A REVIEW OF THE PRINCIPLES AND METHODS OF SOIL STABILIZATION

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ABSTRACT

Construction of roads, dams, and foundations for various structures as well as several other engineering structures in regions possessing poor or low grade soils is a major problem facing engineers. In many instances, subgrade soils which are unsatisfactory in their natural state can be improved through certain geotechnical methods. Mechanical stabilization entails the mixture of two or more soil types with the aim of improving the properties of the host soil, while other methods utilize the addition of certain additives such as cement, lime, grouts, chemicals, etc. to alter the host soil and improve its engineering properties thereby making it suitable for use as highway subgrade, as well as a host of several other engineering applications. The various methods of soil stabilization each possess their unique advantages and limitations which make them ideal for certain engineering purposes yet unsuitable for others. However, the primary factor which determines the utilization of any of the soil stabilization methods is the mineral composition of the host soil followed by the type of structure of engineering work and the nature of the immediate environment amongst others.

Keywords: Soil Stabilization, Mechanical Stabilization, Grouting, Additives, Engineering Properties, Mineral Composition.

INTRODUCTION

Soil stabilization can be described as a process which incorporates the various methods used for improving the strength and stability of a given soil mass as well as other engineering and physical properties. It is usually employed when the soil available for the construction work is not suitable for the intended use. Through stabilization, a better engineering performance with a reduced chance of bad engineering behavior such as washing collapse etc. occurring by increasing the shear strength of the soil, improving the lead bearing capacity and controlling the shrink-swell properties.

Stabilization process includes compaction, pre-consolidation, drainage and many other processes. However, the foremost criteria for stabilization of a soil mass are its composition (Santosh, 1987) as pure sands and pure clays behave differently in the field. The sandy granular particles which are greater than 75 micron in size are responsible for giving strength and hardness to a soil but lack cohesion and binding power between its grains and as such are easily washed away with relatively unstable slopes while clay soils containing particles less than 75 micron in size possess sufficient binding force between its grains but lacks the shear strength, more so when saturated (Santosh, 1987). Therefore, the presence of water is problematic with clay soils but provides an apparent cohesion for sandy soils. The mixing of these two distinct soil types in appropriate proportions generally yields a soil of far more superior engineering particles.

The process of soil stabilization may be carried out without the addition of any admixture or with the addition of several such as lime, lime-pozzolana, cement, etc. It may also involve the use of geotextile or be reinforced with strips to make the soil suitable for the desired construction work.

Although, the main purpose of soil stabilization is to improve the natural soil for the construction of highways and air fields (Arora, 2011), it is used to alter the permeability and compressibility of the soil mass in earth structures for controlling the grading of soils and aggregates in the construction of bases and sub-bases of the highways and air fields, parking areas, site development projects and many other situations where the sub-soils are not suitable for construction. Stabilization can be used to treat a wide range of sub-grade materials varying from expansive clays to granular materials.

BASIC PRINCIPLES OF SOIL STABILIZATION

Different methods of soil stabilization are controlled by different factors and variables, as such an all governing principle cannot easily be described which encompasses all the methods of soil stabilization. However, it is generally accepted that before any method of soil stabilization is used irrespective of which certain factors should be considered such as:

1. Evaluate the properties of the given soil type – As earlier stated, the first and foremost criteria for the stabilization of any soil is its composition. The engineering properties possessed by a given soil depend largely on the composition of the soil. By understanding and evaluating the composition of the given soil, and in so doing, its engineering properties, the appropriate method to be employed in the stabilization of the soil can be identified.
2. Decide the most suitable, effective and economical method of soil stabilization for supplementing the lacking properties – Due to differing engineering properties, the stabilization method used for clay soils may not be suitable when employed for sandy soil. In the event that it is, which is highly unlikely, it may not be economical in both

situations. As such, proper thoughts and considerations need to be put in place in deciding the most appropriate method or methods to be utilized in the stabilization process.

3. Design the soil mix with stability and durability values.
4. Considering the construction procedure by adequately compacting the stabilized layers.

CLASSIFICATION OF SOIL STABILIZATION

With respect to the addition of certain additives, soil stabilization process may be roughly grouped into two:

1. Stabilization of existing soil without any additives.
2. Stabilization of existing soil with the use of additives – Mechanical stabilization is a perfect example of the second which improve the inherent shear strength of the existing soil alongside other examples like cement stabilization, lime stabilization, bitumen stabilization etc. while for the first compaction and drainage are good examples.

Types of Additives

The types of additives include cementing agents, modifiers, water proofing agents, water retaining agents, water retarding agents and several miscellaneous chemicals. The behavior of each of these additives is different than that of the others and as such, possesses certain suitable or particular use and limitations.

In the case of cementing agents, Portland cement, lime, lime-pozzolana and sodium silicate are some examples. Portland cement has been used extensively in many states in the improvement of existing graved road as well as in stabilizing the natural sub-grade soils. Hydrated lime can also play the role of cementing agent through a chemical reaction between the free lime and the silica alumina content contained in the soil. Hydrated lime is best suitable in granular materials and lean clays than in expansive or fat clays. The quantity required for a proper hydration is generally relatively low.

One major down side to the use of cementing materials in soil stabilization is its cost which results in low or small quantities of the material being added to the soil which merely modifies it rather than undergo actual cementing action.

Modifiers which are often used are also Portland cement, lime and bitumen. Relatively small quantities of cement and lime will change the water film on the soil particles, modify the clay minerals to some extent and will decrease the plasticity index of the given soil.

In the case of water proofing materials, bituminous materials are the foremost which coat the soil or aggregate grains retarding and in some cases completely preventing the absorption of moisture. Bituminous stabilization is best suited for sandy soils or poor quality base course materials with its benefit derived by driving off the volatile constituents of the bitumen just prior to compaction. The table below attempts a summary of additives used in different processes of soil stabilization.

STABILIZATION	ADDITIVES USED
MECHANICAL	**NONE**
Cementing Agents	▪ Cement ▪ Lime ▪ Lime-pozzolona ▪ Sodium silicate
Modifiers	▪ Cement ▪ Lime ▪ Bitumen
Water proofing agents	▪ Bitumen ▪ Membranes
WATER RETARDING AGENTS	ORGANIC CATONIC COMPOUNDS
Water retaining agents	▪ Calcium chloride ▪ Sodium chloride
Miscellaneous chemicals	▪ Resin ▪ Calcium acrylate ▪ Sulphite lignin

METHODS OF SOIL STABILIZATION

1. Mechanical Stabilization

The process of mechanical stabilization is one which entails the mixture of at least two or more types of natural soil in an attempt to change its gradation and by so doing improve the properties of the soil. This method tries to combine the engineering properties of the constituents of the soil mixture. It is aimed at reducing the void ratio by filling up the spacing between larger granular soil properties with finer soil particles through the combination of soils possessing different granular sizes followed by thorough compaction (Garg, 2007). This method of soil stabilization can otherwise be known as granular stabilization. The compaction process ensures that the void ratio is reduced improving the soil strength parameters such as cohesion (C) and angle of internal friction (∅).

With respect to mechanical stabilization, these soils can roughly be grouped into two categories (Arora, 2011), namely:

a. Aggregates: These refer to soils with an average particle size greater than 75 microns (75M) in size. Aggregates usually consist of strong, well graded and somewhat angular particles of sand and gravel which serves as a skeletal framework providing internal friction and incompressibility to a soil.
b. Binders: These are soils which possess an average grain size less than 75 microns. They primarily provide cohesion, plasticity and imperviousness to the soil, composed primarily of clays and silts.

These two soil categories are thoroughly mixed or "blended" together to achieve the required gradation of the mixed soil possessing both internal frictions provided by the aggregates and cohesion provided by the binders. The void ratio of this mixture is then reduced through compaction. The compaction of soil can be obtained easily for well graded soils which are usually characterized by high uniformity coefficient (C_u) generally greater than 15 (>15) and coefficient of curvature (C_o) between 1 and 3 (Arora, 2011; Das, 1994, 1985).

