briefly, the following additives were evaluated :

1.**Alcohols and formaldehyde** . Isopropyl alcohol caused the soil to become friable and reduced the swelling as much as lime did for a short period of time . Negative results were obtained with a lime-isopropyl alcohol slurry in an attempt to migrate dissolved lime into the clay. Ethyl alcohol and formaldehyde also reduced swelling, but the tests showed that this reduction was only temporary.

2.Silicone. Silicone 770 and 772 are silicone resin concentrates used for waterproofing masonry, and a water-soluble sodium methyl siliconate used as a dispersing agent in clays and ceramics, respectively. For the percentages tested silicone 770 failed to provide any appreciable swell reductions. Silicone 772 at 3 percent produced results nearly comparable to lime, but at 0.5 percent little swell reduction was obtained .

3.Sodium and magnesium chloride . At application rates of 0.5-2 percent by dry weight, only slight improvements were observed.

4.Phosphoric acid. Phosphoric acid in amounts of 1, 2, and 3 percent by dry weight was added to the soil. When the acid was added to the moist soil instead of being added directly to the mixing water, the soil became friable. However, no reduction in swell was obtained.

5.**11 N11 sodium silicate**. This agent is a concentrated silicate solution which would hopefully cause ion substitution and thereby eliminate swelling. Several mixing possibilities were attempted, but because of the many variables involved, i.e . , polymer size and concentration, pH of water, temperature, calcium or aluminum ions added, and the amount of water used in mixing, the mixing combinations are innumerable. Only slight reduc - tions in swell were obtained for the mixing combinations tried.

6.Emulsified asphalt SS- K. Asphalt mixed with the mixing water in amounts of 1, 2, 3, and 5 percent by dry weight increased friability, but did not significantly decrease the swell.

7.Kerosene. Kerosene, when placed on the surface of compacted specimens, was observed to penetrate the soil quickly. However, after the kerosene had completely penetrated the sample, rapid volume increases approaching 10 percent were observed when water was placed onthe surface. Results of this program showed that none of these agents reduced the swell as effectively as lime.

Other chemical additives and their effectiveness on soils as stabilizers are summarized in Table 9.

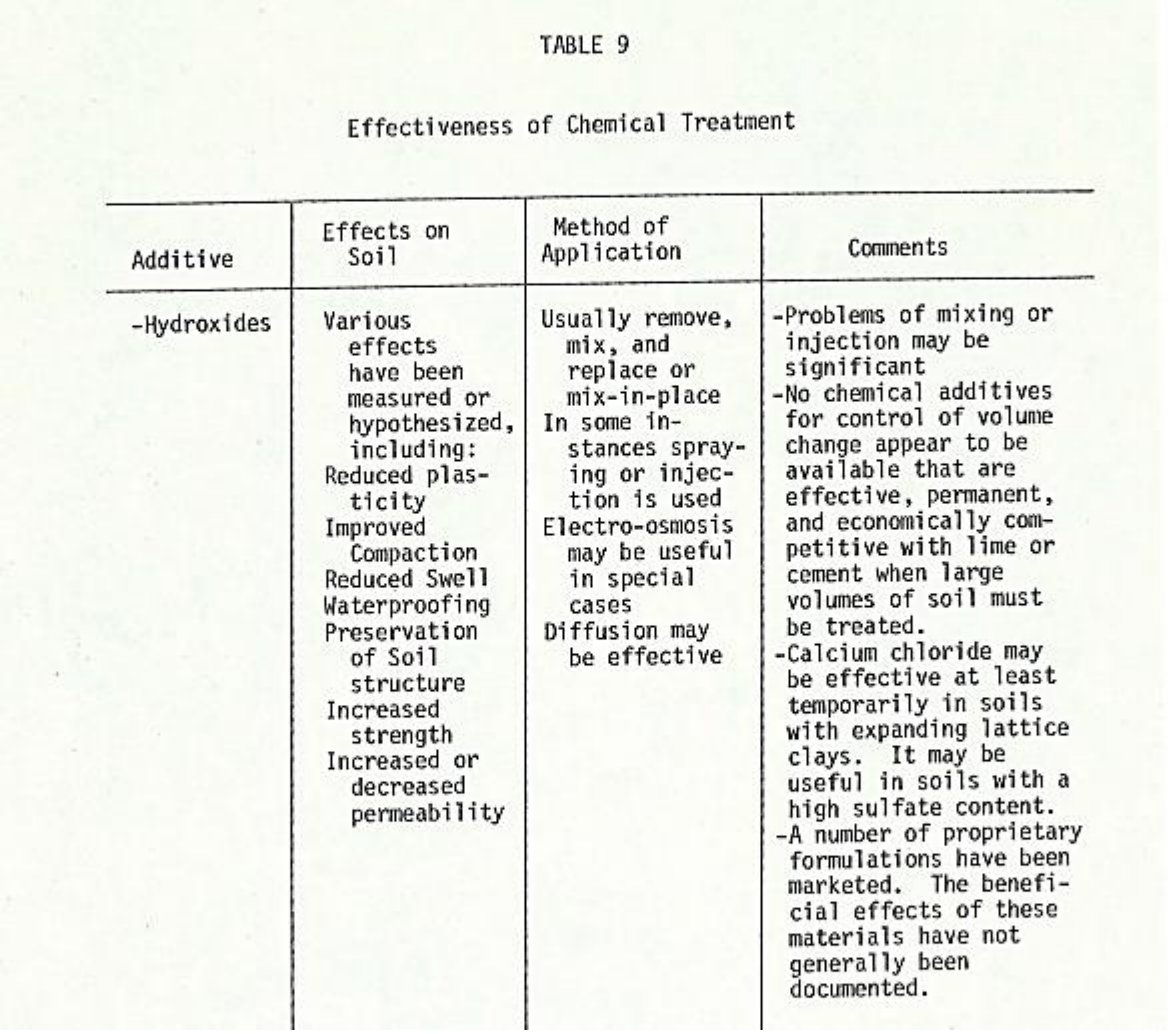


TABLE 9

Effectiveness of Chemical Treatment

Additive	Effects on Soil	Method of Application	Comments
-Hydroxides	Various effects have been measured or hypothesized, including: Reduced plasticity Improved Compaction Reduced Swell Waterproofing Preservation of Soil structure Increased strength Increased or decreased permeability	Usually remove, mix, and replace or mix-in-place In some instances spraying or injection is used Electro-osmosis may be useful in special cases Diffusion may be effective	-Problems of mixing or injection may be significant -No chemical additives for control of volume change appear to be available that are effective, permanent, and economically competitive with lime or cement when large volumes of soil must be treated. -Calcium chloride may be effective at least temporarily in soils with expanding lattice clays. It may be useful in soils with a high sulfate content. -A number of proprietary formulations have been marketed. The beneficial effects of these materials have not generally been documented.

Dispersive Soils

Dispersion occurs in soils when the repulsive forces between clay particles exceed the attractive forces, thus bringing about deflocculation, so that in the presence of relatively pure water the particles repel each other to form colloidal suspensions . In non-dispersive soil there is a definite threshold velocity below which flowing water causes no erosion. The individual particles cling to each other and are only removed by water flowing with a certain erosive energy. By contrast, there is no threshold velocity for dispersive soil; the colloidal clay particles go into suspension even in quiet water and therefore are highly susceptible to erosion and piping. Dispersive soils contain a moderate to high content of clay material but there are no significant differences in the clay fractions of dispersive and non-dispersive soils, except that soils with less than 10% clay particles may not have enough colloids to support dispersive piping. Dispersive soils contain a higher content of dissolved sodium (up to 12%) in their pore water than ordinary soils. The clay particles in soils with high salt contents exist as aggregates and coatings around silt and sand particles and the soil is flocculated .

The mechanism by which dispersive soil is eroded involves the structure of the soil and the character of the interaction between the pore and eroding fluids. It would appear that the stress required to initiate erosion is affected by the type of clay minerals present, pH value, organic matter, temperature, water content, thixotropy, and type and concentration of ions in the pore and eroding fluids.

