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Grout Expectations

Description of and applications for grouts used in the civil engineering field.

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INTRODUCTION

Soils with low strength or high permeability properties may not be desirable for an excavation project and for use as a structural support. A weak slope may fail and injure construction workers. Excessive seepage into an excavation area creates a nuisance and limits the ability of workers to proceed with construction. Various soil remediation techniques using mechanical means, one of which is replacing the poor soil with better quality compacted soil, can enhance soil properties. Despite their simplicity, mechanical methods may not be feasible in certain situations. Excessive construction noise and vibrations may be a nuisance for the nearby community. In cases where the ground surface and building must remain relatively undisturbed, mechanical remediation methods are unacceptable. Time and cost constraints may limit their use as well.

Grouting methods are applied as alternatives to mechanical methods for ground improvement. There are several grouting categories -- 1) compaction, 2) jet, 3) soil fracture, and 4) permeation. The first three are covered as a topic of interest, but permeation grouting will be the main focus in this report.

GROUTING METHODS BY MECHANICAL MEANS

Grouting is the injection of a fluidized material into the soil to enhance its strength, density, or to reduce its permeability. Grouting can be more feasible than the cut and cover method, for example, excavating a trench to put in a tunnel lining and filling in the gap with soil. In the city, traffic may have to be rerouted around the cut and cover project site. For a grouting operation that requires a smaller construction area, moderate traffic can continue through, minimizing the bottlenecking effect on other city routes (Karol, Chemical Grouting, p. 351).

Grouting is used to create foundation curtains that reduce water seepage loss under structures, to halt the settlement of existing structures; to cut off water infiltration into excavations and sewer lines, to strengthen tunnel walls and shafts during construction; to relevel leaning structures built on poor foundations; to anchor reinforcing cables in precast-prestressed concrete structures; and to remediate leaky sheet-pile interlock seals. (See Figure 1 for examples)

COMPACTION GROUTING

Compaction grouting is the high pressure injection of a thick grout into subsurface soils. The grout consists of silty sand or silty gravely sand, cement, and water with a bentonite or clay additive that facilitates pumping. Because of the high grout viscosity, the grout expands radially as a homogenous bulb from the injection point instead of permeating into the soil pores. During injection, the bulb displaces and compacts the surrounding loose soil (Byle and Borden, pp. 6-8), which increases the soil's shear resistance in both the horizontal and inclined directions. Compaction grouting is suitable for reducing the potential for soil liquefaction, for arresting foundational settlement, and for lifting and leveling structures (Ledbetter, pp. 22-23).

JET GROUTING

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>>end of page 1

Jet grouting uses a high velocity and highly pressurized cement slurry jet that hydraulically cuts the soil and mixes it with the grout in-situ. The equipment consists of a jet grouting drill and a pumping unit. Cement slurry injection continues as the rotating drill moves upward away from the bottom of the drill hole, leaving behind a stabilized column

of slurry. Subsequent injections result in a set of interconnected columns that form either a solid block or a series of panels of grouted soil. Applications include structural underpinning, excavation support, anchoring, hazardous waste containment, groundwater control, slope stabilization, erosion protection, and wall support for various shaft and tunneling projects (Byle and Borden, p. 16).

SOIL FRACTURE GROUTING

Soil fracture grouting is the process of creating controlled subsurface ground fractures that are injected with a thick grout. The method densifies the ground, decreases local permeability, creates hardened grout lenses that stiffens and strengthens soil, and lifts or prevents settlement of footings next to an excavation, such as a tunneling operation (Byle and Borden, pp. 18-19).

PERMEATION GROUTS

Permeation grouts are placed into the soil void spaces by high pressure injection through boreholes. A stabilizer added to the grout controls set time. The grout bonds with the soil particles, producing a composite with higher shear and compressive strengths than the ungrouted formation. Permeation grouting also reduces the soil permeability by filling up the voids. (Hausmann, p. 347). Like the other grouting methods, permeation grouting is done within the soil. However, permeation grouting does not use mechanical means to restructure the soil in the process. The soil structure remains relatively undisturbed. Consequently, the operation creates minimal ground disturbances and better ensures against adverse deformation and damage to the ground formation.

Permeation grouts fall into two categories -- suspension grouts and solution grouts. The suspension grouts are known also as cement based grouts, which are dispersions of cement particles and solids distributed in a water medium. Solution grouts are chemically based grouts, which are homogenous molecular mixtures of two or more substances. These include sodium silicates, organic resins, and others (Hausmann, p. 351). Generally, the limited penetration range of cement grouts make them effective only in coarse grain sized soils whereas chemical grouts can penetrate into soil ranges of finer grain sizes.

(See Figure 2 for illustrations on Soil Grouting Methods)

CEMENT GROUTS

The primary cement grout components are water and Type I or Type II Portland cement. Cement grout properties are variable. They can be altered by using other cement types, such as Type III (high early strength), Type IV (low heat of reaction), or Type V (resistance to chemical attack). Varying the water to cement ratio changes the grout's bleeding rate, subsequent plasticity, and ultimate strength (Littlejohn, p. 35). Mixing in an additive, such as bentonite, sodium silicate (a chemical grout), dispersants, retarders, and accelerators, will also alter grout properties (Byle and Borden, p. 14).

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Microfine cement is a new version of cement that overcomes the difficulty of using Portland cement grouts in low permeability soils. The penetration range for microfine cement is approaching or equal to that of chemical grouts. Combined with water and an added dispersant, microfine cement can set in 4 to 5 hours. A sodium silicate additive in the mixture yields a rapid setting time of 1 to 3 minutes. MC-100, MC-300, and MC-500 are microfine cements that have varying soil penetration ranges (Karol, Chemical Grouting, pp. 429-431).

CHEMICAL GROUTS

Chemical grouts constitute the other branch of permeation grouts . Like the cement grouts, the chemical grouts enter the soil by penetration. However, chemical grouts can penetrate into finer grained soils otherwise inaccessible to cement grouts. Chemical grouts can be divided into two chemical categories of different molecular substances: (1) silicate grouts (inorganics), and (2) organic grouts. Silicate grouts are derivatives of silica in the form of SiO_2.