On some highway projects, sometimes it is observed that certain soil deposits may exhibit "show-skip-grading" (Garg, 2007) where the particle size distribution curve possesses a horizontal portion within a given location, reflecting the absence of particles of a given size. Here, small scale utilization of mechanical stabilization is observed, through the addition of the missing size particles, a process known as blending (Garg, 2007). Sometimes cohesionless soils which are usually uniformly graded are mixed with cohesive soil so as to enable them be compacted easily with conventional road rollers. For cohesive and moderately cohesive soil, compaction is generally carried out near the optimum moisture content so as to ensure dry density whereas for cohesionless soil, through vibration when the induced frequency (f) is near the natural frequency of the host soil material (Garg, 2007).

Compaction of shallow depth utilizes rollers, tampers and other mechanical means, however for deeper layers of soil, a method known as dynamic compaction is employed which includes vibro-compaction, heavy weight compaction and blast densification. Vibro-compaction entails the use of a vibratory probe inserted into the ground which vibrates densifying the adjacent soils and is then retracted. It is most effective with silt <12-15% and clay <3% (McCarthy, 1986; Murthy, 2007). Two commonly used vibratory probes are the terra probe and the vibroflot (Donald, 2007). A terra probe consists of a vibratory pile hammer attached to a steel pipe pile (Brown and Glenn, 1976) while a vibroflot contains vibrators and water jets. Heavy weight compaction utilizes a special crane to lift about 5 to 30 ton weight to a height of 12 to 30m and drop them onto the ground. Dropping these weight several times at a given location ensures compaction of the mixed soils, whereas blast densification utilizes a series of drilled borings with explosives then placed in them which upon detonation releases shock waves densifying the surrounding soils.

Factors Affecting Mechanical Stabilization

a. Strength of aggregate used: With increasing strength of aggregates used, the stability of the mixed soil increases as well, although properly designed and compacted mixtures can sometimes accommodate for the relatively low strength of the aggregate.
b. Basic mineral composition: The basic mineral composition of the mixed soils play a fundamental role as it pertains to the stability of the mixture. Generally, weather resistant minerals usually yield mixtures with greater mechanical stability, for instance sodium sulphates and sodium carbonates can result in large volume changes due to hydration and dehydration and thus greatly reduce stabilization.
c. Gradation of mixture: Proper design of the soil mixture is a key to greater mechanical stability as the gradation should be such that the pore spaces of the coarser grains or aggregates are effectively filled with the finer particles of the binders. The effective design of a soil mixture is guided by Fuller's law (Fuller, 1907) which states that the granular soil mass attains a very high density after compaction if the distribution of particle size is as follows:

$$Percentage\ of\ particle\ size\ passing\ any\ sieve = 100 \times \sqrt{D/D_{max}}$$ ……..*Equation 1*

Where;

D = Opening of a particular size
D_{max} = Size of the largest particle

However, according to Arora (2011), it is necessary to have a greater proportion of the material passing a 75 micron sieve than that given by Fuller's equation with an ideal mixture containing about 25% binder.

d. Plasticity characteristics of the soil mixture: Binders are generally soils like clay and silt possessing high liquid limit and plasticity index thus possessing greater cohesion and moisture retention capacity providing a good seal against the downward movement of surface water. However, in terms of plasticity, the requirements somewhat differ with the envisaged use for the soil moisture. For instance, soils meant to serve as base course possess a different plasticity characteristics requirement from those to be used for surfacing, as that of base course is expected to have low plasticity to avoid excessive accumulation of water and the resulting loss of strength as compared to that for surfacing.
e. Adequate compaction of soil moisture: The stability of a good soil mixture can be undermined if poorly compacted as the mechanical stability of the soil mass depends on the extent of compaction attained in the field.

Mechanical stabilization is one of the simplest methods soil stabilization generally used to improve the subgrades of low bearing capacity and has very little environmental side effect, although for deep soil compaction method such heavy weight compaction, due to the substantial amount of shockwaves generated, can be harmful to buildings and other engineering structures and as such cannot be utilized close to existing structures.

2. Lime Stabilization

When lime is mixed with soil, a chemical reaction involving an exchange of cations takes place as every soil particle carries an electrical charge with either a net positive or net negative charge (Lambe and Whitman, 1979). A soil particle in nature attracts ions are relatively weakly held on the surface, they can therefore be easily replaced by other ions. In the same sense, water is attracted to the soil particle but since it's attached to exchangeable ions, they are replaced by a process known as "absorption" (Craig, 1978). Consider clay soils for instance, when lime reacts with clay soils, there is an exchange of cations in the absorbed water layer and a decrease in plasticity of the soil occurs resulting in a more friable clay than the original clay soil thereby making it a more suitable material for construction say as a subgrade or a base course for pavements (Dana, 1994), on embankment slopes and under canal linings on canal slopes.

When lime reacts with wet soil, it changes the nature of the absorbed layer through Base Exchange (Arora, 2011) with calcium ions replacing the sodium or hydrogen ions. The double layer thus becomes depressed as a result of increase in the cation but may also expand resulting from the high pH value of lime. When lime reacts chemically with available silica and alumina in soils, a natural substance composed of calcium alumino silicate complexes is formed which acts as cement although the reaction is a function of the effective concentration of the reactants and host temperatures. Effectively, lime stabilization results in a decrease in the liquid limit of the soil but an increase in the plastic limit thereby reducing the plasticity index and for this reason has been significantly used in stability, highly unstable plastic and swelling clayey soils (Garg, 2007), as the soil becomes more friable and workable with the strength of the soil generally being improved, partially as a result of the decrease in the plastic properties of the soil and partially due to the formation of the cementing material. The increase in the unconfined compressive strength of the soil is sometimes as high as 60 times the original strength with the addition of lime producing a maximum density under higher optimum moisture content than in an untreated soil. The lime treatment increases the size of the clay particles by coagulation to silt sized particles and thus changes the soil structure but stabilizing it by reducing its swelling tendencies.

Lime is generally gotten by burning of limestone in kilns with the quality of lime depending on the material and the production process. There are basically five types of lime, namely (Arora, 2011);

i. High calcium, quick lime (CaO)
ii. Hydrated, high calcium lime [$Ca(OH)_2$]
iii. Dolomitic lime ($CaO + MgO$)
iv. Normal, hydrated dolomite lime [$Ca(OH)_2 + MgO$]
v. Pressure, hydrated dolomite lime [$Ca(OH)_2 + MgO_2$]

The quick lime is more effective as a stabilizer than the hydrated lime, although less safe and convenient. Hydrated lime is more commonly used, better known as slaked lime with increase in its magnesium content resulting in a decrease in its affinity for water and heat generated during the mixing.

The amount of lime required for stabilization varies between about 2 to 10% of the soil with the amount of lime being about 1 to 3% as it depends on the plasticity index of the soil. The greater the value of plasticity index, the larger the amount of lime required. It has however been observed that unless lime is thoroughly and uniformly mixed with the soil, usually with the help of machinery such as pulve-mixers, it does not produce satisfactory results (Garg, 2007) and it is usually not very effective for sandy soils (Arora, 2011).

Pozzolona is a siliceous material which while in itself possessing cementitious properties will in a finely divided form and in the presence of water reacts with calcium hydroxide and form cementitious compounds thereby serving as an admixture. Pozzolona can be naturally occurring volcanic ash or industrial waste such as fly ash or can be produced by calcining clay. Lime-pozzolona is an admixture in extensive use. Fly ash, a by-product of blast furnaces, generally high in silica and alumina, its addition tends to speed up the reaction between the lime and the soil. However, the quantity of fly ash required for adequate stabilization is relatively high. When fly ash is used, the mixture is known as lime fly ash stabilized mixture. Not all soils possess enough quantity of clay mineral with which lime can easily take place. Silts, sandy soils, gravels, crushed stone and slag are some of the material types where lime pozzolona can be successful. The ratio of lime to pozzolona depends upon a number of factors and can vary so widely as from 1:1 to 1:9. The combined quantity in a mixture may vary from 10 to 25%.

Lime pozzolona aggregate mixtures can be used for the superior strength for road bases. A layer of this material has great structural strength and behaves more like a semi-rigid pavement. It can be used in the disposal of huge quantities of fly ash from thermal plants.