The structure of the soil and the osmotic influences set up at the surface of clay particles produce swelling at the particle surfaces. This swelling reduces the interparticle bonding forces and is a significant factor in the erosion of cohesive soils by water. The more dispersed the soil system is, the greater is the swelling caused by the concentration gradients at the clay particle water interface. For a given eroding fluid the boundary between the flocculated and deflocculated states depends on the value of the sodium adsorption ratio, the salt concentration, the pH value and the mineralogy [10].

Collapsible Soils

As we all know that in engineering we have many types of soils and we consider and describe them based upon their properties and characteristics. One of these types of soils that is very important to be described and categorized is the collapsing soil. The collapsing soil is a strong, heavy and full of ingredient soil, which can be act as a good foundation for heavy buildings. But, this soil contains ingredients that coat the other internal ingredients making bonds between them such as the silt, salt and clay. The silt, salt and clay present in the collapsible soil in small amounts but when water reaches them a dehydration and a general chemical reaction's would happen making this strong soil suddenly to lose weight, the size will change and making soil to collapse. Here where the name of collapsible soil came from. By making foundations on this type of soil engineers should consider these important points the density of the soil which is the most important point, the ratio of the natural water under the soil and the value or measuring the proportion of the pressure.

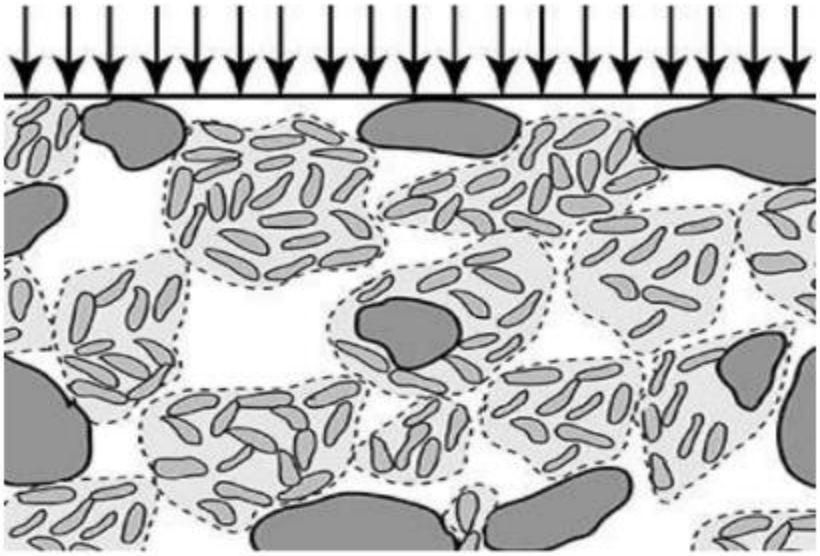


Figure : shows the structure of the collapsiable soil.

Collapsible soils are defined as any unsaturated soil that goes through a radical rearrangement of particles and great decrease in volume upon wetting, additional loading, or both. It should be noticed that the different between the sweeling or expansive soil and collapsible soil ,swelling or expansive clays increase in volume, while loessial collapsing soils decrease in volume when theirmoisture content increases under constant applied stress.

Collapsible soils are generally associated with an open structure formed by sharp grains, low initial density, low natural water content, low plasticity, relatively high stiffness and strength in the dry state, and often by particle size in the silt to fine sand range (Mitchell and Soga 2005).

Identification of collapsible soil is best accomplished by testing specimens. However, geologic and geomorphologic information can be useful in anticipating collapsible soil deposits. Dry density and liquid limit of soils can be used to evaluate the collapsibility of soils.

Figure shows a road constructed on a collapsible soil.

Collapsible soil is clayey silt with metastable structure, and known as loess. This kind of soil has different properties due to various water conditions. It shows high strength and toughness when it is at normal water condition while at the wetting condition, the soil will suffer an unexpected plastic deformation. Existing of collapsible soil can result in structural damages to the construction projects such as cracks in floor, foundations, and walls. However, human activities can be a good assist for soil collapse. Those activities are Irrigation, Water impoundment, watering the lawn, Changing the natural drainage, and Disposal of wastewater. Collapsible soil can be a real danger for homes that are built on it due to moving of the structure or cracks.

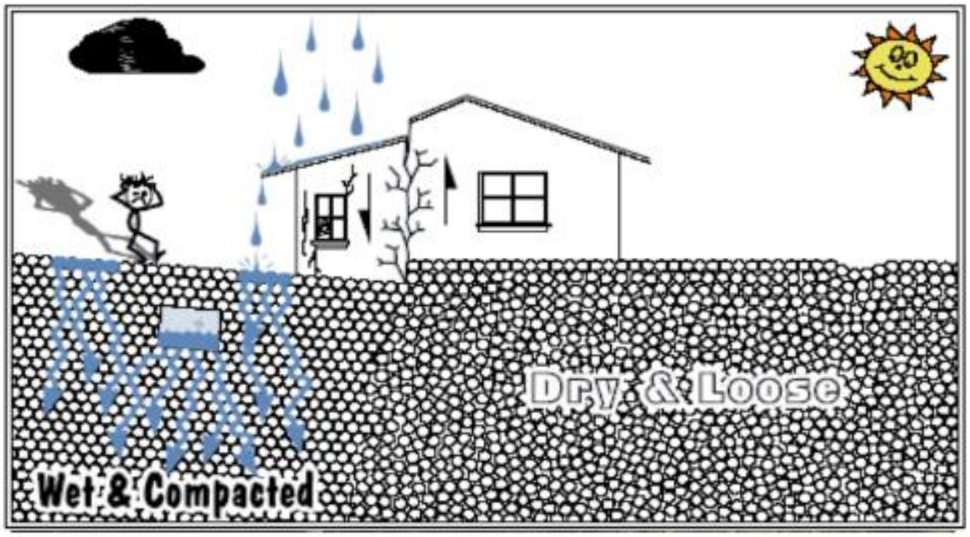
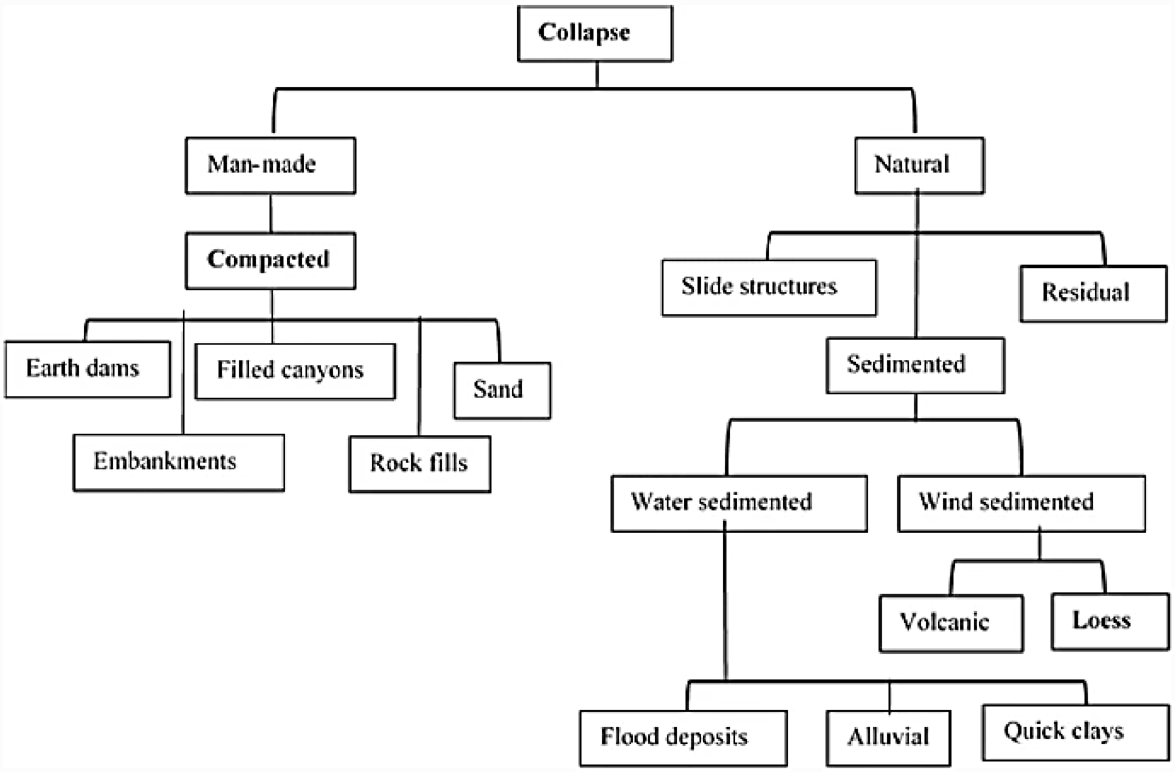


Figure : shows a house constructed on a collapsible soil without any early mitigation.