Organic grouts contain carbon compounds (Clifton, p. 12).
The primary design objectives of chemical grouts are ground improvement and water seepage retardation. Applications include shoring and seepage control for tunneling projects and excavation pits, eliminating infiltration into or exfiltration through underground pipes, sealing sheet-pile interlocks, etc.

PRELIMINARY STEPS FOR THE GROUTING PROCESS

Selecting permeation grouting as a remediation method depends on the design criteria. Addressing these issues is the first step.

-Is seepage reduction the purpose?
-Is soil stabilization required?
-Must the remediation be permanent?
-Is the work space for the remediation project limited in area?
-Compared to other techniques, is permeation grouting the most feasible?

PERMEATION GROUT SELECTION

After deciding to use permeation grouting for a project, the engineer must select the grout type that the ground would easily accept. Groutable soils are those "which will, under practical pressure limitations, accept injection of a given chemical [or cement] grout at a sufficient flow rate to make the project economically feasible" (Karol, Chemical Grouting, p. 210). Groutable soil characteristics depend on the grain size distribution and on the intrinsic soil permeability, that is, the ease with which water is transported through a mass.
An understanding of soil structure and soil properties would provide better insight into the relationship between grain size distribution and intrinsic soil permeability. Soil consists of solid particles, voids, and water distributed in a matrix. The configuration of the solids and non-solids affects the soil's strength and permeability. Ideally, for a granular soil mass such as

>> **end of page 3**

sand, closely interlocking grain particles have a tendency to better resist sliding over each other. In this scenario, the soil's shear strength (resistance to undergo relative displacements) is very high (Karol, Chemical Grouting, p. 281). However, since soil contains both voids and water, this gap between particles reduces the shear strength. An artificial adhesive filler, such as grout that fills up empty and water entrained voids, would provide the additional force to better hold the soil matrix, enhancing its strength. If it effectively reduces the seepage through the voids, the grout also reduces the soil's permeability.
High permeability and coarse grain size ranges are suitable for suspension, or cement grouts. Chemical grouts are more effective for the low permeability and fine grain size ranges. Generally, cement grouts are effective in materials no finer than sands whereas chemical grouts would can still be effective in some silts.(See Figures 3 and 4) For soils containing a mixture of both coarse and fine grains, either cement or chemical grouts can be used, depending on additional factors, such as relative cost of materials, design objectives, and product availability (Karol, Chemical Grouting, p. 48).

GRAIN SIZE DISTRIBUTION

Void size dictates the grout type that can be used. In practice, the average void size must be at least three to ten times larger than the maximum particle size in the grout medium (Karol, Grouting in Geotechnical Engineering, pp. 565-566) otherwise injection becomes difficult. Void size is dependent on grain size. Large particle sized soils tend to have bigger voids than small particle sized soils.
A sieve analysis performed according to ASTM-D422 specifications will yield a grain size distribution curve. The curve aids in identifying the soil type of the sample and in determining whether or not the sample is groutable. The technique involves breaking down a field cored sample into gradated particle sizes by mechanically sorting the sample

through a stack of graduated sized sieves (Sowers and Sowers, pp. 19-20).
A sample sometimes may appear to be composed of mostly uniform grain sizes, but soil naturally contain particles of various grain sizes. Silty-sands or clayey-silts combinations exist. Though a soil type may appear to be groutable in general for a particular grout, there are exceptions because of the soil's heterogeneous nature. According to Reuben H. Karol in Chemical Grouting, soils in which the silt content exceeds 20% can make grouting difficult. (See Figure 5) Dense silts are difficult to grout. Silty clays are ungroutable (Karol, Chemical Grouting, p. 209).

Perform sieve analysis

PERMEABILITY FACTOR

The permeability of the soil also determines whether or not grout injection will be feasible. In-situ field permeability tests give more accurate results than lab permeability tests performed on representative field samples. Laboratory test results often have systematic errors. Furthermore, undisturbed cohensionless soil samples are difficult to obtain since they fall apart easily. In this case, a field permeability test is more appropriate. Permeability is measured in cm/sec expressed by the variable k:

$k = 10^{-6}$ or less: ungroutable
$k = 10^{-5}$ to 10^{-6}: groutable with difficulty by grouts under 5cP viscosity^{+} and ungroutable for higher viscosities

>> end of page 4

$k = 10^{-3}$ to 10^{-5}: groutable by low-viscosity grouts but with difficulty when k is more than 10 cP
$k = 10^{-1}$ to 10^{-3}: groutable with all commonly used chemical grouts
$k = 10^{-1}$ or more: use suspended solids grout or chemical grout with a solids filler

(Karol, Chemical Grouting, p 210)

$^{+}$(1cP=10-3 Pa*s = 0.01 dyne*s/cm2) (Hausmann, p. 352), see section under viscosity for the definition

FIELD PERMEABILITY TESTS

Packer Test

One field permeability test method is the double packer test. A range of permeability values for segregated lengths along the drill hole can be obtained by using an inflatable double packer. (See Figure 6) An inflated double packer looks like a large dumbbell. During the test, the double packer creates a watertight seal in a region within the drill hole, and water is pumped through an inlet tube into that segment. Flow and pressure measurements are taken to calculate k (Karol, Chemical Grouting, p. 212-215).