FIG. 1: An Image of Soil Stabilization Using Fly Ash **(SOURCE:** U.S Department of Transport**)**

3. Cement Stabilization

In cement stabilization, pulverized Portland cement is mixed with the soil alongside water and compacted to attain a strong material with the increased strength, durability and minimal moisture variations (Behzad and Huat, 2008). Thus far, cement stabilization has proved to be an effective method of soil stabilization with all soil types except clay (Garg, 2007), while other organic water, when present in a soil reduces the strength of the cement stabilization for instance, the presence of sulphates in a soil tenders it unfit for improvement by cement. According to Mitchell (1976), soil cement can be grouped into 3 categories.

a. Normal soil cement: This is made up of about 5 to 14% of cement by volume with a sufficient amount of cement mixed with soil to produce durable construction material. The quantity of water used should be just enough to satisfy hydration requirements of the cement and to make the mixture workable. Normal soil cement is quite weather resistant and strong used for stabilizing low plasticity soils such as sandy soils.
b. Plastic soil cement: This soil cement also contains about 5 to 14% of cement by volume but however contains more water relative to the normal soil cement in order to have a wet consistency similar to that of a plasticity mortar at the time of placement. It can be placed on steep or irregular slopes where normal road making equipment have been successfully used for water proofing lining canals and reservoirs, and for protection of steep slopes against erosive action of water.
c. Cement modified soil: It is a type of soil cement containing less than 5% of cement by volume, semi-hardened and somewhat inferior to the previously mentioned two. Due to the small quantity of cement, the soil is not bound in a coherent manner but however

interacts with the silt and clay fractions thereby reducing their affinity for water and thus their swelling characteristics.

Generally speaking, the proportion of cement to be added to a soil is around 5% for sandy soils and 15% for well graded soils and its exact proportion determined experimentally by performing a compressive strength and durability test, though this amount determined should be suitably increased to account for less efficient mixing of soil and cement in the field relative to that of laboratory experiment.

The soil cement must be well compacted to obtain sufficient strength and durability by maintaining optimum moisture content and an equal assumption has to be made in the experimental determination of the required cement proportion. Soil cement can be used as a suitable economical material for sub-bases or bases of roads, as blocks for pitching river and canal banks (Garg, 2005) and for lining irrigation canals.

FIG. 2: Soil Cement Stabilization (**SOURCE**: Research Gate)

Factors Affecting Stabilization with Cements

According to Arora (2011), the following factors affect stabilization using soil cements:

a. Soil type: Granular soils such as sands in the presence of a sizable amount of fines thus far have proved ideal for cement stabilization and require the least amount of cement. Sands lacking the required quantity of fines can also be stabilized but however would require more cement. Although fines such as silty and clayey soils have the potential to produce satisfactory soil cement, those with high clayey contents however are difficult to pulverize with the quantity of clay content and a resultant poor quality of soil cement possessing high shrinkage properties. The presence of organic matter in colloidal form interferes with the hydration of cement and causes a reduction in the strength of the soil cement usually encountered in sandy soils. In such cases, these sandy soils should first be treated with calcium chloride or sodium hydroxide before cementing is carried out.

b. Quality of cement: Well graded sands usually require about 5% cement while poorly graded uniform sand may require about 9% cement, non-plastic silts about 10% and plastic clay about 13% of cement is required for a particular soil is determined from a laboratory test. For base course, samples are subjected to durability test consisting of 12 cycles of freezing and thawing or 12 cycles of wetting and drying with an allowable maximum volume change of 2%. The quantity of cement can also be determined from the minimum unconfined compressive strength with high strength obtained by decreasing the water cement ratio through increase in its cement content.
c. Quantity and quality of water: Sufficient water is required for the effective hydration of cement and the silt-clay cement for making them workable. Generally, the amount of water determined from compaction consideration can serve for hydration while ensuring that the water used is both clean and free from harmful salts, alkalis, acids or organic matter.
d. Adequate mixing, compaction and curing: The soil, water and cement mixture has to be thoroughly mixed as it may affect the stability of the material, if not mixed properly may result in a non-homogenous and weak product, at least until hydration begins when all mixing should be ceased to avoid a loss of strength.
e. Use of additives: Sometimes other additives can be added to the soil cement in order to increase its effectiveness, reduce the amount of cement required and assist in the stabilization of soil which is not responsive to cement alone.

4. Stabilization By Grouting

The grouting method of soil stabilization entails the injection of special fluid like materials either in suspension or solution, called grouts, into the ground with the goal of improving the soil. Grouting is usually done under high pressure. It utilizes stabilizers with high viscosity for soils with high permeability and is not primarily suitable for clay soil due to their low permeability. The method is essentially suitable for stabilizing buried zones with limited extent; say a previous stratum below a dam, and for stabilizing soils that cannot be disturbed. Grouting therefore aids in reducing the void spaces and increasing the load carrying capacity of the soil.

According to Whitaker and Frith (1990), the following are some necessary characteristics to be considered in choosing a grout to be used:

a. Grout stability: During its mixing and injection, the grout should not be set prematurely or sediment.
b. Relative particle size: The size of particles suspended in the grout should be able to penetrate joints/fractures and gouge materials.
c. Low viscosity: The viscosity of the grouting fluid should be sufficiently low for easy flow through the soil.
d. Strength: The grout should be which quickly provides strength to the soil on setting.
e. Performance: The grout should be able to set well and resist chemical attack or erosion by seeping water.

Types of Grouts

Different authors over the years have divided grouts into different categories, a few of the most prominent ones are:

1. Ramamurthy
   Ramamurthy (2014) classified the types of grouts into:
   i. Suspension grouts: Comprised essentially of Portland cement with water. Cement ratio varying from 5:1 to 0.5:1.
   ii. Chemical/liquid grouts: Predominantly sodium silicate, acrylamide, lingo-sulphytes, phenoplasts and aminoplasts.
2. Garg
   Garg (2007) classified them into:
   i. Consolidation grouts: They increase the load bearing capacity of the soil.
   ii. Water proofing gouts: They reduce the permeability of the soil.
   iii. Suspension grouts: They are primarily comprised of bentonite, cement, lime or asphalt emulsion.
   iv. Solution grouts: They include a wide variety of chemicals such as sodium silicates and calcium chloride, a mixture of which forms an insoluble precipitate of silica gel within the pores of the soil.
3. Donald
   Donald (2007) classified them into:
   i. Cementitious grouts: These are primarily Portland cement that hydrates after injection forming a solid mass.
   ii. Chemical grouts: They include a wide range of chemicals which solidify upon injection such as silicates, resin and many others.
4. Arora
   Arora (2011) classified them into:
   i. Cement grouts: Comprised of a mixture of cement and water and is quite effective especially when stabilizing coarse sands.
   ii. Clay grouts: These grouts are composed of very fine soil essentially bentonite and water. The bentonite readily "absorbs" water on its surface with its viscosity, strength and flow characteristics being adjusted to suit the desired conditions and is especially suitable for sandy soils.
   iii. Chemical grouts: These grouts consist of a solution of sodium silicate in water, known as water glass containing both free sodium hydroxide and colloidal silicic acid forming an insoluble silica gel with calcium chloride added to serve as a catalyst in the chemical reaction. They are suitable for medium to fine sands but may not be permanent.
   iv. Chrome-lignin grouts: These are made of lignosulphates and a hexavalant chromium compound, when it is combined with an acid the chromium ions change its valency oxidizing lignosulphates into gel. It is quite suitable for fine sand and silt.
   v. Polymer grouts
   vi. Bituminous grouts: Utilizes emulsified asphalt as grouts to carry out the soil stabilization.

Types of Grouting Methods

Welsh (1986) described four major methods by which stabilization by grouting may be carried out.

a. Intrusion grouting: This is a method of grouting also known as slurry grouting which entails the injection of grouts through pipes to fill up joints or fractures in a soil (and sometimes in rocks as well). The pipes are inserted from the surface or from tunnels. This method of grouting is especially beneficial as there is a decrease in hydraulic conductivity particularly used for foundations using cementitous grouts.
b. Permeation grouting: Here thin grouts are injected into the soil such that they permeate into the soils (Littlejohn, 1993) which upon curing improve the soil by converting into a near solid mass. This method of grouting is usually carried out with the use of chemical grouts as such can sometimes be referred to as chemical grouting. The treated soil at the end usually has a much lower hydraulic conductivity and is stronger and less compressible than before, often used to form groundwater barriers and to stabilize soils in advance of making excavation or tunnels.