Origin and forms of collapsible soils

collapsible soils can be classified into manmade and natural types cutting across soils from nearly all origins (see Fig. 1). Manmade being typically poorly engineered (compacted) or non-engineered soils. The most common types of natural collapsible soils according to the University of Iowa are: water (alluvial), wind (aeolian), and gravity (colluvial) deposits, and residual (from extensive weathering of parent rock) soils. They range from clays, silts, loess, volcanic ash tuffs, and fine sands.

Fig. 1



Understanding soil collapse mechanisms

(1) Collapsible soils have particle sizes ranging from sand, silt, to clay, and angular grains (particularly silts). The size and shape of particles during sedimentation (in the case of natural collapsible soil) or state of compaction (man-made collapsible soil) are responsible for the open structure formed,.

(2) They have high void ratio and low density. This was described as open potentially unstable structure, which allows the soil readily undergo particle re-arrangement and volume reduction by self-weight and/loading upon wetting.

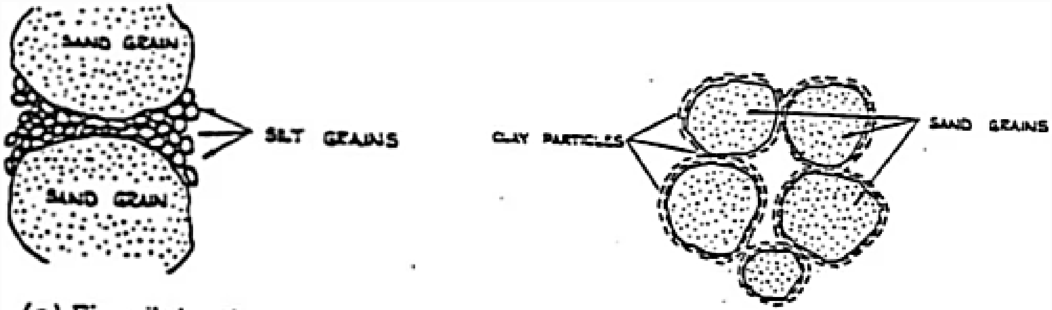
(3) They are highly sensitive. Sensitivity depends on soil mineralogy and type of particle-to-particle bonding agent. For example, quick clays may be more sensitive than sand or silt deposits having calcite as bonding agent.

(4) Collapsible soils are young geological or recently weathered deposits.

(5) Collapsible soils possess relatively low inter-particle bond strength. Collapsing rate was also considered by Barden et al. in terms of bonding strength to be immediate, slower and very slow, depending on whether bonding was by capillary suction (Fig. 2a), clay buttress (Fig. 2b, c), or chemical cementing (iron oxide, calcium carbonate or some other salts), respectively.

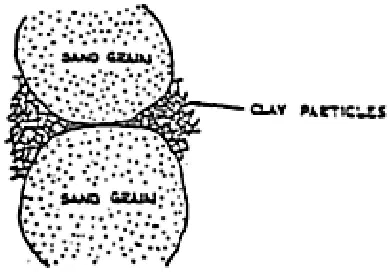
(6) They are mostly partially saturated, except for saturated quick clay in which collapse is not triggered by wetting but rather triggered by drying resulting in significant shrinkage . Collapse also occurs when internal forces surpass bond shear strength .

Fig. 2



(a) Fine silt bond.

(b) Clay onion-skin bond.



(c) Flocculated clay buttress.

Capillary suction bonding and clay bonding in collapsible soils suggested by Barden et al. [7]

How to Deal with Collapsible Soil Before Building Construction

Collapse has been defined as a mechanism of sudden reduction in total volume of a metastable soil structure (i.e. an open structure) under certain loading and/or wetting conditions. These soils are usually capable of sustaining substantial high-applied vertical stress in their in situ conditions without significant volume change but when wetted, undergo rapid and large reduction in volume. Collapse is believed to occur when the particle-to-particle bonding is destroyed by wetting with or without additional loading, thus an initial open structure becomes dense. Therefore, for a geotechnical engineer to be able to prevent such loses, by way of providing economic and efficient engineering solutions, four steps are recommended to follow: (i) identification—determine the existence of a collapsible soil; (ii) classification—if a collapsible soil exists, what is the significance? (iii) quantification—what is the degree of collapse that will occur? (iv) evaluation—what are the design options? recognised that the greatest problems with collapsible soils result from not recognizing the existence and extent of their collapse potential (CP) prior to construction.

Collapse is usually triggered either naturally through flooding/groundwater rise and/or loading (e.g. earthquakes), or artificially by human activity. Human activity can be either unintentional via poor drainage control (e.g. broken water or sewer lines, landscape irrigation, poor surface drainage, roof runoff, etc.), or deliberate through ground improvement, e.g. dynamic compaction. Unlike consolidation where the reduction in volume (or void ratio) is the consequence of time-dependent discharge of excess pore water, the reduction in volume for a collapsing soil is rapid and the result of water ingress into the soil and/or bond breaking caused by increased stresses.

Collapsible soils are known to exhibit certain physical and structural features such as an open and potentially metastable structure, an unsaturated state, high void ratio and porosity, low dry density, enough particle-to-particle bonding agent to hold particles together in their unsaturated state. Their mineralogy spans a wide range but particles usually varying between sand and clay sizes. Capillary water, clay minerals, calcium carbonate and other soluble salts have been argued to play a role in the formation of bonding between elements, providing the initial stability in these metastable soils. However, wetting, eliminates this bonding and sudden restructuring occurs (cited in.

How to Treat Collapsile Soil?

There exits various method for mitigation of collapsed soil. However, the applicability of any method depends on several factors including, the kind of projects to be constructed, and the expected settlement to occur because of the project, the elevation of collapsed soil, the possibility of the foundation and risk zone to become wet, and the stress distribution of the project on its foundation. Engineers try to use multiple methods for solution in order to come up with the proper one for the type of collapsed soil. For instance, compaction method by roller would not give a good result for deep deposit lands and sometimes for shallow deposit as well

The methods that are still used for treating the field with such properties are as follows:

- Minimizing foundation pressures
- Elimination of the collapsed soil
- Hydrocompaction

- Densification of the soil
- Solidification of the soil without decreasing its sheer strength
- Using caissons, blasting with prewetting, piles, and more.

Minimizing foundation pressure is a method used to solve problems associated with collapsible soil. This method is more reliable with structures, such as canal structures. There are different techniques in engineering world used to minimize foundation pressure. One of those techniques that is commonly used is floating foundation, in which minimizes the soil loads by eliminating those materials that their weights are equal or close to the structure's weight. Along with this, elimination of collapsible soil is an economical method and used when there is less depth of collapsed soil especially for concentrated sites.

Hydrocompaction is an effective method prior to any types of construction. There are two ways of this method. One way is to make small lakes along the field with infiltration wells in order to wet the land or soil in a great depth. Another way is by prewetting the surface to a certain depth with infiltration wells. Both ways leads to accelerate the collapse of soil to happen, and increase the water content of the soil. Therefore, it helps easier construction excavation and better soil compaction. However, the soil can also be solidified by adding additives such as Portland cement and then compacting the soil, so it minimizes the collapse of soil. Densification of soil is the process to densify low unit weight of soil. There are also two ways of executing this method, such as dynamic compaction and vibrocompaction. In dynamic compaction, a large heavy weight is dropped within a certain height to densify the soil and obtain a desired weigh with respect to a desired depth. A maximum depth reached by dynamic compaction is about (10 m). In vibrocompaction, a large suspended vibroflot probe is used, in which it produces a vibration system by a hydraulic motor. It compresses the soil to higher unit weight state. Thus, a denser soil is obtained which has less voids and porosity and is stronger.