Well Pumping Test

Another field permeability test method is the well pumping test. When pumping reaches equilibrium levels, field measurements are taken at the main well and at the observation wells. The data is used in an equation to calculate the permeability. (Karol, Chemical Grouting, p. 211)

<u>CHEMICAL GROUT TYPES</u>

Since about 1970, silicate and acrylamide-based grouts share a market percentage in the United States estimated at between 85% and 90%, with the remaining portion of the market divided among other products. Chemical grouts fall into the following categories:

1. Silicate formulations
2. Acrylics (includes acrylamide and acrylate grouts)

3. Lignosulfonates
4. Phenoplasts
5. Aminoplasts
6. Other materials

(Karol, Chemical Grouting, pp. 66-67)

SILICATE FORMULATIONS

The largest single group of related grouting materials is the silicate derivatives -- fluorosilicates, silicon esters, methyl silicate, and sodium silicates. Only sodium silicate (SiO_2*Na_2O) is used to any extent for chemical grouting. Sodium silicate is basic (pH > 7) (Karol, Chemical Grouting, pp. 67-68). Known also as "water glass," sodium silicate is prepared by heating sand or

>> end of page 5

any form of silica with Na_2CO_3 at around 900°C. After passing through the refinement process, sodium silicate becomes a viscous solution. Dilution with water yields various concentrations to suit client needs (Clifton, p. 24).

The grout gels by neutralization with the addition of an acid or salt acid reactant. Both the grout and reactant can be diluted with water, making the mixture more manageable to grout. Dilution slows down the reaction that otherwise with high concentrations would be too rapid for practical purposes.

For sodium silicates in particular, the silica/alkali ratio (SiO_2/Na_2O) quantifies the grouting suitability. A solution that bonds well to the soil after setting falls in the silica/alkali ratio range between 3 and 4, with 4 and above being unstable (Karol, Chemical Grouting, pp. 67-68). An unstable solution tends to "bleed," that is, the solids and liquid separate when the grout becomes stationary (Hausmann, p. 354).

Commercial Products

For a period since its introduction in 1960, the trade name SIROC was the most widely used sodium silicate grout in the United States. In the SIROC system, an accelerator or cement is generally used in conjunction with the silicate and reactant (Karol, Chemical Grouting, p. 69), commonly formamide. Other commercial sodium silicates are GELOC-4, TERRASET, and HARDENER 600. These three grouts are currently wide used non-toxic sodium silicates that uses organic esters as reactants (Baker, p. 521).

Research and development on sodium silicates has continued in Japan since 1974 (Yonekura and Kaga, p. 726). Japanese publications discuss new aspects in chemical grouting with sodium silicates.

Toxicity Concerns

Sodium silicates are generally considered to be non-hazardous to health and environmentally safe. The organics used as reactants may be toxic, corrosive, or have an unfavorable effect on the environment (Karol, Chemical Grouting, pp. 80-82). Japanese literature indicates that silica sol, colloidal silica, and activated silica are non-pollutants and non-hazardous (Yonekura and Kaga, p. 726).

ACRYLICS

Appearance of acrylamide grouts began in 1953 with AM-9 in the US. This chemical grout starts out as a white powder consisting of a mixture of two organic monomers (single-chained molecular units) which polymerizes (causes the chemical units to link up) into long molecular chains at ambient temperature. The water content comprises (87-97%) of the grout by weight. AM-9 can have a viscosity lower than 2cP. AM-9 uses ammonium persulfate as a catalyst, trietanolamine as an activator, and potassium perricyanide as an inhibitor (Nonveiller, p. 67).

Toxicity Concerns

Acrylamide grouts are neurotoxic. Laboratory experiments indicate that it is carcinogenic in animals. Skin contact with acrylamide is extremely hazardous since it is readily absorbed through the skin. Chronic occupational exposure to the chemical is a hazard because of its high degree of cumulative toxicity. Exposure causes muscular weakness and disequilibrium and locomotion disorders. 56 cases of acrylamide poisoning have already been reported by workers exposed to the chemical. Despite the toxicity, field experiments show that with proper ground placement, a 10%

solution of acrylamide gel would contain

>> end of page 6

a concentration of only 0.02% free acrylamide or less, which is low enough to be non-hazardous (Karol, Chemical Grouting, pp. 88-104).

Commercial Names

The Japanese produced Nitto SS, marketed as AV-100 in the U.S., and the French marketed Rocagil BT. Nitto SS had the same toxicity as AM-9; Rocagil BT had half (Karol, Chemical Grouting, pp. 88-104).

In 1979, the U.S. manufacturer of AM-9 ceased production of its product because of a reported case of neurotoxicity poisoning in Japan in 1974 due to the careless use of an acrylamide (Clifton, p. 8). Replacing it was the less toxic AC-400, a mix of acryl monomers, that had the same properties as its predecessor. The new acrylate gels are suitable for works that require low viscosity and well controlled gel time. Cost, however, is higher than sodium silicates (Nonveiller, p. 67).

Applications

Acrylamide based grouts come closest to satisfying the attributes of an ideal grout. They show easy penetration. They 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, Chemical Grouting, pp. 87-88).

The acrylamides, then later, the acrylates are used to seal leaky sewer joints. In old cities where pipes are more than 40 to 50 years old, groundwater infiltration make up over half the sewer line flow. As the pipes get older, infiltration into the pipes grow, forcing wastewater treatment plants to expand to handle the excess flow or forcing the city to replace leaky sewers. Replacing sewers and expanding a treatment plant are costly jobs. A quicker and cheaper method is impermeabilizing the zone surrounding the leaky pipe joint with chemical grout. (See Figure 7) The method is effective for pipes as small as 4 inches and up to 24 inches in diameter. Video monitoring equipment and proper grouting equipment enable sewer rehabilitation specialists, such as CUES and National Power Rodding Company, to provide good quality assurance (Karol, Chemical Grouting, pp. 336-337).

>> end of page 7

LIGNOSULFONATES

Lignosulfonates are waste by-products of wood processing in paper manufacturing. Lignosulfonate composition depends on the wood type and the manufacturing method. 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, p. 67). If the lignosulfonate is acidic ($pH < 6$), no additive is required. Acids and acid salts are used only to control $pH > 6$ (Karol, Chemical Grouting, p. 113). The grout has a viscosity range between 3cP to 8cP with a strength comparable to acrylamide grouts (Nonveiller, p. 67).

