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A Review of Stabilization of Soft Soils by Injection of Chemical Grouting

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Abstract: Soil stabilization has become one of the useful solutions to treat the soft soils to achieve the required engineering properties and specification so that structures can be placed safely without undergoing large settlements. The use of admixture such as lime, cement, oils and bitumen is one of oldest and most widespread method for improving soil. When mixed with soil, it forms a material called soil-cement. The original technique known internationally as the deep mixing method (DMM). It is an in-situ soil treatment technology whereby the soil is blended with cementitious and/or other materials. Jet Grouting is suitable to be used as the injection method for the DMM. It utilizes a fluid jet (air, water and/or grout) to erode and mix the in-situ soft or loose soils with grout. Chemical stabilization is the effective method to improve the soil properties by mixing additives to soils. Usually the additives are cement, lime, fly ash and bituminous material. The chemicals usually used are sodium silicate, acrylamide, N-methylolacrylamide, polyurethane epoxy resins, aminoplasts, phenoplasts, lignosulfonates, among others. The choice of a particular chemical for soil stabilization will depend upon many factors like, purpose, soil strength desired, toxicity, rheology among others. This paper is aiming to show the difference between the some famous chemical grouts and the usage of them in the field.

Key words:

INTRODUCTION

Soil stabilization is defined as a technique to improve the engineering characteristics in order to improve the parameters such as shear strength, compressibility, density, hydraulic conductivity. The techniques of soil stabilization can be classified into a number of categories such as vibration, surcharge load, structural reinforcement improvement by structural fill, admixtures, and grouting and other methods (Kazemian and Huat, 2010). There are many techniques that can be used for different purposes by enhancing some aspects of soil behavior and improve the strength and properties of soil (Edil, 2003). The important features of ground treatment includes: improving the bearing capacity of the ground, reducing the potential for total and differential settlement, reducing the time during which the settlement take place, reducing potential for liquefaction in saturated fine sand or hydraulic fills, reducing the hydraulic conductivity of the ground, removing or excluding water from the ground (Kazemian and Huat, 2009).

Deep Mixing Method (DMM):

It uses rotating mixer shafts, paddles, or jets that penetrate into the ground while injecting and mixing Portland cement or some other stabilizing agent. These techniques include deep cement mixing, soil mix walls, deep mixed method and other. The treated soil has greater strength, reduced compressibility and lower hydraulic conductivity than the original soil (Bromes et al., 1999; Raison, 2004).

Deep mixing method emphasizes on column type techniques using lime/cement. It is a soil improvement method, which is performed to improve the strength, deformation properties and hydraulic conductivity of the soil (Bruce, 2000). It is based on mixing binders, such as cement, lime, fly ash and other additives, with the soil by the use of rotating mixing tools in order to form columns of a hardening material since pozzolanic reactions between the binder and the soil grains are developed. The main advantage of these methods is the long-term increase in strength, especially for some of the binders used (Anagnostopoulos and Chatziangelou,

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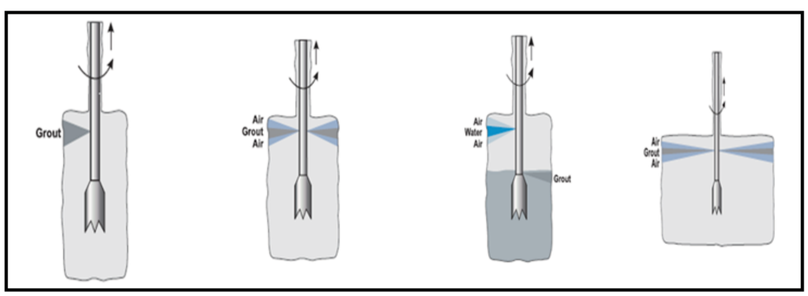
2008). Pozzolanic reaction can continue for months or even years after mixing, resulting in the increase in strength of cement stabilized soil with the increase in curing time (Bergado, 1996; Hashim and Islam, 2008).