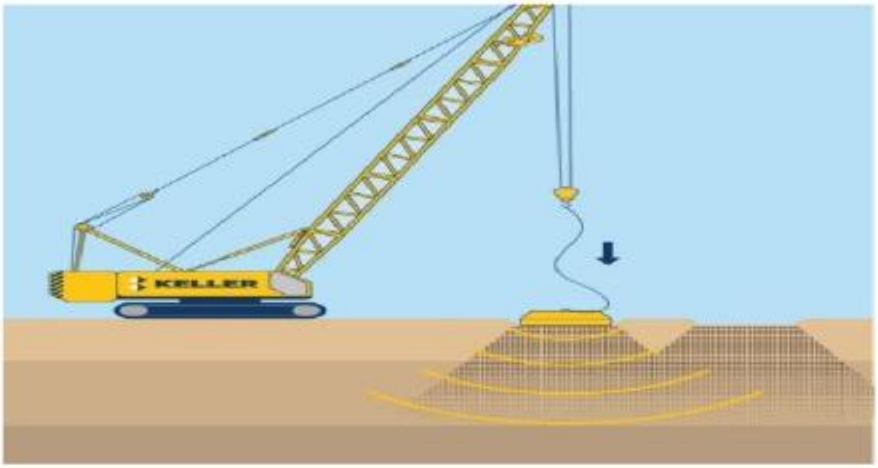


Figure : Dynamic compaction used for compacting soil

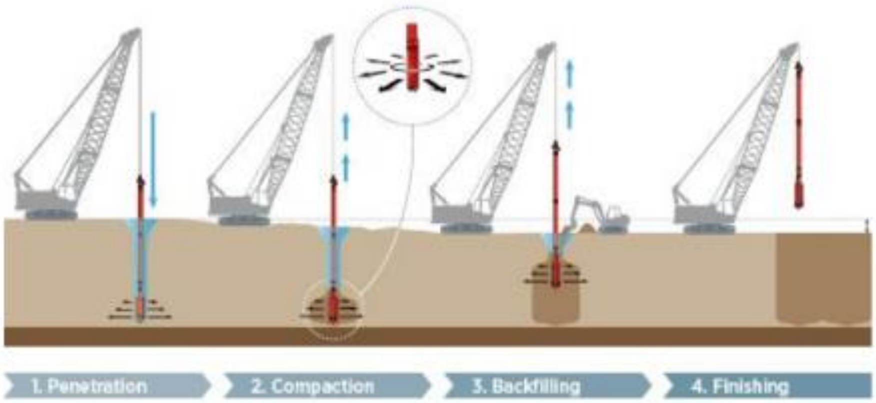
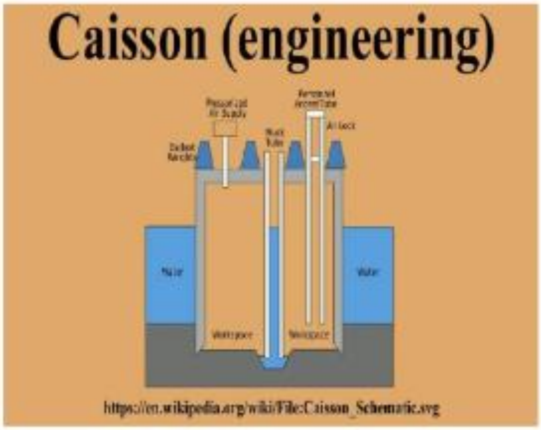


Figure : Vibrocompaction used for densifying soil by a vibrating system

Figure : Vibroflot probe makes the vibration system to compact the soil

Piles and caissons play an important role in such a significant subject as well. They are applicable when the collapsible soil is not in a great depth by penetrating the piles with prewetting foundation. As the piles are penetrated, the loose materials and soils are compacted and left with a more dense foundation. These piles and caissons help to distribute and direct all stresses on the capable and strong soil not the collapsed one.



https://en.wikipedia.org/wiki/File:Caisson_Schematic.svg

Figure : Caissons used to drainage the work place.

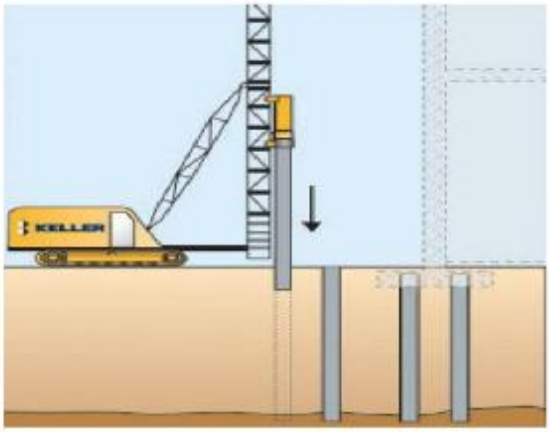


Figure : Piles driven to reach capable soil to build a project on

The identification and applicable mentioned solutions of collapsed soil leads to result a safer and stronger construction projects. It has been experienced that mitigation the problems relate to collapse of soil is better before start building the project because of two reasons. First reason is that before building the project there are various method applicable to solve the problem, and the methods are more effective in a way that it either prevent collapsing or minimizing to a great extent. Second, it is more economic because in some projects collapsed soil sometimes has no way to solve rather than destroying the whole project.

Other Mechanisms To Treating The Collapsile Soil

1. Soil Replacement: On the off chance that the collapsible soil layer is slender, at that point the evacuation of the soil layer is the best arrangement. From that point forward, reduced the building site during reviewing. The expelled material is either positioned in a few compacted layers or supplanted with solid filler materials.

Sand or crushed stone is a reasonable material for collapsible soil substitution. Not exclusively does the new material increment the bearing limit of the building site, however it likewise diminishes settlement prospects significantly. The technique is appropriate for street asphalt development.

2. Synthetic Stabilization: Synthetic adjustment includes the change of soil properties to diminish settlement potential. Concrete, lime, or whatever other concoction added substances that can respond with soil can be utilized for collapsible soil treatment. The expansion of fly debris to concrete or lime would additionally improve soil soundness.

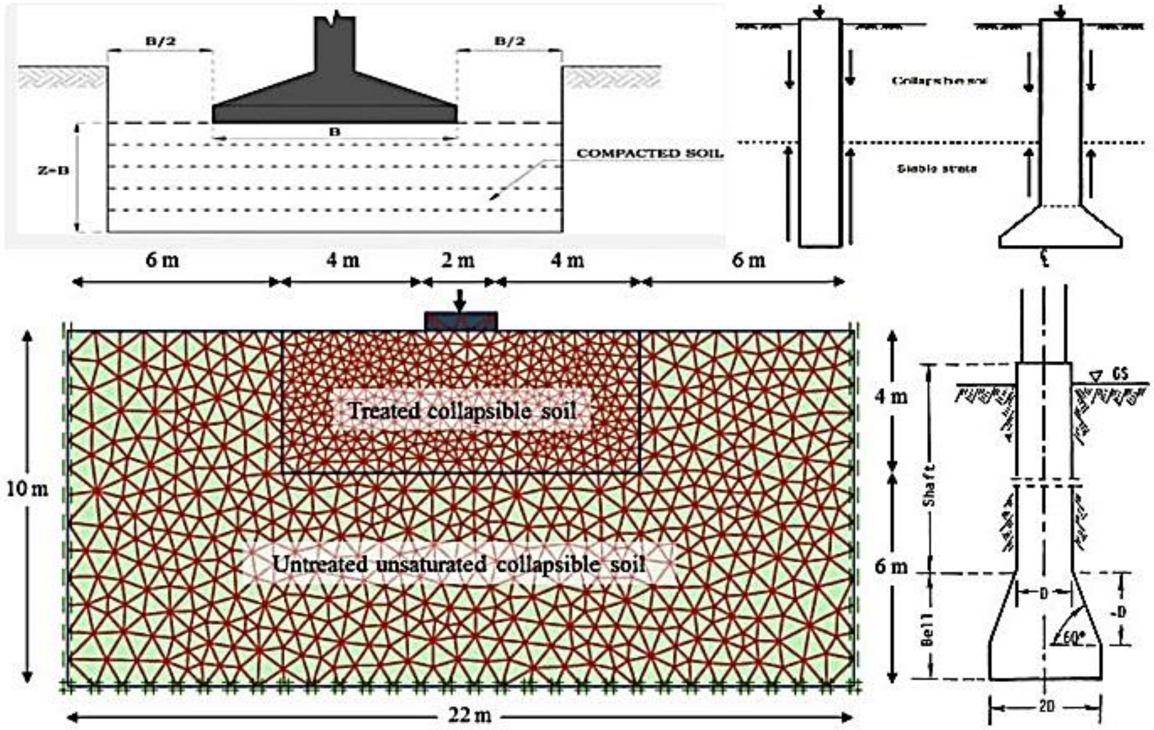
Flooding channels with arrangements of sodium silicate and calcium chloride to settle the soil is conceivable. The material arrangement should arrive at the ideal profundity; else, it would not be successful.