Toxicity Concerns

Hexavalent chromium, a highly toxic substance in the gel, may leach into the environment at levels exceeding the U.S. Public Health Service limits. Sodium dichromate salt and the benzene type molecules in lignosulfonates are also highly toxic. Lignosulfonates are not currently used domestically (Karol, Chemical Grouting, p. 123).

Commercial names

A lignosulfonate product called Terra Firma had disappeared from the marketplace. (Karol, Chemical Grouting, p. 119).

PHENOPLASTS

Phenoplasts are "polycondensates resulting from the reaction of a phenol on an aldehyde." According to The American Heritage Dictionary, a phenol is "[a] caustic, poisonous, white, crystalline compound, C_6H_5OH, derived from benzene and used in various resins, plastics, disinfectants, and pharmaceuticals," and an aldehyde is "any of a class of highly reactive organic chemical compounds obtained by oxidation of primary alcohols."

There are several factors that control the phenoplast gel time. pH affects setting time. 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 3cP. Like the acrylics, phenoplasts maintain a steady viscosity and gels rapidly in the end.

Phenoplasts set in high temperature environments. At ambient temperatures, phenoplasts require an acid medium to set. However, some grouts can react in ambient temperatures without an acid medium. One of these is resorcinol, which is used with formaldehyde.

The strength of phenoplasts is comparable to high-concentration 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.

Toxicity Concerns

Phenoplasts are toxic. The phenol, formaldehyde, and alkaline base are all health hazards and environmental pollutants. At low atmospheric conditions, formaldehyde causes chronic respiratory problems. Gels are generally inert, but improper mixture proportioning could allow unreacted substances to leach into the environment.

Commercial Products

Commercial names are Rocagil 3555, Geoseal, and the phased out Terranier.

>> end of page 8

Applications

Phenoplasts have been used in oil well drilling for many years. The geothermal gradient in deep holes provide the high temperature necessary to make these grouts set (Karol, p. 123-125).

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. Known also as a precondensate or a prepolymer, this intermediate stage grout has a higher initial viscosity than the urea solution, but better gel time control makes it easier to handle. The prepolymer is in a suspended reaction state that reanimates when an acid catalyst brings down the pH. Urea-formaldehyde soil composites have comparable strengths to phenoplasts, are less sensitive to testing strain rates, and are relatively inexpensive compared to other grouts. Aminoplasts with formaldehyde and acid catalyst contents are toxic and corrosive.

Toxicity Concerns

Aminoplasts contain formaldehyde and an acid catalyst, which are both toxic and corrosive. In the gelled state, the aminoplast may contain leachable unreacted formaldehyde.

Commercial Products

Commercial names include Rocagil, Herculox, Diarock, and Cyanaloc 62.

Applications

Like the phenoplasts that require high temperatures to set, aminoplasts were used initially in the oil well drilling industry. At ambient temperatures, gelling takes place only in an acidic environment, like in a coal mine where the ground and groundwater have pH levels well below 7, for instance (Karol, Chemical Grouting, pp. 129-131).

CHEMICAL GROUT PROPERTIES

Gel time and viscosity characteristics affect the grouting project.

GEL TIME

The transformation of a chemical grout into a viscous gel and eventually into a solid requires adding a reagent, such as an acid or metal salt (Karol, Chemical Grouting, pp. 67-68). Gel time, generally measured in minutes after injection,

determines when the grout loses its flow[illegible] property and begins to set. In order [illegible]e effective, the grout must have good gel time control. Ideally, it should remain fluid long enough to penetrate the soil matrix and fill up the voids before it sets (Hausmann, p. 357). A grout that sets too early would not have permeated the soil enough to significantly enhance its strength or impermeability. One that sets too late could be washed away by subsurface water flowing near the target area. Thus, a chemical grout rated good or excellent has a broad range of gel times that can be accurately and repeatedly obtained. Fair or poor grouts have only a narrow gel time range, and whose gel time control is difficult (Karol, Chemical Grouting, p. 62).

>> end of page 9

The time lag from injection till final gellation depends on the concentration of the activator (a second component required for setting), inhibitor (a setting retarder), and catalyst (a substance that accelerates setting) in the grout. Gel time is relatively independent of the grout concentration for most solutions (Karol, Chemical Grouting, p. 62). Agitation from turbulent flows within the grout stream also tends to increase gel time (Baker, p. 521).

POLYMERIZATION

Polymerization is the formation of a large molecular chain or network of chains from smaller chemical units. In polymerization, permanent chemical bonds hold the molecular chains together. Only a chemical reaction would dissolve these bonds. Polymerization is different for silicate and organic grouts. Organics form three-dimensional networks of chemical chains that are hooked together, whereas silicates tend to form gels through attractive charge effects, which may involve some permanent bonding (Clifton, pp. 13-14).

VISCOSITY

Viscosity affects the ease with which a grout penetrates a soil mass. An ideal grout has the same viscosity as water of about 1 centipoise (cP) at $20^{O}C$. At this low viscosity value, the grout easily enters and fills up the pore spaces in soil (Hausmann, p. 352).

Dilution with water lowers the grout viscosity. In all silicate-based grouts, sodium silicate content directly affects viscosity and strength. Dilution with water also improves workability, but reduces the strength (Karol, Chemical Grouting, pp. 68-69). For projects that require a high unconfined compressive strength of 700kN/m, for example, the viscosity must be increased to approximately 10cP (Nonveiller, p. 66), which makes the grout hardly injectable for soils below $k = 10^{-2}$ cm/s (Karol, Chemical Grouting, p. 54). Similarly, achieving adequate soil impermeabilization by filling up most of the soil voids requires using grout of approximately 3cP at the expense of strength (Nonveiller, p. 66). Depending on the priorities, one must compromise between low viscosity and increased strength.

HEALTH CONCERNS WITH CHEMICAL GROUTS

Toxicity and causticity are intrinsic characteristics for many of the chemical grouts mentioned in this paper. The degree of toxicity may range from causing a simple skin rash to the more serious effects of being carcinogenic or neurotoxic. Often, the grout, catalyst, or reactant is dangerous by itself, but when they are mixed and bonded to the soil, the toxic elements may become inert (Karol, Chemical Grouting, p. 64). A major concern regarding chemical grouts is the health effects on work crews. If the chemicals are mishandled, the crew would endanger not only themselves, but also the public.