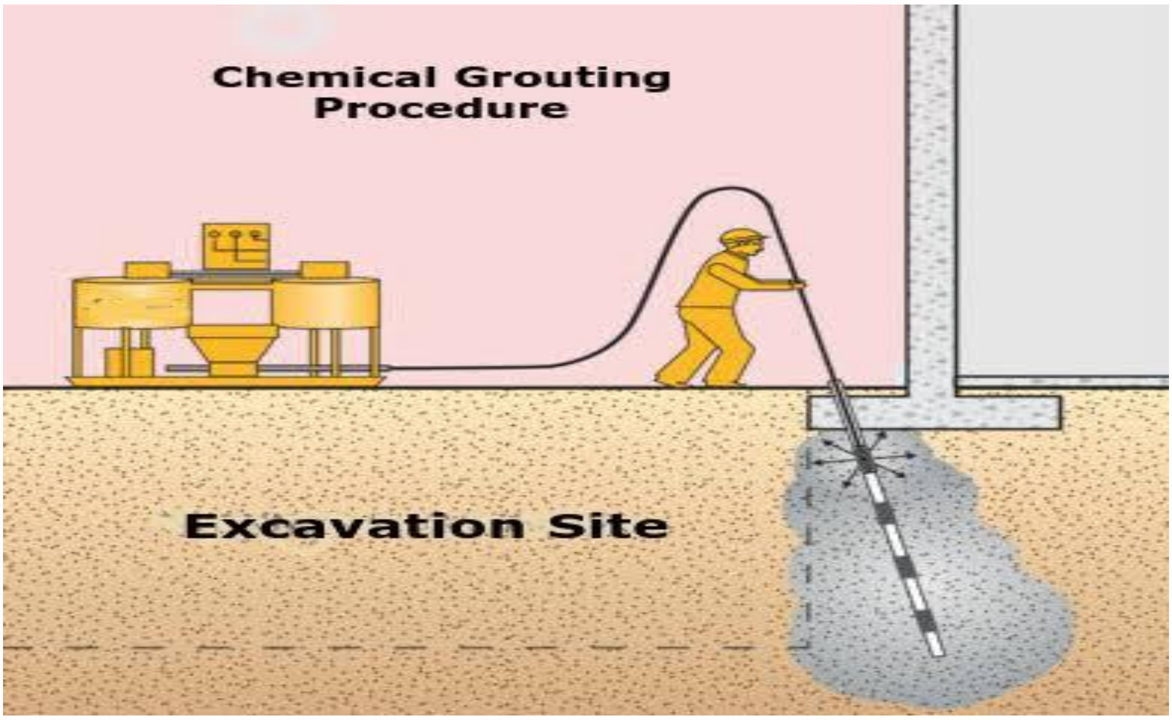

FIG. 3: An Image Showing Chemical Grouting Procedure (**SOURCE:** GSI foundationrepair.com)

c. Compaction grouting: This method of grouting utilizes a stiff grout (about 25mm slump) which is injected into the ground under high pressure through a pipe to form a series of inclusion (Rubright and Welsh, 1993). This method of grouting is usually utilized for the repair of structures that have experienced excessive settlement since it both improves the underlying soils and raise the structure back into position.

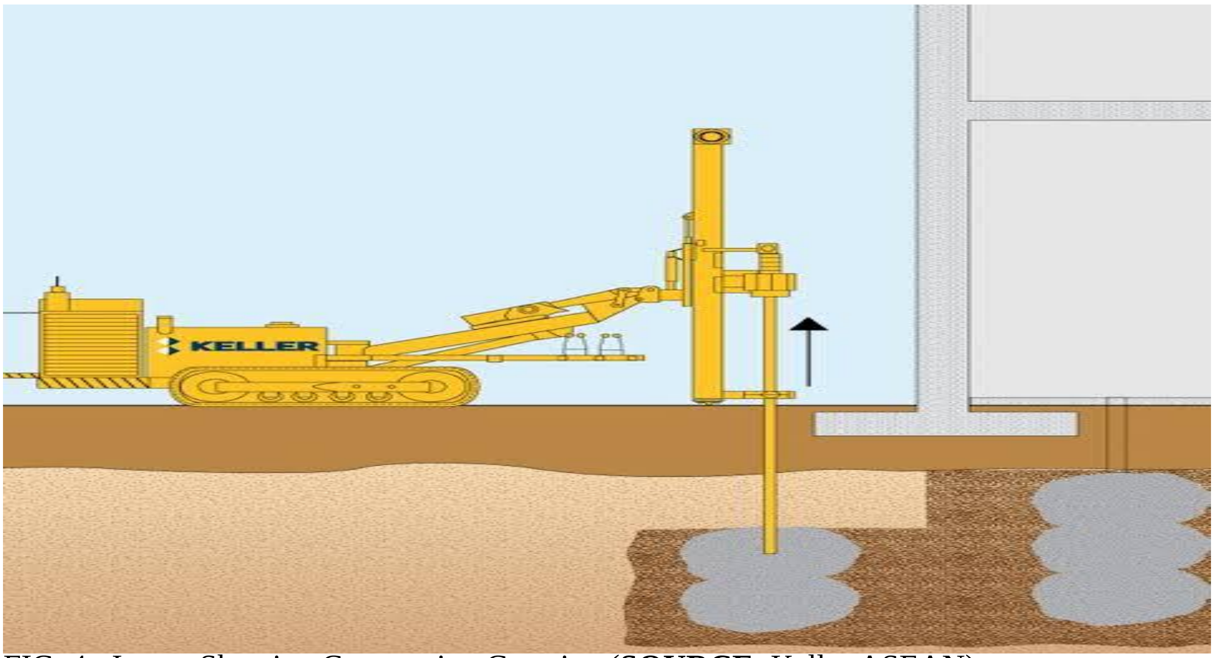

FIG. 4: Image Showing Compaction Grouting (**SOURCE**: Keller ASEAN)

d. Jet grouting (Bell, 1993): This is the most recent form of grouting developed in Japan in the 1960s and 1970s and uses a special pipe equipped with horizontal jets that inject grouts into the soil at high pressure, with the pipes first inserted to the desired depth, then they are raised and rotated while the injection is in progress, thus forming a column of treated soil which as a result of its associated high pressure is quite useful on a wide range of soil types, especially used for groundwater control, under pinning, stabilization in advance of tunneling and several others.

Objectives of Grouting

Although the end point of grouting is stabilization of the given soil, grouting however achievers certain objectives as described by Lancester-Jones (1969). They entail:

i. To consolidate and strengthen the foundations below structures.
ii. To cut-off water flow and strengthen weak soil.
iii. To transmit or redistribute stress.
iv. To rectify blasting damages.
v. To minimize seepage for an excavation below water table.
vi. To minimize leakages below dams.
vii. To control uplift pressures below structures in combination with adequate drainage facilities.
viii. Control seepage/pore pressure in rock abutments of dams.

Over the last couple of decades, grouting as a technique of stabilization has been developed considerably from a technical and economic view point providing solution to foundation problems, say for instance in the construction of foundation below the water table. It has been used extensively to control ground water flow under earth and masonry dam. Although, it is an expensive and highly specialized field as the injection technique and its control require a lot of experience but however shows great benefits in difficult soils.

5. Bituminous Stabilization

Bitumens are non-aqueous systems of hydrocarbon soluble in carbon di-sulphide. Bituminous substances such as asphaltic bitumen, tar, emulsions, etc. can be utilized to stabilized soil especially to serve as sub-grades or bases of roads particularly effective for granular sandy soils. Tars are obtained by the destructive distillation of organic materials such as coal. Asphalts are materials gotten primarily from natural or refined petroleum bitumens. These bitumen additives when spread over the soil layer, acts as a binder and a water proofing agents. As asphalts are usually too viscous to be used directly, these are used as cut back with some solvent such as gasoline used also as emulsion but require a longer drying period. Moderately cohesive road bases with such sprays would give satisfactory service during dry periods though maybe slippery after rains (Garg, 2007). Cut-back bitumens may also be mixed and pulverized with soils like that of cement so as to obtain stabled soils.

Any inorganic soil which can be mixed with asphalt is suitable for bituminous stabilization although dry conditions are properly together. In cohesionless soils, asphalt binds the soil particles together and this serves as a bonding or cementing agent whereas in cohesive soils, the asphalt protects the soil by plugging its voids and proofing it, aiding it to maintain low moisture content and to increase the bearing capacity with the amount of bitumen required varying between 4 to 7% by weight as determined by trial.