3. Pre-wetting: Flooding or driving water through a collapsible soil layer is another answer for tackle its settlement. The soil layer would densify and arrive at balance conditions as water travels through the soil. Flood or power water through wells into the structure impression to wet the soil layer.

Subsurface examination is important to check the viability of the arrangement strategy. Prewetting ought to be utilized in blend with preloading or dynamic compaction to accomplish the ideal outcome.

In any case, flooding or compelling water into collapsible soil ought to be stayed away from if there are structures around development. The structures contiguous the building site may get harmed.

4. Select Suitable Foundation: Now and then, suitable establishments can manage the issues of collapsible soils. A profound establishment can sidestep collapsible soil and move superstructure burden to a hard soil layer. Also, a tangle or pontoon establishment can withstand huge anticipated settlement of the collapsible soil.



Soft Soil

Soft Soil means soil that is susceptible to excessive penetration of water due to its density or composition or is highly compressible; Sample 1. Soft Soil means soil which is unstable under its geotechnicalconditions, such as raveling sand, gravel and/or cohesivesoil with low un drained shear strength

Soft soils are undesirable soils due to their low shear strength and high compressibility. Should such soils be used for pavement subgrade, remediation is essential to avoid potential pavement failure because strength and volume stability are important properties in subgrade construction.

Soft soil can be improved by soil improvement techniques like Sand Compaction Pile (SCP), Dynamic Compaction (DC) and Prefabricated Vertical Drain (PVD) are most commonly used recently.

How do you strengthen soft soil?

The following techniques can be used for improving bearing capacity of soil as per the site condition.

1.Increasing depth of foundation.

2.Draining the soil.

3.Compacting the soil.

4.Confining the soil.

5.Replacing the poor soil.

6.Using grouting material.

7.Stabilizing the soil with chemicals.

Threr are top four techniques for improvement of soft soil. The techniques are:

1. Stone Columns

2. Chemical Grouting

3. Geotextiles

4. Unequal Settlement.

1. Stone Columns:

Stone columns are compacted columns of gravel or crushed stone installed in soft soil below the foundation. The stone columns provide vertical support for load transferred from the structure above. They also provide drainage of the soil. These columns also provide resistance to horizontal or inclined shear like normal piles.

Cylindrical holes are made by vibrating probe penetrating in jet method with the help of casing pipes, which go down by its own weight. The diameter of the holes is 0.60 to 1.00 m. The hole is filled with gravel or crushed rock.

The fill is compacted simultaneously as they are filled in layers varying from 0.4 to 0.8 m in depth and the casing pipe is withdrawn. The depth of column depends upon the soil condition and may go up to 20.0 m. The columns are installed in a configuration of square or rectangular grids and spaced at 1.50 to 3.50m intervals.

The primary concern of the column below the foundation is its supporting capacity and settlement. The load bearing capacity of a stone column depends upon the passive resistance of the soft soil that can be mobilized to withstand radial bulging and by the friction angle of the compacted material in the column.

The required minimum depth of the column in soft soil can be estimated based on the shearing strength along the sides and the end bearing capacity. Several methods of determination of the supporting capacity and load-settlement behaviour of stone column based on empirical estimates and analytical method indicate that allowable vertical stress, δv, on a single column can be expressed by:

$$\delta_v = \frac{25\tau}{FS}$$

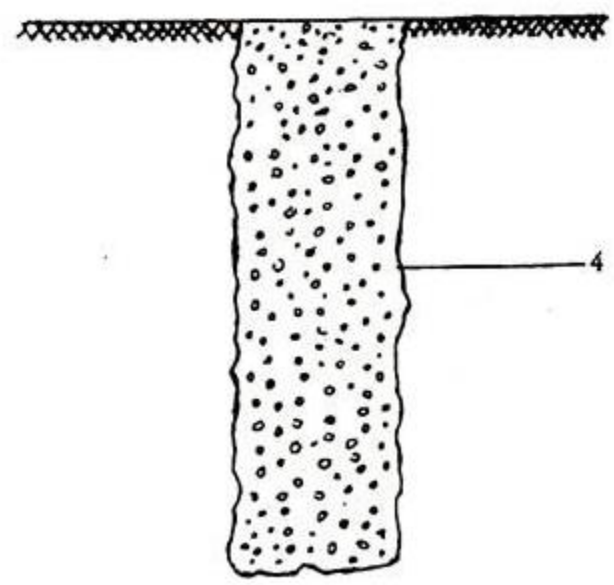


Fig. 2.4 Stone Column
1. Compacted stone column

where τ is the undrained shear strength of the soft ground and FS is the factor of safety, which is normally recommended as 3.

2. Chemical Grouting:

Grouting is a process by which fluid-like materials either in suspension or in solution form are injected into subsurface soil or rock for one or more purposes:

i. Decrease permeability,

ii. Increase shear stress strength, and

iii. Decrease compressibility.

Cost of improving soil by grouting is comparatively high than other methods, due to which its application is limited in special cases only.

Different types of grouting:

i. Permeation grouting:

The grout fills the soil pores. The volume or structure of the ground is not essentially changed.

ii. Displacement grouting:

The grout which is a stiff mixture fills voids and remains more or less intact and exerts pressure on the soil and densities the medium,

iii. Encapsulation or uncontrolled displacement grouting:

The grout is injected under high pressure. The ground is fractured hydraulically and fissures occur. Grout penetrates rapidly into the fractured zone and coats, but does not permeate the individual chunk of soil.

Types of grout:

i. Permeation grouts are of two types:

Particulate or suspension grouts are made up of cement, soil or clay or mixture of these.

ii. Chemical grouts are composed of various materials in solution.

iii. Displacement grouts or compaction grouts are stiff, low slump mixtures of cement, soil and/or clay and water.

Lime slurries are most commonly used encapsulation-type grouts.

Advantages of chemical grouting:

Chemical grouts have certain advantages over particulate grouts:

i. the grout can penetrate smaller pores,

ii. ii. grouting can be better controlled for set time.

But the technology of chemical grouts is complex and the cost is high.

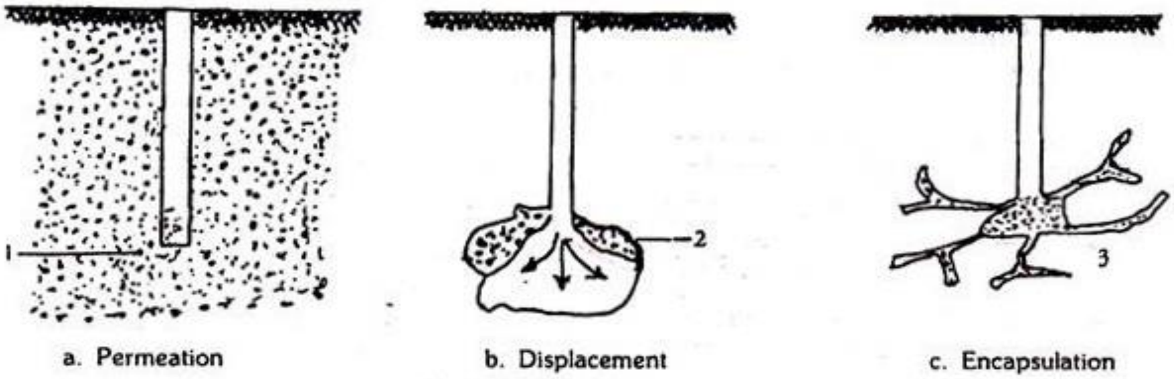
The most common chemical grout classes are: Silicates, lignins, resins, acrylamindes and urethenes.