Of all the grouts mentioned, sodium silicate and acrylates are the least toxic. Training personnel and providing proper equipment are essential preventive measures against accidents. Negligence, such as placing the grout in a known reactive environment, which causes the gel to leach into nearby groundwater, would endanger public health. However, once placed in the ground under appropriate conditions, the gel poses no significant hazard to the public. Grouts could be used effectively when used with safe and proper handling procedures (Clifton, p. 8).

>> end of page 10

LIMITATIONS OF PERMEATION GROUT EFFECTIVENESS

A durable grout exposed to external influences resists deterioration and retains most of its mechanical properties (Krizek and Madden, p. 2). Obviously, cement and chemically grouted soils do not last eternally. Aging and harsh environmental conditions may affect their permanence and strength.

EXTREME ENVIRONMENTAL EFFECTS

Environmental changes may accelerate degradation of chemically grouted samples. A freeze/thaw or wet/dry cycle can mechanically deteriorate a grouted mass containing high amounts of free water. Grouts placed in certain soil regions may never experience complete wet/dry cycles, such as close to the water table, or complete freeze/thaw cycles, such as below the frost line. In the vicinity of a leaky underground steam pipe, the wet/dry cycle phenomenon occurs often (Karol, Chemical Grouting, p. 49). Dry environments cause cement grouts to shrink after setting, forming microfissures that increase permeability (Littlejohn, pp. 42-46).

GROUNDWATER INFLUENCES

Chemical grouting can be effective near groundwater, provided the chemical and hydraulic effects of the groundwater are taken into consideration. High groundwater flows may disperse the liquid grout significantly before setting. Groundwater can also dilute the grout (Karol, Chemical Grouting, p. 372). One can overcome these effects by injecting the grout at a rate that exceeds the grout dispersion rate and shorten the gel time enough before excessive dilution takes effect (Karol, Chemical Grouting, pp. 153-154). The ground and groundwater may contain organics that alter the gel time or react with the grout. Consequently, the solidified gel-soil matrix would lack the intended strength and impervious qualities. For sodium silicate grouts, a high pH groundwater environment prevents initial gellation and encourages grout degradation with time. Low pH accelerates setting for sodium silicates, but retards setting for acrylamide or acrylate grouts (Baker, p. 519)

Cement grouts are susceptible to deterioration as well. The common causes for deterioration of cement grouts after placement are reaction to sulfate in groundwater, prolonged exposure to sea water, and large scale temperature fluctuations (Littlejohn, pp. 42-46).

SYNERESIS

Syneresis, a condition in which a cured gel shrinks and exudes water, can destroy the initial impervious qualities of the chemically grouted sample. The effects are more predominant in gels with a low silicate content and long setting times. For medium to fine sands, syneresis effects are negligible (Karol, Chemical Grouting, p. 77). An experimental test performed in Japan showed that syneresis effects on colloidal silica were negligible (Yonekura and Kaga, p. 732).

LONG TERM STRENGTH

Over time after placement, deteriorating grouts lose their strengths. Hayward Baker, a grouting engineer, comments on sodium silicates:

projected lifetime of grout?

>> end of page 11

"Silicate grouts may provide excellent waterproofing characteristics and low strength structural improvement for temporary works up to several months. They should not be considered to be permanent with a lifetime of several years, unless the particular silicate catalyst system has been shown to be permanent under the expected service conditions." (Clifton, p. 26)

In static conditions, such as under a constant hydraulic head, the grout may weaken. Studies conclude that acrylamide gels are permanent, lasting for many years, whereas sodium silicates are not. The acrylamide gels resist less severe chemical attacks. Strong acids and bases, though rarely found in soils, are detrimental to acrylamide gels (Karol, Chemical Grouting, p. 98).

Results of Laboratory Strength Tests

Lab tests on acrylamide samples stored in saturated conditions for over 10 years show no loss in strength, and field jobs completed after 20 years show adequate performance (Karol, Chemical Grouting, p. 98).

In Japan, long term strength tests were performed on fine grain sand samples grouted with silica sol, sodium silicate, and colloidal silica. Samples were cured in a constant temperature (20°C) and moist environment (98%). The sodium silicate-glyoxale sands showed a decrease in strength over the 3 year test period due to leaching. The silica sol reached a peak strength twice its initial strength and weakened to 2/3 the initial strength due to syneresis. But, colloidal silica samples showed a gradual strength increase throughout the test. R. Yonekura and M. Kaga developed a semi-empirical formula to estimate the strength of stabilized sands with sodium silicate grout (Yonekura and Kaga, pp. 727-734). Results from another experiment with silicate grouted samples placed under dry cured conditions show a constant strength for at least 11 years. Those submerged in water for 21 days showed a substantial strength decrease (Graf, Clough, and Warner, pp. 477-478). The strength differences for dry and wet samples are a result of desiccation. Grouted samples that have dried tend to have higher strengths than saturated samples. Karol comments,

Shrinkage of the grout between soil grains sets up forces analogous to capillary tensile forces but often much stronger. This increases the resistance to relative motion between grains and adds shear strength to the soil mass. Thus, desiccated grouted soils will show strengths equal to or higher than wet strengths, often higher by as much as 10 times (Karol, Chemical Grouting, p. 55).

>> end of page 12

APPLICATIONS

GROUND IMPROVEMENT

Grouting either enhances the strength of soil or makes it more waterproof. In excavation projects, such as in an open pit, tunnel, or shaft, grouting improves the soil bearing capacity, which reduces the movement of slough into an excavation and the potential for ground collapse. Grouting reduces the inflow of water that otherwise would promote undesirable ground movement or allow an unacceptably large amount of water to leach into a construction area (Baker, p. 516).