Types of Soil Bitumen

According to the Highway Research Board of USA (Arora, 2011), there are four types of soil bitumen.

a. Soil bitumen (proper): This is a water proofing, cohesive soil system. The best results are obtained if the soil satisfies the following criteria:
   i. Passing No.: 4 (4.76mm) sieve 50%
   ii. Passing No.: 40 (0.425mm) sieve 35 to 100%
   iii. Passing No.: 200 (0.074mm) sieve 10 to 50%
   iv. Plastic limit less than 18%
   v. Liquid limit less than 40%
   vi. The maximum size of the particle should not be greater than third the compacted thickness of the soil bitumen.
b. Sand bitumen: This is a bitumen stabilized cohesionless soil system. The sand should be free from vegetal matter or lumps clay, may require filtering and should not contain more than 25% minus No.: 200 sieve materials for dune sands (Graber *et al.*, 2008) and not more than 12% in case in other types of sands.
c. Water proofed clay concrete: A soil passing a good gradation is water proofed by a uniform distribution of 1 to 3% of bitumen in this system. Soils of 3 different gradations have been recommended for which the percentage passing through No.: 200 sieve varies between **i.** 8 to 12 **ii.** 10 to 16 **iii.** 13 to 30.
d. Oiled earth: Here a soil surface consisting of silt-clay material is made water proof by spraying bitumen in two or three applications with slow or medium curing bitumen or emulsion used. The bitumen penetrates only a short depth into the soil.

Factors Affecting Bituminous Stabilization

a. Type soil: Bituminous stabilization is very effective in stabilizing sandy soils having little or no fines. If a cohesive soil has the plastic limit less than about 20% and liquid limit less than 40%, it can be effectively stabilized. However plastic clays cannot be properly treated because of the mixing problem and large quantity of asphalt required. Fine grained soils of the arid regions have values and contain dissolved component which do not respond to bituminous stabilization (Graber *et al.*, 2008).

b. Amount of asphalt: The quality of the bitumen stabilized soil improves with the amount of asphalt up to a certain limit. However, if the amount of the asphalt is excessive, it results in a highly fluid mixture that cannot be properly compacted.
c. Mixing: The quality of the product improves with more thorough mixing.
d. Compaction: The dry density of the bitumen soil depends on the amount and type of compaction. It also depends upon the volatile content.

6. Chemical Stabilization

Chemical stabilization entails the stabilization of soil through the addition of different chemicals with a major advantage of its setting time and curing time being controlled, although it is generally more expensive. Some of the chemicals successfully utilized for stabilization are:

a. Calcium chloride: When added to soil, it causes colloidal reaction and alters the characteristics of soil water. Since calcium chloride is deliquescent and hygroscopic, it reduces the loss of moisture from the soil. It also reduces the chances of frost heave as the freezing point of water is lowered. Calcium chloride is very effective as dust palliative. As the soils treated with calcium chloride do not easily pickup water, the method is effective for stabilization of silty and clayey soils which lose strength with an increase in water content.
   Calcium chlorides cause a slight increase in the maximum dry density (Abood *et al.* 2007). However, the optimum water content is slightly lower than that for the untreated soil. It causes a small decrease in the strength of the soil. However, if the compacted soil is put to water imbibitions, water picked up is reduced and the strength of the treated soil is greater than that of the untreated soil.
   It may be noted that most of the benefits of stabilization require the presence of the chemical in the pore fluid. As soon as the chemical is leached out, the benefits are lost. The performance of treated soils depends to a large extent on ground water movement.
b. Sodium chloride: The action of sodium chloride is similar to that of calcium chloride in many respect, however the tendency of moisture is somewhat lesser than that of calcium chloride. When sodium chloride is added to the soil, crystallization occurs in the pores of the soil and it forms a dense hard mat with the stabilized surface. The pores in the soil get filled and retard further evaporation of water. Sodium chloride also checks the tendency for the formation of shrinkage cracks. Sodium chloride should not be applied directly to the surfaces of the soil with only about 1% of the soil weight required.
c. Sodium silicate: Sodium silicates as well as other alkali silicates have been successfully used for soil stabilization. The chemical is injected into the soil. Sodium silicate gives strength to soil when it reacts with it. It also makes the soil impervious. It also acts as a dispersing agent. The maximum compacted density is increased. The quantity of the chemical required varies between 0.1 to 0.2% of the weight of the soil. Although inexpensive, it is not suitable for long term bases.
d. Polymers: Polymers are long chained molecules formed by polymerizing of certain organic chemical called monomers. Polymer maybe natural or synthetic. Resins are

natural polymers. Calcium acrylate is a commonly used synthetic polymer. When polymer is added to a soil reaction takes place. Sometimes, the monomers are added with a catalyst to the soil with polymerization occurring along with the reaction.

e. Chrome-lignin: The chemical lignin is obtained as by-product during the manufacture of paper from wood. Chrome-lignin is formed from black liquor obtained during sulphite paper manufacture. Sodium bicarbonate or potassium bicarbonate is added to sulphate liquor to from chrome-lignin. It slowly polymerizes into brown gel. When the chemical is added to the soil, it slowly reacts to cause bonding of particles. The quantity of lignin required varies from 5 to 20% by weight. Due to the solubility of lignin in water, chrome-lignin cannot be utilized as a permanent method of soil stabilization.
f. Other chemical: A wide variety of other chemicals are also used such as;
    i. Some water proofers such as alkyl chloro silanes, siliconates amines and quaternary ammonium salts, have been used for water proofing of soils.
    ii. Coagulating chemicals such as calcium chloride ad fabric chloride have been used to increase the electrical attraction and to from flocculated structure in order to improve the permeability of the soil.
    iii. Dispersants such as sodium hexa-metaphosphate, are used to increase electrical repulsion and to cause dispersed structure. The compacted density of the soil increased.
    iv. Phosphoric acid combined with a wetting agent can be used for stabilization of cohesive soils. It reacts with clay materials and forms an insoluble aluminium phosphate.

7. Stabilization By Geotextile And Fabrics

Geotextiles are those permeable sheets of synthetic fibres like polyester, polypropylene, polyamide nylon, etc (Tingle *et al.*, 2002) while the geomembranes are basically impermeable sheets or films made from a polymer and which may be reinforced with a textile or may be made by spraying asphalt or resin directly on the ground or unto a geotextiles. The geotextiles though permeable can thus be diversified into impermeable geomembranes. The permeability of geotextiles is comparable to that of fine sand to coarse sand. They are quite strong and durable (Yetimoglu and Inanir, 2005; Puppala and Musenda, 2000). These are not affected by even hostile soil environment (Onyelowe, 2011). The use of geotextiles has increased considerably in the last two decades.

Geotextiles are manufactured in different thickness ranging from 10 to 300 miles (1 mile = 1/100 inch = 0.0254mm) and in width up to 10m and in roll lengths up to about 600m. Geotextiles are manufactured in different patterns such as woven, non-woven, grid and hybrid.

Non-woven geotextiles are made from continuous or stable fibres joined at the fibre cross-overs, either by mechanical bonding (needle punching) or thermal or chemical bonding. They have been extensively used for filtration, separation and drainage function and also to form impermeable barriers. Woven fabrics are made from continuous mono-filament or split film fibres. The woven are largely used for soil reinforcement function and are cost effective with very good potential.

Geotextiles are relatively new forms of synthetic material in the form of nets of different sizes manufactured from selected polymers by two methods. One entails extruded mesh produced by a specialized plant while the other method includes special processes which align molecular chain of polymers and thereby produces material of high tensile strength compared to extruded polymeric mesh are though the basic raw material is the same. Geogrids are essentially nonfilters with a principle function of reinforcement while separation being their second function in some application. Some of the common applications for geogrids include reinforcement of granular bases for flexible pavements, ground reinforcements, retaining walls, stabilization of beds of railway tracks, erosion control on slopes, etc. As against these applications of geogrids, the common of geotextiles include track foundations, steeper beds, rock fill and earthen dams, bearing capacity improvement, river bank protection, etc. geogrids differ fundamentally from geotextiles in the manner in which they reinforce the soil. In the case of geotextile, the reinforcing function is dependent upon surface friction between the fabric and the fill. In the geogrid however, the reinforcement is achieved by positive interlocking of the fill material into the aperture or opening of the geogrid.