Grouts containing 25 to 30 per cent silicates are typical water-proofing applications.

Sodium silicate (Na2SiO4, also called ‘water glass’) is commercially available as a relatively inexpensive aqueous solution.

Impact of chemical grouting on environment:

Prior to deciding upon chemical grouting, intensive studies should be made to ascertain the probable impact of the chemicals proposed to be used in grouting, specially on ground water. Methods should be devised to detect and estimate the pollution potential of the chemicals to be injected.



a. Permeation b. Displacement c. Encapsulation

Fig. 2.5 Types of Grouting

1. Grout fills voids 2. Grout bulb displaces soil 3. Grout Fractures soil mass and coats chunks

Technique # 3. Geotextiles:

Geotextile is also called geosynthesis, geogrid, etc

Geotextile is the genetic name of a large spectrum of synthetic membranous products made out of materials like polyester, polypropelene, polythylene, etc. They are available in woven and non-woven form and then again in various types of bonding like thermal bonding and chemical bonding and even un-bonded.

Usages of geotextile in Civil Engineering works:

i. Separation,
ii. Reinforcement,
iii. Drainage,
iv. Erosion control, and
iv. Formation of impermeable membrane.

The most important functions in relation to ground improvement are reinforcement and drainage.

Reinforcement function:

Geotextile with innate tensile capabilities can well complement materials in tension. Geotextile mobilises its tensile strength by deformation of sub-base. It not only increases bearing strength of the soil, but use of geotextiles for soil stabilisation depends heavily on the textile capacity of the fabric. The excellent filter properties of geotextiles, resulting from manufacturing method, make them very highly suitable materials for sub-surface drainage function.

Mechanism of geotextile action:

The fabric in the ground, when deformed due to applied loads, becomes stressed in tension. This, in turn, reacts with the medium in contact, increasing its effective confinement and, therefore, its stiffness. The usefulness of fabrics increases markedly as sub-grade strength decreases.

Use of the geotextiles not only improves mechanical properties of the soil, but also its hydraulic functions.

Most of the design procedures are based on empirical approaches. Design depends upon variations of parameters.

In soft soil, where construction of foundation is not considered favourable, geotextile having the above qualities can improve the strength of the soil below foundation.

Geotextile has grown leaps and bounds since the 1990s. It has revolutionised ground reinforcement and stabilization of soil.

It can be used to increase the load bearing capacity of weak soils and earth-filled foundation mattresses.

Natural Geosynthetics:

The strength of jute and coir textiles is no less than that of geosynthetics at the installed stage. The strength (durability) can be increased by various treatments. The natural geotextiles are degradable pretty soon. These materials can be used for short-term strength requirement. After use, by the time, the natural geotextiles get degraded, the soil would get stabilised. In Japan, natural geotextile is being used by the name of Geojute.

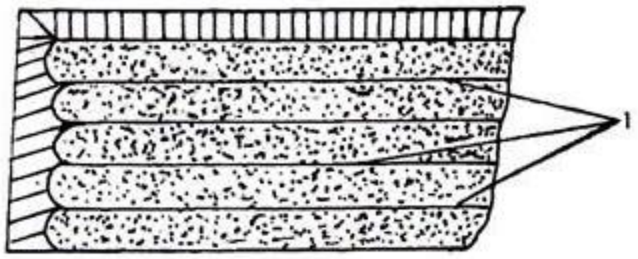


Fig. 2.6 Geotextile as reinforcement
1. Geotextile reinforcement

Technique # 4. Unequal Settlement:

When settlement of portions of foundation of the building occurs differentially, it is called unequal settlement or differential settlement. This is generally followed by structural cracks in the buildings, if the differential settlement exceeds permissible limit varying from 0.003 cm/m — 0.007 cm/m.

Differential settlement generally occurs due to:

a. Non-uniform nature of soil,

b. Unequal load distribution on soil strata, and

c. Eccentric loading of the structure.

Organic Soil

Organic soil is composed primarily of plant materials, and often amended with compost to ensure its nutrient levels are optimized to cultivate plant life. Organic soil is composed primarily of plant material, making it far more adept at cultivating plant life than its non-organic alternatives. The soil which contains 30% or more organic matter its consider organic soil.

The general characteristics of Organic Compounds are: Organic compounds include complex structures and high molecular weights. These are soluble in organic solvents and mostly insoluble in water. Mostly depend on only three elements: Carbon, Hydrogen and nitrogen. These compounds are combustible in nature. The topsoil has the highest concentration of organic matter, nutrients and is where most of the soil's biological activity occurs. Soil that is not protected by residue or living cover is subject to erosion.

Organic soil is a mixture of fragmented organic material formed in wetlands under appropriate climatic and topographic conditions, derived from vegetation that has been chemically changed and fossilized. This type of soil has low shear strength and high compressive deformation. Though there are a variety of improvement methods which can be adopeted, problems with bearing capacity and settlement are generally solved by using pile foundations. Friction piles tend to be the pile foundations of choice in this type of soil: they transfer the load to the soil through interface friction between soil and pile material. One of the important parameters for frictional resistance is the friction coefficient between the pile material and the soil. The majority of the design interface friction values are based on empirical correlations. They are related to soil shear strength parameters. In current geotechnical engineering practices, the soil–structure friction values recommended by the Naval Facilities Engineering Command (NAVFAC) Design Manual (DM) 7.02 (US Department of Navy, 1986) are widely adopted.

The four characteristics of organic compounds?

1 . They all contain carbon.

Organic compounds are compounds that contain carbon bonded with other elements, such as hydrogen, nitrogen, sulfur, and more.

2 . Most of them are flammable.

One group of organic compounds, the hydrocarbons, are one of the reactants for hydrocarbon combustion, and therefore are flammable.

3 . They are all soluble in non-polar solvents.

Since organic compounds are generally non-polar, they are not going to be soluble in water, which is polar. The non-polar molecules of organic compounds are attracted to other non-polar molecules, so they will be soluble in non-polar solvents.

4 . They are most, if not all, are covalently bonded molecules.

Carbon has 4 valence electrons to share with, so it is very easy for other elements to form covalent bonds with it. With the addition of hydrogen which has 1 valence electron, millions and millions of different compounds can form.

On the basis of organic matter content, soils are characterized as mineral or organic. Mineral soils form most of the world's cultivated land and may contain from a trace to 30 percent organic matter. Organic soils are naturally rich in organic matter principally for climatic reasons. Although they contain more than 30 percent organic matter, it is precisely for this reason that they are not vital cropping soils.

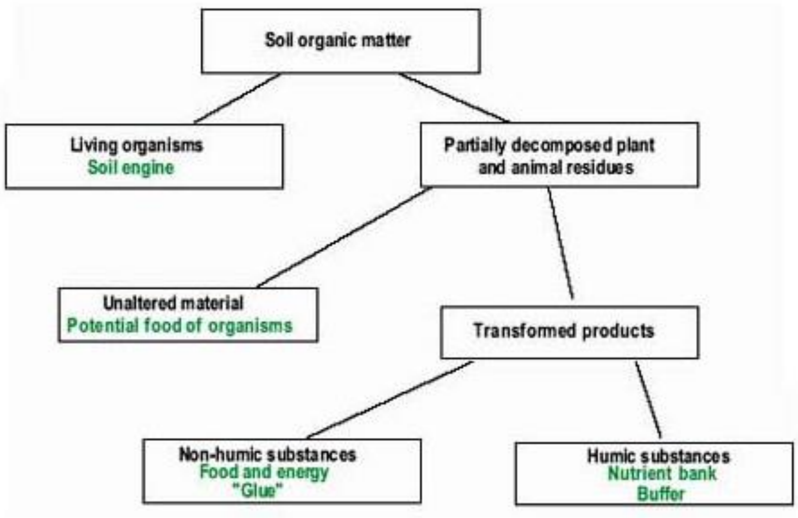
This soils bulletin concentrates on the organic matter dynamics of cropping soils. In brief, it discusses circumstances that deplete organic matter and the negative outcomes of this. The bulletin then moves on to more proactive solutions. It reviews a “basket” of practices in order to show how they can increase organic matter content and discusses the land and cropping benefits that then accrue.