Hydrology

Because grouts can reduce soil permeability, they have several applications in hydrology. Currently, for any large dam project, foundation grouting may be necessary to create an impermeable barrier, a grout curtain. This curtain significantly reduces foundation seepage flow that would otherwise reduce the reservoir level or create piping conditions. Foundation grouting with cement grout curtains were performed at Hoover Dam on the Colorado River, for instance (Nonveiller, p. 5). Chemical grouts have been used in landfill projects. Barriers made of non-leachable grouts can divert uncontaminated landfill percolates to drainage systems (Graf, Rhoades, and Faught, p. 94).

Tunneling

Structural chemical grouting provides underpinning. Chemical grouting increases the strength of granular foundation soils so that excavation is permissible next to footings (Baker, p.516). In tunneling projects, chemically grouted soils provide temporary structural support and a better seal against water infiltration into the construction area (Karol, Chemical Grouting, p. 308). Cave-ins may occur at pockets of sandy or soft soils located at the excavation front. However, grouted soils create a safer working environment because they provide additional structural support while the tunnel is being constructed. The 1993-1996 Muni Metro Turnback Project in San Francisco used sodium silicate grouting to stabilize the soil in conjunction with compressed air for tunneling work(Sutter, Connolly, and Wu, p. 38).

(See Figure 8 for illustrative examples of structural chemical grouting applications)

CHEMICAL AND CEMENT GROUT COST COMPARISON

Information on chemical and cement grout cost is limited, but a cost comparison between the two generally shows that chemical grouts cost much more. The following information is from 1985, comparing the cost of the treatment area for both chemical and cement grouts:

-Particulate (cement) grouts	Relatively less expensive ($3.00 - $30.00/m^3)
-Chemical grouts	Relatively very expensive ($75.00 - $250.00/m^3)

(Ledbetter, p. 10)

A 55-gallon drum of sodium silicate can cost $95.00. After diluting 1:1, the cost with other reagents would be approximately $1.15 per gallon or possibly less (Clifton, pp. 29-30).

>> **end of page 13**

CHEMICAL-CEMENT COMBINATIONS

Grouting techniques are not limited to either chemical solutions or cement mixtures. Combinations with either one or the other being the additive are possible. Acting like mutual accelerators, sodium silicates and cements used in small quantities greatly reduce the setting time of the other. Portland cement is compatible with any chemical grout with a pH >=8. Portland cement additives produce shorter gel times and higher strengths. Chemical grouts added to cement grouts will control setting time better. Commonly used silicate- and acrylamide-cement combinations have excellent gel time control and high strength. Unconfined compressive strengths as high as 6000 psi are possible with acrylamide-cement combinations as well as with acrylates and silicates (Karol, Chemical Grouting, pp. 345-347). (See Figure 9)

PLANNING AND PREPARATION

After tests confirm that the soil is groutable, the engineer can proceed with a grouting plan. The engineer determines the necessary steps that ensure satisfactory completion of the project. Grout effectiveness is attained by achieving uniform penetration throughout the target area. Injection hole spacing, the injection pressure range, and the grout volume to be used will directly affect uniform penetration.

ANTICIPATING GROUT FLOW BEHAVIOR

To determine the above parameters, the engineer must understand the fundamental flow behavior of a grout originating from an injection point. Typically, a grout flows radially outward in three dimensions from an injection point source, forming a "grout bulb" that initially looks like an irregular spheroid or ellipsoid (Baker, p. 525). One placement method, called the injection-pull technique, requires the formation of a uniform column of grout for maximum effectiveness. The grout pipe is open at the tip where the grout exits into the formation. Studies suggest that if such a column is to be achieved, the distance that the grout pipe is pulled up should not exceed the grout flow distance normal to the pipe. Otherwise, injection points separated too far apart will produce a column of useless grouted spheres (Karol, Chemical Grouting, pp. 154-177). (See Figure 10)

Low viscosity chemical grouts under extremely low injection rates tend to deform into droplets under gravitational effects (Karol, Chemical Grouting, p. 42). In stratified soil zones, the chemical grout forms fingers as it penetrates and disperses in between soil layers (Karol, Chemical Grouting, pp. 154-177).

VOLUME ESTIMATION

Another consideration is calculating the volume of grout needed for the project. Given the volume of soil to stabilize, one can estimate the necessary volume of chemical grout by assuming:

a) the grout fills almost all of the soil voids
b) the grout flows radially away from the injection points and fills all voids within its path, and

>> **end of page 14**

c) that because of the spherical shape of the grout bulb, some grout will penetrate beyond the intended grout zone.

The equation to calculate grout volume i

Liquid Grout Volume = Vz (n *F)(1 + L)

where
Vz = the total volume of the treatment zone,
n = soil porosity (varies from 25% for very dense, well-graded silty sands to 50% for loose, uniform sands)
F = void filling factor (varies from 85% -100% for sodium silicates) and,
L = loss factor for grout placed outside the treatment zone (varies from 5% to 15%, depends on grouting zone shape, frequency of injection points per unit volume, and presence of highly porous soil layers)
(Baker, pp. 527-528)

INJECTION SEQUENCING

Layout

The simplest injection hole layout is the parallel pipe array, in which all the injection pipes are placed parallel to each other. Construction constraints may require a fan array, in which the pipes diverge from one area (Baker, p. 528). (See Figure 11) The curtain pattern for dam foundations is a parallel array with a minimum of three injection rows, which often achieves satisfactory water cutoff conditions (Karol, Chemical Grouting, p. 184).

(See Figure 12 for a photo of a foundational grouting project)

Staging

Injection staging involves primary, secondary, tertiary, and quaternary grouting stages, the last two being optional depending on the project requirements. Primary grouting refers to initial grout placement in ungrouted zones where adjacent grout bulb boundaries are either in partial contact or not in contact. Secondary grouting refers to grouting the gaps between primary grout boundaries. (See Figure 13) Tertiary and quaternary grouting targets spots that the first two stages missed. The result is a soil mass with overlapping grout bulbs.