Grouting and Injection Method:

Typically, grouts that are continually moving will turn into a gel less quickly, and the penetration from continuous injection will be greater than that from the same volume of grout used in batch injection. When gelling occurs before pumping is halted, the last injected grout typically moves to the outside of the grouted mass, and both large and small openings are filled (Kazemian and Huat, 2010). Jet Grouting is suitable to be used as the injection method for the deep mixing method (DMM). It utilizes a fluid jet (air, water and/or grout) to erode and mix the in-situ soft or loose soils with grout. It utilizes high velocity, 28 to 42MPa backpressure and jet to hydraulically shear the soil and adding suitable binder to form a column. The result is significantly increased shear strength and stiffness of the soil (Mitchell and Jardine, 2002). The first patent regarding jet grouting was applied for in England in the 1950s; however, the actual development of jet grouting was in Japan during 1960s and 1970s. Jet grouting is the newest method compared with other methods. In the mid 1970s, jet grouting was exported to Europe and has become popular worldwide. This technology was initially aimed at improving the effectiveness of water tightness, in chemical grouting, by eroding the untreated or partially treated soil, which was then ejected to the surface for disposal being replaced with cement-based slurry for imperviousness (Moseley, 2000; Moseley and Kirsch, 2004).

Jet grouting is the construction of hard, impervious column in the ground by the enlargement of a drill hole using rotating fluid jets to liquefy and mix grout with, or to excavate and replace, soil (Raison, 2004). Jetting and grouting are carried out during controlled withdrawal and rotation of the drill string and the jetting head from the hole. There are several variations depending on the nature and pressure of the jetting and grouting the in-situ soil may be mixed with the grout, partly mixed and partly removed or wholly replaced. In general, as shown in Figure 1 and 2, there are four basic jet grouting systems which are widely used and classified as Single phase (grout injection only), Dual phase (grout + air injection), Triple phase (water + air injection and followed by grout injection), Super Jet Grouting (air injection + drilling fluid by grout injection) (Keller, 2009; Kazemian and Huat, 2010).



Single phase Dual Phase Triple Phase Super Jet grouting

Fig. 1: The System in Jet Grouting (Keller, 2009)

3. Chemical and Cementation Grouts:

Chemical stabilization is the effective method to improve the soil properties by mixing additives to soils. Usually the additives are cement, lime, fly ash and bituminous material. These additives enhance the properties of soil. Generally, two major reactions for the chemical stabilization are cation exchange reaction and cementation (Mitchell, 1993). The common chemical agent for cementation process is Portland cement, lime, fly ash, sodium silicate polyacrylamides and bituminous emulsion.

Kazemian and Huat (2010) stated that, many of chemical grouts are based on the combination of sodium silicate and a reagent to form gel. The Joosten process used in coarse granular soils uses calcium chloride as a reagent. Other reagents are organic ester, sodium aluminates and bicarbonates. The reagent and the proportion can be chosen to control the gel time, the initial viscosity and the order of strength of the grouted soil.

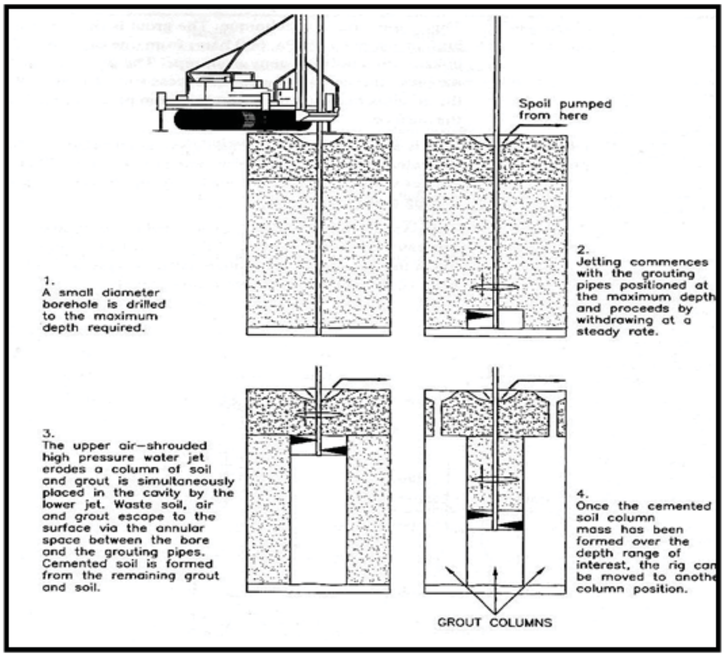


Fig. 2: Procedure for forming a jet grouted column by triple system (Rawlings, 2000)

Chemical grouts are injected into voids as a solution, in contrast, to cementitious grouts, which are suspension of particle in a fluid medium. The difference between chemical grout and cementitious grout is the chemical grout can be used to fill the finer voids of soil particles up to 10 to 15ηm in diameter. In other word, it has better penetration ability than the cementitious grout (US Army Corps of Engineers, 1995).