Soil organic matter is any material produced originally by living organisms (plant or animal) that is returned to the soil and goes through the decomposition process (Plate 1). At any given time, it consists of a range of materials from the intact original tissues of plants and animals to the substantially decomposed mixture of materials known as humus (Figure 1).

Plate 1

Crop residues added to the soil are decomposed by soil macrofauna and micro-organisms, increasing the organic matter content of the soil.

FIGURE 1
Components of soil organic matter and their functions



Most soil organic matter originates from plant tissue. Plant residues contain 60-90 percent moisture. The remaining dry matter consists of carbon (C), oxygen, hydrogen (H) and small amounts of sulphur (S), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg). Although present in small amounts, these nutrients are very important from the viewpoint of soil fertility management.

Soil organic matter (SOM)

Soil organic matter (SOM) is the organic matter component of soil, consisting of plant and animal detritus at various stages of decomposition, cells and tissues of soil microbes, and substances that soil microbes synthesize. SOM provides numerous benefits to the physical and chemical properties of soil and its capacity to provide regulatory ecosystem services. SOM is especially critical for soil functions and quality.

The benefits of SOM result from a number of complex, interactive, edaphic factors; a non-exhaustive list of these benefits to soil function includes improvement of soil structure, aggregation, water retention, soil biodiversity, absorption and retention of pollutants, buffering capacity, and the cycling and storage of plant nutrients. SOM increases soil fertility by providing cation exchange sites and being a reserve of plant nutrients, especially nitrogen (N), phosphorus (P), and sulfur (S), along with micronutrients, which the mineralization of SOM slowly releases. As such, the amount of SOM and soil fertility are significantly correlated.

SOM also acts as a major sink and source of soil carbon (C). Although the C content of SOM varies considerably,[3][4] SOM is ordinarily estimated to contain 58% C, and "soil organic carbon" (SOC) is often used as a synonym for SOM, with measured SOC content often serving as a proxy for SOM. Soil represents one of the largest C sinks on Earth and is significant in the global carbon cycle and therefore for climate change mitigation.[5] Therefore, SOM/SOC dynamics and the capacity of soils to provide the ecosystem service of carbon sequestration through SOM management have received considerable attention recently.

The concentration of SOM in soils generally ranges from 1% to 6% of the total mass of topsoil for most upland soils. Soils whose upper horizons consist of less than 1% of organic matter are mostly limited to deserts, while the SOM content of soils in low lying, wet areas can be as great as 90%. Soils containing 12% to 18% SOC are generally classified as organic soils.

The primary source of SOM is vegetal detritus. In forests and prairies, for example, different organisms decompose the fresh detritus into simpler compounds. This involves several stages, the first being mostly mechanical, and becoming more chemical as decomposition progresses. The microbial decomposers are included in the SOM, and form a food web of organisms that prey upon each other and subsequently become prey.

There are also other herbivores that consume fresh vegetal matter, the residue of which then passes to the soil. The products of the metabolisms of these organisms are the secondary sources of SOM, which also includes their corpses. Some animals, like earthworms, ants, and centipedes contribute to both vertical and horizontal translocation of organic matter.

Composition

The water content of most vegetal detritus is in the range of 60% to 90%. The dry matter consists of complex organic matter that is composed primarily of carbon, oxygen, and hydrogen. Although these three elements make up about 92% of the dry weight of the organic matter in soil, other elements are very important for the nutrition of plants, including nitrogen, phosphorus, potassium, sulfur, calcium, magnesium, and many micronutrients.

Organic compounds in vegetal detritus include:

Carbohydrates that are composed of carbon, hydrogen, and oxygen, and range in complexity from rather simple sugars to the large molecules of cellulose.Fats that are composed of glycerids of fatty acids, like butyric, stearic, and oleic. They also include carbon, oxygen, and hydrogen.

Lignins that are complex compounds, form the older parts of wood, and also are composed primarily of carbon, oxygen, and hydrogen. They are resistant to decomposition.Proteins that include nitrogen in addition to carbon, hydrogen, and oxygen; and small amounts of sulfur, iron, and phosphorus.Charcoal, which is elemental carbon that is derived from incomplete combustion of organic matter. It is resistant to decomposition.

Construction over Organic Soil

Construction over organic soils has historically been a problem due to the typic~lly low strength and high compressibility that is common to these materials. Designs usually call for supporting the total structure, including floor slabs. on deep foundations extending through the compressible deposits. However, this often leads to difficulties with entering utilities and any attached structures. Alternatively. if the structure is floated over the organic soils in an effort to try to have everyt~ing settle together. there is the difficulty of predicting the magnitude and rate of the anticipated settlement

Soil for Your Building Foundation

Different types of soil will affect your building's foundation in different ways. Determining the type of soil a building will be built on affects the project's construction and future repairs.

Here are several of the most common types of soil foundation used in construction. We explore which type is generally the best type of soil to build on.

Common Types of Soil Used in Construction

Clay

Clay is not an ideal soil for buildings due to its tendency to shift around as it dries or moistens. This can cause cracks or fissures in the building and result in uneven floors. Clay soil foundation depths are generally deeper to increase stability.

When it comes to clay soil, the best house foundation would be between a drilled pier foundation or a slab-on-grade foundation. Drilled pier foundations will anchor deeper into the clay for more structural stability while slab-on-grade foundations combat clay soil's tendency to shrink and expand.

Sand and Gravel

Sand and gravel have large particles which allow this soil to drain water quickly (which is good for buildings). Retaining less water means less risk for the building to shift around and form structural and non-structural cracks. Compacted sand and gravel offer even more stability and are a great option to build a foundation on.

Over time, sand can be washed away. In these cases, a helical pier (also referred to as helical anchors, screw piles, or screw anchors) is a suitable foundation technique for sandy soil.

Rock/Bedrock

There are many types of rock (sandstone, limestone, etc.) and they are all excellent options due to their high bearing capacity (making this type of foundation ideal for larger buildings). Bedrock is a layer of rock underneath a surface layer of soil.

Unlike with clay, which can expand and shift, bedrock is more stable and resistant towards water damage. Your building is, therefore, less likely to crack as it shifts or settles. The most important thing about building foundation on rock is to ensure the surface is level before construction.

Loam

Loam is the best soil type for construction due to its ideal combination of silt, sand, and clay. It combines the best of all their qualities into the ideal balance for supporting a foundation. Loam generally does not shift, expand, or shrink drastically and handles the presence of water very well.

The one potential drawback of building on loam is the possibility of undecomposed material, which can and should be filtered prior to construction.

Peat

Peat is often found in areas such as bogs and other wetlands and consists of decaying vegetation and/or organic matter. It can hold a large amount of water and is considered a very poor soil type for a foundation due to how much it can shift around and its low bearing capacity. You can build on peat soil, but the building would be at great risk of cracks or other types of damage.

Silt

Like peat, silt is another poor soil option for building a foundation due to its prolonged ability to retain water. This quality causes silt to shift and expand, which does not provide the building any support and puts it under repeated, long-term stress. This can cause structural damage or failure. If possible, construction should be pursued with a more suitable type of soil.]

Effects of Not Considering Soil Type Before Construction

Failing to select the best type of soil for your project can result in immediate or future foundation issues. Make sure you understand the different characteristics of each soil type and prevent possible damage.

There are several factors beyond water retention that builders should be aware of, so it's crucial that you get an expert opinion.

Soil and Foundation Challenges

Engineers, and, more specifically, geotechnical engineers, classify soils according to their tactile and engineering properties and as they relate to their use for site development and foundation support. Current engineering classification systems are designed to allow for an easy transition of field observations and predictions of the soil's engineering properties and behaviours.

The 6 Main Soil Type Foundation Challenges

Clay Soil Foundation Challenge

When soft to firm, clay can exhibit large settlements under load. These settlements are likely to occur slowly due to clay's poor drainage characteristics. Pore pressures within the clay particle spaces move slowly, leading to long-term consolidation settlement. Regionally, different clays exhibit different and unique properties.

Swelling clay exists in many areas (particularly throughout the prairie provinces). This clay can shrink or swell upon changes in moisture content. This can lead to subsidence or settlement. Soil heave is also an issue when it comes to clay, and swelling clay in particular, having the potential to push the foundation and the structure above upwards.