In making the grout curtain, for example, injection begins with the two outer rows. Injection of each hole is patterned in an alternating sequence where each subsequently grouted hole is located diagonally across from the previously grouted hole. The middle row is grouted to fill in the gap between the outer rows (Karol, Chemical Grouting, p. 184). (See Figure 14) The minimum practical thickness of a grout curtain is usually 1.5 meters or more (Karol, Chemical Grouting, p. 255).

Spacing

Injection hole spacing for most grouting projects range from 0.8 to 1.5m. When grout holes are spaced further apart, more ungrouted regions remain between grout bulbs. Typically, the farther the distance between injection holes, the less definitive the

>> end of page 15

grout front becomes. When grout holes are spaced too close, the result is excessive drilling costs (Baker, p. 528).

The spacing between rows and between holes in each row is dictated by placement cost of grout holes and by the cost of grout volume required. In Chemical Grouting, Karol refers to Keith Foglia, who wrote a computer program in BASIC that calculates the optimum spacing arrangement for a grout curtain job. Variables, such as the grout curtain extent below the dam, horizontal span of the grout curtain, cost to install grout pipes per linear foot, the cost per gal of grout in place, and grout zone porosity are inputted. The program calculates not only the optimum spacing required, but also the total job cost (p. 255).

GROUT MIXING

H. J. Joosten, a Dutch engineer, demonstrated the reliability of the chemical grouting process by developing a two-batch grouting technique using sodium silicate grouts with calcium chloride in 1925. One hole receives the sodium silicate solution. Another hole adjacent to the first receives the calcium chloride (Karol, Chemical Grouting, p. 14). The reaction takes place in the region between grout holes. The result is a mass of hardened chloride solution lenses

and fingers embedded within the sodium silicate. The extremely rapid chemical reaction does not allow enough time for a complete reaction. The Joosten method became obsolete because of this drawback (Karol, Chemical Grouting, p. 68). Currently, cement grouts are mixed using the batch system since separately pumping the dry and wet ingredients is impractical. Consequently, all the ingredients are combined and mixed in a single tank and pumped into the injection hole.

However, the batch system does not work well for chemical grouts. Grouts with short gel times will set prematurely during the mixing process, clogging the tanks, pumps, and discharge hoses and making the grout placement difficult or impossible. The two-tank single-pump system allows separate placement of chemical grout components and catalyst. Gellation starts at the injection point where the two components mix, avoiding damage to the internal equipment and improving control of gel time. Knowing when gellation will start, the operator can better control the grout flow with the proper injection rate and pressure modifications so that the grout reaches the desired location before the final setting stage (Karol, Chemical Grouting, pp. 188-189).

GROUT INJECTION

After the drilling is completed and the slough removed, the hole is fitted with a grout pipe. In an open ended pipe, grout enters the soil solely through the pipe tip initially set at the borehole bottom. Each subsequent injection takes place above the previous after pulling the pipe a short distance up along the grout hole.

The sleeve-port grout pipe, also known as a tube-a-manchette, is a system consisting of a 3-6 cm diameter PVC pipe with rubber jackets covering small grout holes equally spaced along the pipe. These jackets act as check-valves that permit the grout to flow only out of the pipe. After grout pipe installation, the annular space between the pipe and the borehole wall is sealed with a brittle cement-bentonite mortar. A device called an internal packer isolates the immediate vicinity of the grout hole on the inside of the grout pipe. When the rubber gaskets at both ends of the packer are inflated, the packer creates a tight seal with the inside wall of the pipe. During grouting, the injection pressure expands the rubber jacket that covers the grout holes, and the mortar seal fractures, allowing grout to flow through into the soil. After the grout is pumped from that confined

>> end of page 16

pipe section, the packer is deflated and pulled up over the next sleeve-port for the subsequent injection. (See Figure 15)

The tube-a-manchette system has its pluses and minuses. The advantage is that re-injection into the same pipe is possible, thus, cutting down additional pipe installation costs. The disadvantage, however, is that in order to initially break the outside mortar seal, the injection pressure will be briefly very high for the first few moments. Exact grouting pressure due to the grout front movement is ambiguous since part of the pressure is attributed to keeping the grout hole jacket open during injection (Baker, pp. 528-530).

QUALITY ASSURANCE AND QUALITY CONTROL

Continuous monitoring during the injection process is necessary, if not essential, to the successful completion of the grouting job. During the procedure, the grouting operator must not only monitor the injection pressure, grout volume take, and injection rate, but also make adjustments to prevent damage to the equipment or to the treated ground.

Metering equipment assists the operator. A pressure gauge, which constantly measures the pressure in the injection tube, alerts the operator of excessive pressures that may damage the ground formation. An automatic pressure shutoff device is absolutely necessary to protect against overpressuring in the formation and in the equipment because of plugging by gelled grout. Accurate, variable volume pumps enable the operator to quickly adjust or fine-tune the amount of grout injected. The rate meter used in conjunction with the pressure gauge indicates whether or not the formation can continue to accept grout or if the intake has reached the maximum point (Baker, p. 534).

Quality assurance involves ascertaining that the grouting process will proceed as effectively as possible for the particular project requirements. Factors to consider are:

1. The amount of grout required in the project zone.
2. The adequacy of the grout hole placement method.
3. The injection plan.

4. The quality of the grout.

All of the above may have reasonable answers. Yet, the project is not guaranteed to be successful. These factors address only the extent of consideration put into the grout plan design (Karol, Chemical Grouting, p. 90).
The following should be considered during grout injection:

-low viscosity facilitates permeation into tight voids
-injection pressure must be low enough to prevent hydraulic fracturing of formation or to prevent ground heave (Byle and Borden, p. 11)
-injection rate controls treatment time for a given area -- higher rates shorten treatment times
-high injection pressures or low viscosity grouts require large injection rates
-gel time must be long enough so that gellation takes place before the grout front passes the treatment boundary (Hausmann, p. 366)

>> end of page 17

In practice, injection rates range from 2 to 20 liters/min. Sometimes, they may be as low as 1 liter/min or be as high as 40 liters/min. Beyond 40 liters/min, grouting is hard to control because high pressures induce uncontrollable ground fracturing that damages the formation. Grout will travel through newly created fissures instead of permeating the soil mass. For rates below 1 L/min, grouting becomes impractical because of extremely low volume placement (Baker, p. 518). Ideally, the grout flows continuously through the soil matrix in steady-state equilibrium. This condition optimizes injection control and minimizes the chances of ground fracturing (Karol, Chemical Grouting, p. 46).