Chemical grout can be classified in single step and two step processes. In one step process, all the ingredients are premixed prior to injection, the system are designed that the reaction takes place in-situ. In the two step process, the initial chemical is injected into soil mass then follow by the second chemical material to react with the first in-situ and to stabilized the mass. There are several types of chemical grouts, each type of grout have different characteristics and different applications. The most common are sodium silicate, acrylate, lignin, urethane, and resin grouts (Shroff and Shah, 1999).

3.1. Sodium Silicate System:

Sodium silicate grouts are most popular grouts because of their safety and environmental compatibility. It has been developed into various grout system such as silicate chloride amide system, among others. Most of the systems are based on the reacting a silicate solution to form a colloid which polymerizes further to form a gel that binds the soil particles. The silicate solution concentration that may be used in grouting is in range of 10 to 70 percent by volume, depending on the material being grouted and the desired result to achieve. For a system of using amide as reactant, the amide concentration may vary from less than 1 to greater than 20 percent by volume. In practice, the amide concentration ranges between 2 to 10 percent (US Army Corps of Engineers, 1995).

The initial minimum viscosity of a grout that can produce a gel has a SiO_2:Na_2O ratio of 3.6 with a pH value of 8.5 to 9.2 for a given dilution within an ideal framework of gel time. The rate of reaction and strength of gel are directly proportional to the concentration of silicate and catalysts in the grout at constant temperature respectively (Shroff and Shah, 1999). Sodium silicate is noncorrosive to metals. Reactants such as amide and their water solutions will attack copper and brass, but they are noncorrosive to aluminates and stainless steel. The chloride solutions are not corrosive to iron and steel in the sense that acids are; however, if steel in a chloride solution is exposed to air, rusting will occur at the junction of the liquid and air. Bicarbonate is noncorrosive (US Army Corps of Engineers, 1995).

3.2. Silicate Chloride Amide System:

The silicate chloride amide system is one of the widely use silicate grout system containing sodium silicate as a gel forming material. The silicate aluminates-amide system has been used for strength improvement and water cut-off. Its behaviour is similar to the silicate-chloride-amide system but is better for shutting off seepage or flow of water. The cost is slightly higher, and this system can be used in acidic soils. Amide will act as a reactant and the calcium chloride, sodium aluminates will be used as the accelerator. These reagents bring an almost instant setting time and produce very low penetrability type gel that are unsuitable for permeation treatments (Rawlings, 2000).

The function of the accelerator is to control gel time and impart strength to the gel. The effect of the accelerator is important at temperatures below 37 °C and increases in importance as the temperature decreases. Excessive amounts of accelerators may result in undesirable flocculation or formation of local hardening. This causes variations in both the gel and setting times that would tend to plug injection equipment or restrict penetration, resulting in poorly grouted area. Therefore, a retarder should be added in the mixture for delaying the setting time and formation of gelation (US Army Corps of Engineers, 1995). Table 1 shows different rheology parameters of silicate grout in different concentration.

Table 1: Physical properties of chemical grouts (US Army Corps of Engineers, 1995)

Class	Example	Viscosity (cP)	Range of gel time (s)	Specific gravity	Strength (kPa)
Silicate (low concentration)	Silicate-Bicarbonate	20	0.1-300	1.02	Under 345
Silicate (high concentration)	Silicate- Chloride	4-40	5-300	1.10	Under 3450
		30 -50	0	-	Under 3450

3.3. Comparison of Chemical Grout Properties:

Over the last 30 years, a few hundred different compounds of chemical grout are available. However, the origin of chemical grout still remains a few types such as silicates, acrylamide, epoxy, and some fatty acid derivates. Generally, chemical grouts are intended to penetrate and fill narrow joints or soils with very small pore size. Basically, the comparison will made according to the penetrability of grout in soil and the range of curing time for each type of grout (Magill and Berry, 2006).