Geostrips are used as soil reinforcement in the form of cut fabrics or long strips of geotextiles. They are generally produced from polypropylene and high density poly-ethylene. They can be connected with anchors at the end. The anchors may be in the form of loops, rings or spirals which may help in confining soil elements.

Geoweb or geocell mattresses: They are used for confinement of soil/concrete cells made from prefabricated polymeric system. These systems are made from thick HDPE strips 50 to 200mm wide, stitched or welded together at 50 to 200m intervals. The hexagonal or rhomboidal cells can be made of geosynthetic honeycomb design. They can be transported to the job site in folded configuration and are unfolded and placed directly on the soil and then filled with soil material. The material is compacted inside the cells. When filled with soil, they do not need any other treatment except compaction. These geocells are used for footing foundation, road and canal lining.

Geocomposite are made by suitably bonding the geomembranes and geotextiles or any of their like forms for specific application in drainage, erosion control and bank protection.

FIG. 5: Geogrid Used In Soil Stabilization (**SOURCE**: Geosynthetics.com)

FIG. 6: Image Of Geo Cells (**SOURCE**: agriculturesolutions.com)

FIG. 7: Geo Fabrics in Use (**SOURCE**: indiamart.com)

Functions of Geotextiles

a. Separation function: Geotextile have been used to separate the sub grade soils of roads from the ground base course, thereby preventing the ingress of gravel into the clayey sub-grade, consequently increasing the life of the roads. Road construction on wet soils or on weak soil like black cotton soils in water-logged areas usually fail quickly due to penetration of road crust into sub-grade or ingress of soft sub-grade soil into the gravel of the base course. Sometimes, inadequate drainage of sub-grade and base becomes the major cause of road failures. To prevent such pavement failures, conventional methods have been used of which geotextiles can improve upon the existing conventional method of construction reducing the possibility of failure because of its physical functions which include:

i. Geotextiles acts as an effective separator and prevent entry of sub-grade into the voids of the granular sub-base.
ii. Highly permeable nature of geotextiles facilitates rapid removal of water from the road section and prevents pumping action in the pavements giving drainage function.
iii. Tensile strength of geotextiles help in spreading traffic loads over wider areas and thereby minimizes the possibility of localized stresses in the pavement which invariably increases the life of the pavement by increasing their shear strength and California Bearing Ratio value of the sub-grade and thus helps in reducing the required thickness of the pavement crust (John, 2011).

b. Soil reinforcement function: A geotextile layer provides reinforcement through the tensional membrane and tensile member functions acting as reinforcement. It ensures better load distribution especially true for heavy weight and high modulus fabrics (Park and Tan, 2005). The deformation under dynamic loads induces tension in the fabric and due to membrane action acts as reinforcement. Geotextiles keeps the stress level low and mobilized by the vertical loads. Fabric is placed under tension and it spreads the load in wider areas thereby decreasing its intensity. Geotextiles stabilizes the underlying soil on which it is place. It increases the shear strength of the soil thereby increasing its bearing capacity consequently enabling the soil to withstand greater loads (Maher and Woods, 1990). This effect is further strengthened by the drainage action of the geotextile under which the water seeping through the ballast flows through the geotextile and is removed from this road bed.

Geogrid reinforcement provides a practical and permanent solution to the problems of stability enabling banks of simple and economical cross sections to be constructed to the required height. The mesh is placed horizontally at the base of the embankment and thereafter in layers at calculated heights as construction proceeds, extending from the face of the slope to the grip length beyond the calculated lip plane. Geogrid adds a high tensile resistance to the shear strength of the soil. The resistance is achieved by virtue of the friction developed between the grid structure and the soil. The geogrid layers may either be curtailed at grip lengths beyond the calculated plane of failure or maybe kept continuous throughout the width of the bank depending upon the stability analysis and location of failure planes.

When geotextiles are used as soil reinforcement, their prime role is to provide tensile strength to the soil which otherwise would comparatively be strong in the compression and weak in tension. It is important that the adopted geotextile is capable of providing this tensile strength at a strain level which is compatible with the performance of the soil structure. As large deformations are usually unacceptable in such structures, a high tensile stiffness is usually also required for geotextile soil reinforcement.
Compared with other soil reinforcing materials, geotextiles have the following advantages:

i. They are resistant to all chemical attacks naturally occurring in soils particularly to alkalis and acids.
ii. They are found to be stable over a temperature range of -60 ^{o}C to 100 ^{o}C. However, the strength is known to reduce at substantial high temperatures.
iii. They are durable in conditions exposed to prolong sunlight or wet conditions.
iv. They are resistant to organic attacks like bacteria and fungus and are not attractive to rats and termites.
v. The synthetic fibre mats are known to support vegetation like grasses and expand their growth.
vi. The geotextiles contain sufficient black carbon which gives them adequate protection during outdoor storage prior to actual use.

c. Filtration function of geotextiles: While designing the upstream and downstream protection works of a weir or a barrage floor, a protection inverted filter is laid on the ground and is covered with concrete blocks having filled open joints. This inverted filter consist of layers of fine sand, coarse sand and some stone aggregate laid from bottom to top. Such an arrangement allows the escape of water seeping from below the weir floor without allowing the foundation soil to be lifted upwards thereby reducing the possibility of piping. The filter gradation is such that while it allows free flow of seepage water, the foundation soil does not penetrate to clog the filter, thus reducing the possibility of failure of weir by piping undermining.

Such protective stone aggregate filters are expensive and difficult to install especially if the filter is required to be placed under water and are therefore being substituted by geotextile filters with the role of permitting free flow of water without significant loss of soil particles. The geotextile filter should therefore possess good soil retention and should at the same time have good transverse permeability. There are some certain design criteria for the use of geotextiles as filters (Garg, 2007) which are:
i. Piping criteria
ii. Permeability criteria

d. Drainage function of geotextiles: Granular drainage filters are traditionally laid behind the masonary, a concrete retaining wall supporting a soil mass which helps in transmitting water. However, such filters are quite susceptible to clogging and are difficult to construct as such composite geotextile called fin drain have recently been used as an alternative consisting of a water conducting filter in the form of a water conducting core backed with a geotextile filter on either one or both sides. The use of fin drains behind retaining walls and simple structures have become popular due to the following advantages over traditional granular drainage:
i. They are less susceptible to clogging.
ii. They are much easier to install and therefore involves less labour costs.
iii. They protect water proof coating on the back of the wall from drainage during back filling.
iv. A wide range of back fill material can be used because of the presence of the water filter sheet on the fin drain.
v. Sometimes the fin drain is pre-assembled with a polyethylene on the face against the wall with no other water proof coating needed to protect the concrete.

8. Stabilization With The Use of Reinforced Earth

Soils can be stabilized with the introduction of thin strips in it; basically a reinforced soil is a composite material which is formed by the association of frictional soil and tension resistant demerits in the form of sheet, strips, nets or mats of metal, synthetic fabrics or fibre reinforced plastic (Swami, 2011) arranged in the soil mass in such a way as to reduce or suppress the tensile strain which might develop under gravity and boundary forces. It is well known that most granular soils are strong in compression and shear but weak in tension. The performance of such soils can be substantially improved by introducing reinforcing element in the direction of tensile strain in the same log as in reinforced concrete. In reinforce earth, thin metal strips or strips of wire or geosynthetics are used as reinforcement to reinforce the soil. The essential features of the reinforced earth are that friction develops between the reinforcement and the soil. By means of friction the soil transfers the forces built up in the earth mass to the reinforcement. The tension develops in the reinforcement when the soil is subjected to shear stresses under loads.