Another unique clay exists in the Ottawa and St. Lawrence Valleys. Leda clay, also known as Champlain Sea Clay or Quick Clay, is highly sensitive clay that exhibits rapid loss of shear strength under excitation and can also change properties under sufficient stress. Leda clay has a much lower remolded strength, which is a measure of the residual shear strength measured in a direct vane test following initial shearing. Clay sensitivity is defined as the ratio of the initial shear strength to the remoulded residual shear strength. Typical clays can have a sensitivity in the low range (s = 1 to 3). Leda clays have sensitivities of up to as much as 20.

Aside from the Ottawa area, soft-to-firm clays that do not generally exhibit swelling or sensitivity exist in certain areas of Ontario. The main challenge with any soft-to-firm clay is the total settlements they can exhibit under load and time rate of settlement. When loading clays with large area loads such as embankment fills or area grade raise fill, thicker deposits of soft clay can create settlement and scheduling problems.

GeoSolv’s suite of Ground Improvement, Rigid Inclusion, and Specialty Piling Systems were specifically designed for the clay soils of Ontario and across the nation. Superior stiffness, massive lateral stress build-up, and drainage characteristics of the Geopier Rammed Aggregate Pier systems make them a cost-effective, high-capacity solution for clays. No ground improvement contractor has more experience with clay soil in Ontario than GeoSolv.

Sandy Soil Foundation Challenge

Sandy soil has naturally shifting characteristics; drainage through sandy soil further increases its shifting properties. This poses a clear challenge for any structures being built on this type of soil.Loose sand can be subject to large settlements, and these settlements tend to occur quickly due to the free-draining granular nature of sands. This can pose foundation challenges and loose sand requires densification in order to provide sufficient settlement control and bearing for new structures.

Clean sands (sands with fewer fine particles mixed in) underwater can be prone to liquefaction when subjected to excitation such as vibrations or seismic forces. Seismic forces causing liquefaction increase pore pressure to a point where the sand becomes suspended and the natural angularity of the sand no longer affords high shear strength. The temporarily suspended sand-in-water mixture behaves as a liquid and any objects sink to a point where the weight of the object is equal to the weight of the sand-water liquid. Once the excitation stops and pore pressure dissipates, the sand becomes frictional again and the settlement stops. By then, the damage has been done.

GeoSolv’s suite of Ground Improvement, Rigid Inclusion, and Specialty Piling systems were designed specifically for sandy soils for both settlement control and liquefaction mitigation. Superior stiffness, vertical ramming and crowd pressure set our systems apart from stone columns and also other rigid inclusion approaches.

Silty Soil Foundation Challenge

Silt can be a challenging soil to characterize as it can behave more like sand when the majority of the silt particles are in the larger range of the silt particle-size band. More often, silt behaves more clay-like and often silts and clays are mixed. A large percentage of clays encountered in Ontario are in fact, silty clays (where silt comprises a large fraction of the total weight of the soil but clay is the predominant particle). Soils with large volume fractions of silt and clay are often the most troublesome to the geotechnical engineer.

Since they are very similar in appearance to the eye, silts are often mistaken for clay, often with unfortunate results. Certain field tests can help to broadly differentiate the clays from silts, however often, a hydrometer test must be conducted to properly define the particle size fraction of a silt-clay. There are several important differences in the behaviour of silts compared to clays.

Pure silt or soils with a very large fraction of silt-sized particles do exist in regions of Ontario. These silts tend to exhibit dilantency (change of volume with change of shape) where more clayey materials tend to exhibit plasticity (retention in volume with change of shape). Silts can therefore create significant challenges in construction and the dilatancy also makes them more difficult to improve.

Silt soils tend to hold their moisture and are difficult to drain. It is difficult to dewater in silt soils and high moisture silts tend to flow or run with sometimes catastrophic results.

GeoSolv has done many interesting Ground Improvement, Rigid Inclusion, and Piling system projects in silts and silty clays. We work with the geotechnical engineer to properly identify these soils to ensure that we treat the soil according to its engineering properties.

Peat and Organic Soil Foundation Challenge

Peat and organics are typically problematic for construction. These soils easily become waterlogged and are often extremely acidic in nature. Peat/organic soils exhibit extremely high compressibility characteristics. The shear strength of peat can be difficult to predict and is often low, although fibrous peat tends to exhibit higher shear strength due to wood fibres in the peat as compared to amorphous peat. Engineering properties are challenging to determine in peat and due to the possibility of future volume loss due to decomposition, it is difficult to rely on engineering properties in peat soils. Peat also tends to off-gas during decomposition and methane becomes a concern for buildings where peat is left in place. Peat and highly organic soils are therefore typically removed and replaced with engineered fills.

GeoSolv is one of the few ground improvement contractors that attacks peat head-on and provides unique ground improvement and rigid inclusion approaches that can provide for reliable engineered properties in peat and organic soils.

Fill Soil Foundation Challenge

In urban centres, infilling of built areas is occurring at an increased rate. Often, remaining sites in urban centres are more difficult to develop and have been passed over in favour of sites with lower development costs. As these areas get built out, and as municipalities struggle to find room for burgeoning populations, the leftover sites are targeted for development. Such sites often require extensive remedial effort to develop including massive excavation and replacement or disposal.

There are a few types of fill soils: Engineered Fill, Dumped (undocumented fill) or hydraulically deposited fill.

Engineered fill is of course used widely for replacing other non-engineered fills for the purpose of supporting structures. It consists of granular materials or select subgrade soils compacted in thin lifts to a minimum level of compaction. When properly constructed and monitored, engineered fill can be relied on for foundation support, with perhaps somewhat limited bearing capacity.

Dumped or undocumented fill is by nature highly variable and the typical reaction is to remove and either re-engineer it back in place, or, if it cannot be re-engineered, replace it with approved engineered fill soils.

Hydraulic fill is placed typically using water in some way, either through stream or river action, or by land reclamation in water bodies, such as what occurred along Toronto's waterfront over many years. Hydraulic fill is often characterized by either select particle size or by heterogeneous or multilayered soils that could include organics and deleterious materials. Old hydraulic fill deposits are sometimes treated as native soil when reasonable compressibility characteristics are expected.

Over ¾ of GeoSolv's ground improvement projects to date have involved some sort of poor fill soils. There is no ground improvement contractor in Ontario with more experience providing robust solutions for fill soils than we have.

The attributes and behaviours of soils can be complex and reliance on the Geotechnical Engineer for soil properties is important. GeoSolv's Ground Experts have a clear understanding of the characteristics of varied soil types and can work collaboratively with the design and construction team to determine the right approach on your challenging soil project to reduce risk and save time and money. We are always happy to provide an obligation-free feasibility study or proposal for your challenging soil projects. Better yet, feel free to reach out to us anytime to register your company for a complimentary Educational Session.

Book your No-Charge Project Assessment for advice on your next challenging project. We are happy to answer any question you may have, and all free-of-charge.

Gravel Soil Foundation Challenge

In areas where gravelly soil is the predominant particle, stabilizing plant life often cannot grow. Depending on the type of gravel in which you are working in, there can be significant challenges from a structural foundation perspective. Depending on grading and state of natural density, gravel can be unstable, and if evenly graded or rounded, the gravel can be easily rearranged by external forces. This can restrict the ability to build on a truly sound foundation in non-engineered gravel soils.

It should be noted that some of the better-engineered fill materials available are gravel-based, but these are often crushed, sorted and graded materials for specific purposes. Engineered angular gravel, too, is the main ingredient of a Rammed Aggregate Pier element. Engineered gravel is used in massive quantities for construction across Canada, either in a quarried crushed form (typically angular to sub-angular particles) or from sand and gravel pits (more rounded and sub-rounded particles, unless further crushed down). Engineered gravel is used as a road base, a sewer and pipe bedding, infiltration galleries, or as foundation drainage layers.

GeoSolv can help your foundation project to be a success, even in gravelly soil conditions. Utilizing the Rapid Impact Compaction system (RIC) allows us to create stable foundations in loose gravel, gravelly sands or sandy gravels. RIC can even be used to stabilize blast rock, or rock fills in the right conditions.

Book your No-Charge Project Assessment today to find out how our ground improvement systems can help you with your next foundation project.