3.4. Acrylamide:

Acrylamide based grouts come closest to satisfying the attributes of an ideal grout. They show easy penetration and maintain their initial viscosity until at the very end of the gelling stage when they rapidly set. They have good gel time control and adequate strength for most applications (Karol, 1990). The grout exhibits good penetrability, with a constant low viscosity during induction period and better gel control with adequate strength. However, it is highly toxic and unsuitable for potable water application (Shroff and Shah, 1999). Acrylamide has a low chemical resistance toward acidity condition; therefore, it is not suitable for application in peat because peat is acidic in nature. The new acrylate gels are suitable for works that require low viscosity and a well controlled gel time, however, the cost is higher than sodium silicates (Nonveiller, 1989).

3.5. N-Methylolacrylamide:

N-Methylolacrylamide (NMA) is inert and essentially non-toxic if properly catalyzed. So it is better than acrylamide grout. However, NMA has an extremely low viscosity with about 1 to 2 cP. The viscosity is similar to that of water; therefore the pumping flow rate will be same as the water. It has low stability under constant head pressure of the groundwater and is especially bad where acidic conditions and organic contaminants are present. The gel time is affected by the temperature and catalyst concentration. Acrylate grout is rarely used in geotechnical field since the gel will swell considerably in the presence of water. As a result, strength of the grout will further reduce since existence of water will dilute the concentration of grout (Magill and Berry, 2006).

3.6. Polyurethane:

Polyurethane chemical grout is composed of two components of water activated material called hydrophobic and hydrophilic resin. However, many of other type resin are produce base on these two resins. The viscosity of grout is very high with is range from 300 to 2500cPs. The limitation is that the pH of water will affect the reactivity of grout. A higher pH value with more than pH 7 will increase the activity of grout. Thus, it is favorable for the alkaline soil and unsuitable for the acidity soil like peat. Besides, the gel time of the polyurethane is controlled by the molecular weight, intermolecular forces, and stiffness of chain units, crystallization and cross linking (Vinson, 1970). The polyurethane is toxicity in nature, so, it mostly applicable in forming to block water inflow (water reactive resins).

3.7. Epoxy Resins:

Epoxy resins are liquid pre-polymers with hardening agent, they usually exhibit very high tensile, compressive and bond strength. Generally epoxy resins will have either good chemical resistance or good heat resistance (Magill and Berry, 2006). The low viscosity has a better penetrability but greater shrinkage and less strength due to the weak bonding lead to more subsidence, whereas the high viscosity may better if adequate pressure is maintained long enough to permit the grout filling into small void (Erickson, 1968). However, the epoxy is one of the resins types which are toxicity nature and a special care during the handling (Rawlings, 2000).

3.8. Aminoplasts:

Aminoplasts consist of urea and formaldehyde. The rapid grout reaction in hot and acidic environments makes this product difficult to handle. An intermediate stage between liquid and solid urea-formaldehyde is used instead of the pure liquid phase. Aminoplasts with formaldehyde and acid catalyst contents are toxic and corrosive. Aminoplasts contain formaldehyde and an acid catalyst, which are both toxic and corrosive. In the gelled state, the aminoplast may contain leachable, unreacted formaldehyde. It is suitable for ground with pH less than 7 (Karol, 1990)

3.9. Phenoplasts:

Phenoplasts are "polycondensates resulting from the reaction of a phenol on an aldehyde." There are several factors that control the phenoplast gel time including pH. For any given solution concentration, a pH slightly above 9 achieves the shortest gel time. Nonetheless, a catalyst, usually sodium hydroxide, is required to control pH. Another variable factor affecting gel time is the diluted grout concentration. Initial viscosity for field work ranges from 1.5 to 3 cP. The strength of phenoplasts is comparable to the high-concentration of silicates. Phenoplasts are less sensitive to the rate of testing strain than other grouts, and their creep endurance limits comprise a greater percentage of their unconfined compression values. However, phenoplasts are toxic. The phenol, formaldehyde, and alkaline base are all health hazards and environmental pollutants.

3.10. Lignosulfonates:

Lignosulfonates are waste by-products of wood processing in paper manufacturing. Though the grout is non-toxic by itself, both in its original liquid state and dried form, the sodium dichromate additive is highly toxic (Nonveiller, 1989). If the lignosulfonate is acidic (pH < 6), no additive is required. Acids and acid salts are used only to control pH > 6 (Karol and Dekker, 1983). The grout has a viscosity range between 3 to 8 cP with strength comparable to acrylamide grouts (Nonveiller, 1989). However, it is highly toxicity and not suitable used in domestically.