The incorporation of the reinforcement in the earth mass particularly in case of non-cohesive soil, is not only for carrying the tensile stress but instead meant for anisotropic suppression or reduction of one normal strain rate. The basic mechanism of reinforced earth can be explained in different ways, one of which is the stress theory. If a 2-dimensional element of cohesionless soil is subjected to uniaxial stress, it will not be able to remain in equilibrium as the Mohr's circle of stress will cut the strength envelop of the soil. If the element is subjected to equal stresses, it will undergo uniform compression and if one of the stresses $say(\theta_1)$ is increased while maintaining the others constant, a compression of the element in the direction of σ, and an expansion in the direction of the other stress σ_3 will result when the lateral strain reaches critical proportions, failure of element results, similar to the failure of a sample in a triaxial compression test and σ, at this stage is related to σ_3 as:

$\sigma_3 = K_a - \sigma_1$……………………….*Equation 2*

Where;

$$K_a = coefficient\ of\ active\ earth\ pressure$$

$K = tan^2\left(45 - {}^{\emptyset}/_{2}\right)$…………… *Equation 3*

Where;

$$\emptyset = angle\ of\ internal\ friction\ of\ the\ soil$$

At this instance, the Mohr's circle of stresses is tangential to the strength envelop. To hold the element without failure, the lateral stress must be increased. If reinforcement is provided in the direction of σ_3, interaction between the soil and reinforcement will generate frictional forces along the interface. Tensile stresses will be produced in the reinforcement and a corresponding compression in the soil element as long as there is no slippage between the soil and reinforcement. The additional lateral pressure will move the Mohr's circle to the right and away from the failure envelop and the soil element will remain in equilibrium. Thus, soil reinforcement friction is fundamental to the concept of reinforced earth (Swami, 2011).

Vidal (1978) describes reinforced earth as a cohesive material with the cohesion assumed to be induced due to introduction of the reinforcement in an otherwise cohessionless soil. The anisotropic cohesion is produced in the direction of reinforcement and the concept is based on the behavior of triaxial samples of reinforced earth.

The most effective orientation of reinforcement can be determined with the help of zero extension characteristics which are thought to represent potential slip or rupture surfaces. The normal strain rates along these characteristics are zero but the normal stresses in the arc segment containing the minor principal strain direction $\emptyset_3$ are tensile.

The main application of the reinforced earth is in the reinforced earth wall. The wall consists of a facing element, reinforcement and the back fill. At the exposed vertical surface of the earth mass, facing are used to provide a sort of barrier so that the soil is contained. The facing units are generally fabricated from units which are small and light so that they can be easily transported and placed in position. These are usually made of steel, aluminium reinforced concrete or back fill, and should as such be easy to fasten to the reinforcement. The facing units generally require a small plain concrete footing at the bottom so that they can be easily built.

The reinforcement is connected the facing element and extended back into the back fill zone. The friction developed in the reinforcement restrains the facing element. First, a layer of reinforcement strips is placed at the level ground surface and the backfilling is done with a granular soil. The soil with less than 15% passing through No.: 200 sieve is used. The entire process of lying strips and backfilling is continued till the required height of the reinforced earth wall is attained.

Galvanized steel strips are commonly used as reinforcement. Each strip is about 50-100mm wide and several meters in length. The thickness is up to 9mm. Sometimes metal rods, wires and geotextiles are used as reinforcement.

In the design of a reinforced earth wall, the following assumptions are made (Swami, 2011):

i. The backfill is horizontal without any surcharge.
ii. The earth pressure acting on the facing element is the same as that acting on a rigid vertical face retaining concrete walls.
iii. Rankin’s earth pressure theory for active pressure holds.
iv. The failure plane makes an angle of$45^o + {}^{\emptyset}/_{2}$.

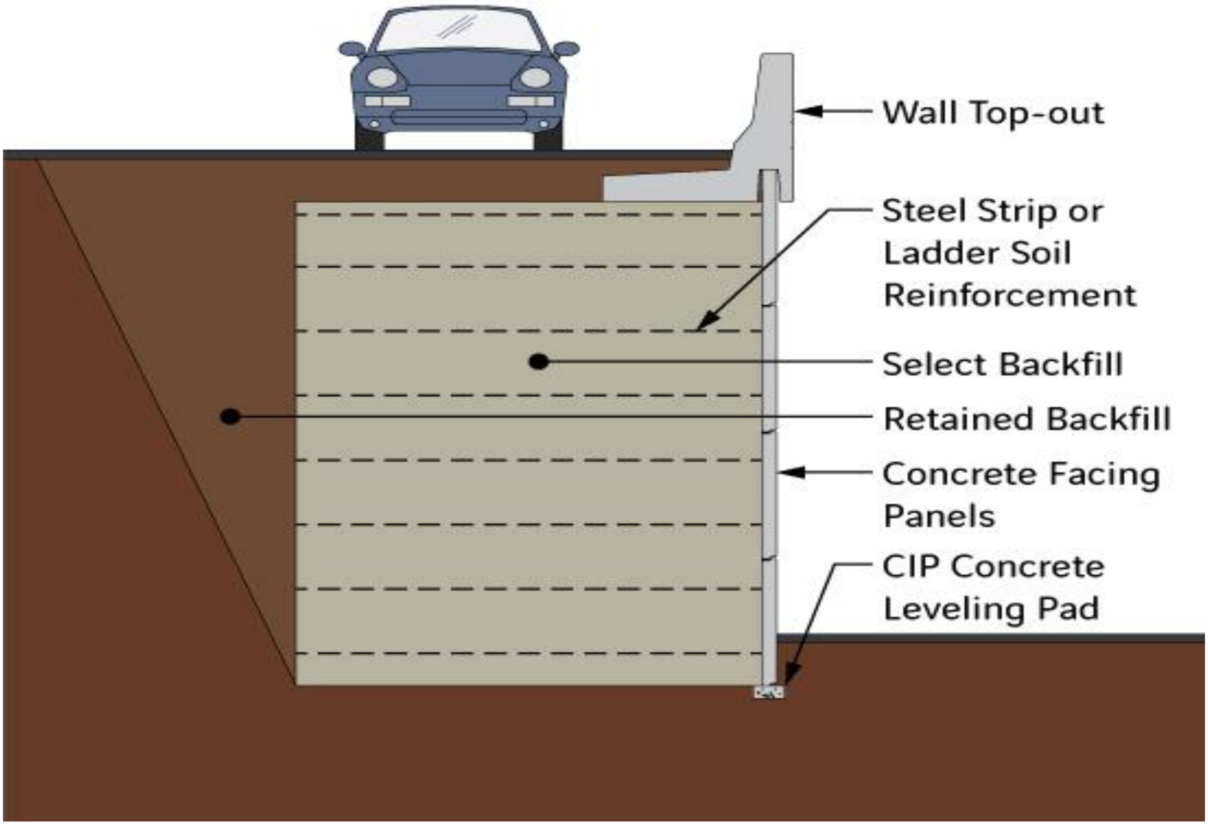

FIG. 8: Image of Reinforced Earth (**SOURCE**: Reinforcedearth.com)

9. **Thermal Stabilization**

Thermal changes have been proven to cause marked improvement in the properties of the soil. Thermal stabilization is done either by heating the soil or by cooling it:

a. Heating: As the soil is heated, its water content decreases, electric repulsion between clay particles is decreased and the strength of the soil is increased. When the temperature is increased to more than 100 ^{o}C, the "absorbed" water is driven off and the strength is further increased. When the soil is heated to temperatures of 400 ^{o}C to 600 ^{o}C, some irreversible changes occur which make the soil non-plastic and non-expansive. The clay clods are converted to aggregates. With further increase in temperature, there is some fusion and vitrification and a brick-like material is obtained (Arora, 2011) which can b used as an artificial aggregate for mechanical stabilization. This method of stabilization is quite expensive because of large heat requirement and is rarely used.
b. Freezing: Cooling causes a small loss of strength of clayey soils due to an increase in interparticle repulsion. However, if the temperature is reduced to the freezing point, the pore water freezes and the soil is stabilized with ice so formed acting as cement. Water in cohesionless soils freezes at about 0 ^{o}C. However, in cohesive soils water may freeze at a much lower temperature. The strength of the soil increase as more water freezes. This method of stabilization is very costly and used only in some special cases. It has been successfully used to solidify soils beneath foundations (Arora, 2011). The method is commonly used when advancing tunnels or shafts through loose silts or fine sand. Freezing may cause serious trouble to adjacent structures if the freezing front penetrates

these areas. It may cause excessive heaving and this method is used only after considering this impact.

10. Electrical Stabilization

Electrical stabilization of clayey soil is done by a process known as electro-osmosis with a direct current passed through a clayey soil causing pore water to migrate to the negative electrode (cathode). This is as a result of the attraction of positive ions (cation) that are present in water moving towards the cathode. The strength of the soil is considerately increased due to removal of water. Electro-osmosis is an expansive method originally developed for drainage of cohesive soil, but consequently improves the properties of the soil.