4. Decision on Choosing the Grout:

In order to choose a grout type, several properties of grout should be concerned such as rheology, setting time, toxicity, strength of grout and grouted soil, stability or permanence of the grout and grouted soil and the penetrability and water tightness of the grouted soil (Rawlings, 2000). Moreover, the spreading of grout plays an important role in the development of grouting technology. In the actual filed, the grouting method requires a extensive consideration on the grout hole equipment, distance between boreholes, length of injection passes, number of grouting phases, grouting pressure and pumping rate (Shroff and Shah, 1999). According Table 2 and Figure 3, some clue can get for selecting the grouts.

5. Conclusions:

Soil stabilization has become one of the useful solutions to treat the weak soils to achieve the required engineering properties and specification so that structures can be placed safely without undergoing large settlements. The treated soil has greater strength, reduced compressibility and lower hydraulic conductivity than the original soil. Based on the review of articles, the following conclusions can be drawn:

- Due to the scarcity of construction land in urban areas, soil stabilization has become one of the useful solutions to treat the soil so that structures can be placed safely without undergoing large settlements.
- Selecting the right method for deep soil stabilizing however, depends on several conditions like the type and alternative layers of soil, load size, the situation and type of project, among others.
- Compared with other similar ground improvement methods, the DMM is the method specially designed to treat the soft soils.
- Chemical stabilization is the effective method to improve the soil properties by mixing additives to soils.

- The additives used in chemical stabilization are cement, lime, fly ash and bituminous material. Many of chemical grouts are based on the combination of sodium silicate and a reagent to form gel.
- The chemicals usually used are sodium silicate, acrylamide, N-methylolacrylamide, polyurethane epoxy resins, aminoplasts, phenoplasts and lignosulfonates.
- The choice of a particular chemical for soil stabilization will depend upon many factors like, purpose, soil strength desired, toxicity, rheology among others.

Table 2: Ranking based to Toxicity, Viscosity and Strength. (Shroff and Shah, 1999)

Grouts	Toxicity	Viscosity	Strength
Silicate			
Joosten process	Low	High	High
Siroc	Medium	Medium	Medium- High
Silicate –Bicarbonate	Low	Medium	Low
Lignosulphates			
Terra Firma	High	Medium	Low
Blox- All	High	Medium	Low
Phenoplasts			
Terramier	Medium	Medium	Low
Geoseal	Medium	Medium	Low
Aminoplasts			
Herculox	Medium	Medium	High
Cyanaloc	Medium	Medium	High
Acrylamides			
AV-100	High	Low	Low
Rocagel BT	High	Low	Low
Nitti- SS	High	Low	Low
Polyacrylamides			
Injectite 80	Low	High	Low
Acrylate			
AC- 400	Low	Low	Low
Polyurethane			
CR-250	High	High	High

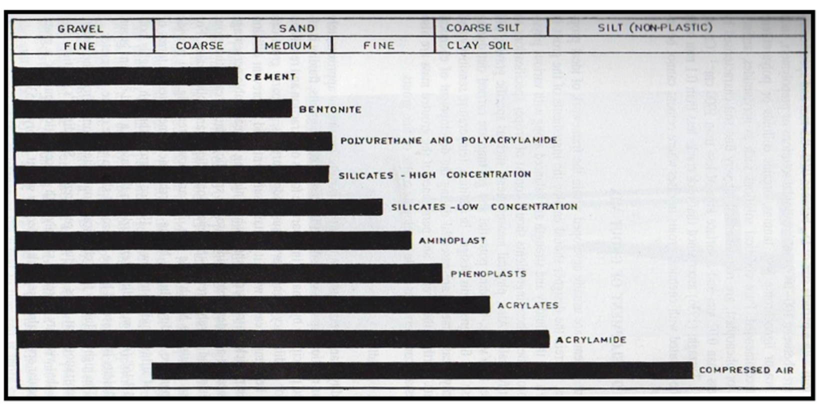


Fig. 3: Penetrability of various grouts (after Karol and Dekker, 1983)

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