11. Use of Organic Stabilizers

A number of organic stabilizers have been used for chemical stabilization of soils, some of which are sodium silicate, lignin, resins, molasses, etc. Sodium silicates react in aqueous situations with soluble calcium salts forming insoluble and gelatinous calcium silicates. Calcium needed for the reaction can either be present in the soil itself or be added in aqueous solutions. The amount of chemical needed may vary from 1 to 10%. The natural binding material that holds together the fibres in wood is lignin.

The stabilization is by the cementing bond that develops between the soils particles due to the presence of binder. The material also closes the voids and thus reduces penetration of water through the layer. It retards the rate of evaporation of water and arrests loss of moisture. Molasses is a waste product from the process of manufacturing sugar from sugarcane. A thick syrupy liquid, it is hygroscopic and can be used as a dust palliative and as a binder for incorporation during compaction.

12. Complex Stabilization

This is defined as the method of stabilization with more than one stabilizer. Difficult soils such as organic soils, highly plastic clays and soils with easy soluble salts require more than one stabilizer for their effective treatment. Complex stabilizers involve the use of binding material and surface active addictives or electrolytes. At present, the following combinations are considered best:

i. Cement, calcium chloride and lime
ii. Cement and bituminous emulsions
iii. Cutback and lime
iv. Cement and naphtha soap

IMPACT OF STABILIZATION ON THE ENVIRONMENT

In the case of lime stabilization, the production of calcium-based material during its process involves the calcinations of calcium carbonate (Ibtehaj *et al.*, 2014), which takes place at high temperatures resulting in the production of a considerable quantity of carbon dioxide emission in addition to high energy consumption (Birchal *et al.*, 2000; Shand, 2005). Thus, the production of calcium-based additives affects the environment negatively.

Cement stabilization within aquatic region could result in an increase in the pH of the water which may affect plant growth and alter the species composition. This could have a subsequent impact on aquatic fauna. For fishes, although less susceptible to pH changes can be indirectly affected by the alteration of the food supply chain and the sedimentation of the water courses can smother fish eggs and damage fish gills through abrasion.

The handling and mixing of the soil-cement may result in a localized increase in dust particles. Fresh cement may contain traces of hexavalent chromium, a known allergen to certain individuals which may affect their health (Shell E & P, 2004).

Soils stabilized with the use of bitumen cannot support plant growth around its immediate adjourning regions but rather have harmful impact of the environment, making the land unsuitable for agricultural purposes. Water around the region becomes toxic and may be harmful to humans as well as animals and other aquatic organisms if taken. Consumption of such water may most likely cause certain water related diseases and even death in the case of animals (Ogedengbe, 2009).

These and many more are the adverse effects of soil stabilization using various means. Though some of these effects can be meditated, or remedied, proper considerations should be given to the effect of a chosen method of soil stabilization on the environment, both on a long term and short term bases.

CONCLUSION

One of the main problems facing the engineering field is dealing with poor soil during construction and techniques by which suitable soils may be improved through stabilization. Several stabilization techniques have different conditions governing them as well as their merits and demerits all of which should be considered before choosing any given method alongside its environmental impact. The economic benefits derived from the stabilization procedure will determine whether the stabilization process is warranted.

REFERENCES

Aboud, T. T.; Kasa, A. B.; and Chik, Z. B. (2007). "Stabilization of Silty Clay Soil using chloride compounds", JEST, Malaysia, Vol. 2, Pg. 102-103.

Arora, K. R. (2011). "Soil Mechanics & Foundation Engineering", Standard Publisher Distributors, seventh edition, Delhi.

Behzad, K. & Huat, B. B. K. (2008). "Peat soil stabilization using ordinary Portland cement, polypropylene fibres and aire curing", EJGE, USA, Vol. 13. Pg. 1.

Bell, A. L. (1993). "Jet Grouting", chapter seven, in-ground improvement M. P. Mosely, Ed., Chapman & Hall, London.

Birchal, V. S. S., S. D. F. Rocha & V. S. T. Ciminelli (2000). "The effect of Magnesite Calcination Conditions on Magnesia Hydration", Miner, Eng., **13** (14-15): 1629-1633.

Brown, R. E. & Glenn, A. J. (1976). "Vibroflotation & terra-probe comparison", *Journal of the geotechnical engineering division,* Vol. 102, No., GT10, pp. 1059-1072.

Craig, R. F. (1978). "Advanced Soil Mechanics, McGraw-Hill Book Co.

Dana (1994). "Soil stabilization for pavements", Army TM5-822-14 Air force AFJMAN 32-1019, USA, Chaps. 1-5.

Das, B. M. (1985). "Principles of Geotechnical Engineering", PWS-KENT Publishing Co., Boston.

Donald, P. C. (2007). "Geotechnical Engineering: Principles & Practices", Prentice Hall, India, New Delhi.

Gary, S. K. (2005). "Soil Mechanics & Foundation Engineering", sixth edition, Kharma Publishers, Delhi.

Gary, S. K. (2007). "Geotechnical Engineering. Soil Mechanics & Foundation Engineering", Khanna Publishers, seventh revised edition, New Delhi.

Graber, E. R., Fine P., & Levy, G. J. (2006). "Soil stabilization in semi-arid & arid land".

Ibetehaj, T. J., Mohd, R. T., Zaid, H. M., & Tanveer, A. K. (2014). "Soil stabilization using lime: Advantages, disadvantages and proposing a potential alternative", *Research journal of Applied Sciences, Engineering & Technology.*

John Atkinson. "The Mechanics of Soils & Foundation", McGraw-Hill Books.

Lambe, T. W. & Whitman, R. V. (1979). "Soil Mechanics S. I. Version", John Wiley & Sons, New York.

Lancaster-Jones, P. F. F. (1969). "Methods of improving the properties of rock masses, Chapter 12, pp. 385-429, rock mechanics in engineering practice, KG Stagg & OC Zienkiewiez (Eds.), John Wiley & Sons, London.

Maher, M. H. & Woods, R. D. (1990). "Static response of sands reinforced with randomly distributed fibres", Journal of geotechnical engineering, ASCE, **116** (7), 116-1131.

McCarthy, D. F (1986). "Essentials of Soil Mechanics & Foundation" Boston Publishing Co. Inc. Boston.

Mitchell, J. K. (1976). "Fundamentals of Soil Behavior", John Wiley & Sons, New York.

Murthy, V. N. S. (2007). "A textbook of Soil Mechanics & Foundation Engineer – Geotechnical Engineering Series", CBS Publishers & Distributors, New Delhi.

Ogedengbe, E. & Akinbile, C. O. (2009). "Environmental impact of Bitumen on soil, water & plant in Iodasa are, Ode-iriele, Ondo State, Nigeria". *Journal of Science & Technology,* Vol. 29, No. 1, April, 2009.

Onyelowe, K. C. (2011). "Geosynthetics and Geotechnical properties of soils in a developing world: A lesson for Nigeria", EJGE, USA, Vol. 16, Pg. 1481-1487.

Park, T. & Tan, S. A. (2005). "Enhanced performance of reinforced soil walls by the inclusion of short fibres, Geotextiles & Geomembranes", 23, 345-361.

Puppala, A. J. & Musenda, C. (2000). "Effect of fibre reinforcement on strength & volume change in expansive soils", Transportation research record, 1736, paper No.: 00-0716, 134-140.

Ramamurthy, T. (2014). "Engineering in rocks for slopes, foundation & Tunnels", PHI Learning, 3rd Edition, Delhi.

Santosh, K. G. (1987). "Soil Mechanics", Khanna Publishers, Delhi.

Shand, M. A. (2006). "The Chemistry & Technology of Magnesia", Wiley-interscience, New York.

Shell E & P, Ireland Limited (2004). "Peat Stabilization", Vol. 1, March, 2004.

Tingle, J. S., Santoni, R. S. & Webster, S. L. (2002). "Full Scale field tests of discrete fibre - reinforced soil", *Journal of transportation engineering* ASCE **128** (1), 9-16.

Whitaker, B. N. & Frith, R. C. (1990). "Tunneling, Design, Stability and Construction", the Institute of Mining & Metallurgy, London, UK.

www.wikipedia.org/wiki/soil-stabilization

Yetimoglu, T. & Inanir, O. E. (2005). "A study on bearing capacity of randomly distributed fibre-reinforced sand fills overlying soft clay", Geotextiles & Geomembranes **23** (1), 174-183.