TESTING THE EFFECTIVENESS OF GROUT REMEDIATION

The type of verification method used depends on the importance of the parameters measured, required accuracy, site limitations, method limitations, and other factors. The verification method requires measuring the ground characteristics before and after grouting to determine its effectiveness. Selection of a verification method depends mainly on what soil properties were intended to be improved (Byle and Borden, pp. 44-49). If the project objective is impermeabilization, it may be more critical to ensure that no pockets of ungrouted soil remain than it is to verify for adequate strength. Various test methods can be used to verify the presence of grout in the treatment zone, to compare the permeability change before and after grouting, and to measure the density and strength of grouted field samples. Practical methods are categorized into mechanical and hydraulic methods.

MECHANICAL

Excavation
Mechanical methods involve probing the ground. Excavation visually reveals the presence of grout. A test pit, for example, exposes the treated subsoil for observation or for testing. Test pits are cost effective up to 7 meters. Beyond that depth, the cost for shoring makes test pits less cost effective.

SPT
The SPT (Standard Penetration Test) retrieves field samples that can be visually inspected for grout and later sent to a lab for a strength and property analyses. This test involves driving a sampler into the ground to core out a sample. This technique is both time consuming and expensive if the treated zone is very dense. Similar coring tests such as the Shelby Tube or Pitcher Sampler are effective in weakly grouted, loose fine-grained soils.

CPT
The CPT (Cone Penetrometer Test) used before and after grouting can determine the effectiveness of treatment. The method is quick because no drilling is necessary. Data on side friction acting against the soil along the full depth of the probe can be continuously obtained. However, this test cannot retrieve any field samples and cannot penetrate very hard or dense materials or grouted materials whose strength is too high (Byle and Borden, pp. 24-34).

>> end of page 18

CHEMICAL

Chemical methods verify the presence of grout in the soil matrix. Phenophalin turns pink when it comes in contact with a high pH sample, like sodium silicate. During injection, dyes added to the grout can show the extent of the treatment zone (Byle and Borden, pp. 24-34).

GEOPHYSICAL

Geophysical methods measure the physical properties of the ground. There are seismic, earth probing radar, and acoustic emissions.

Seismic

Seismic methods require producing ground waves using a hammer blow, explosive charge, or a wave generator. Receivers, such as geophones or accelerometers, can distinguish the change in wave characteristics after the waves have passed through the grouted soil. Based on the data collected, ground characteristics are determined indirectly. This method can measure the overall stiffness of the treated zone.

There are limitations to this test. In the vicinity of a buried structure, the results are meaningless. Because of the high sensitivity of seismic methods, they are performed frequently at night or on weekends when background vibrations in busy areas are at a minimum.

Earth Probing Radar

An earth-probing radar can be used to verify the presence of grout in soil. This technique uses the existing grout holes to perform the measurements. A radar transmitter and receiver are each placed in separate boreholes and simultaneously drawn up while continuously collecting radar signals. The radar image will indicate either the presence or absence of grout between the two holes. Since grout absorbs radar signals, grouted regions produce no radar image whereas ungrouted regions will produce an image. The limits of the treatment zone can be determined, but structural competence of the area cannot. Subsurface objects may produce results that erroneously appear to be a grouted region (Huck and Waller, pp. 782-786). Borehole alignment must be verified in radar probing otherwise a skewed alignment produces inaccurate results (Byle and Borden, p. 38).

Acoustic Cross-Hole Shooting

Acoustic cross-hole shooting uses the same principle as the earth-probing radar, except the transmission signals are acoustic waves. (See Figure 16) Acoustic cross-hole shooting is sensitive to the stiffness of the grouted material. It is an indirect measurement of strength. Any indirect test method is subject to erroneous interpretation (Huck and Waller, pp. 782-786).

HYDRAULIC

Hydraulic methods can be performed either in the field or in the laboratory. Comparison of the permeability before and after grouting will quantify the effectiveness. In the lab, a flow test is conducted on a field sample. However, the lab sample may be disturbed during transport and would not provide representative soil property values. Systematic errors in the experiment may give values deviating significantly from the actual. In the field, a water leakage test can be performed in the grout holes. Often a packer, like the one used to place the grout in the tube-a-manchette, isolates a section of the hole before water is injected. In fully grouted soils, injection is difficult; in poorly grouted soils, the formation accepts the injected water. Equipment setup for

>> end of page 19

this requires time and money (Byle and Borden, pp. 44-47).

CONCLUSION

Cement and chemical grouting can be used as alternatives to mechanical grouting for soil stabilization projects. The same objectives can be achieved -- providing structural support for soil and reducing soil permeability. Cement and chemical grouts enhance the soil without disturbing the soil structure unlike the mechanical grouting methods. Literature on chemical grouts suggest that sodium silicate and acrylate grouts can be effective used, given proper

handling procedures for the solutions.

Compared to cement grouts, chemical grouts are relatively new. They have been commercially available since about the 1940's when polymer research began to grow whereas cement grouts have been extensively applied and researched. In the US, civil engineering organizations usually subcontract grouting services to grouting specialists, who may deal only with cement-based or chemical based grouts (Clifton, p. 11). Consequently, the knowledge and experience are mainly kept separate from civil engineering. Nonetheless, authors and government departments and bureaus are publishing more literature on chemical grouting in order to disseminate the technology. In addition, ASTM have developed standards for testing chemically grouted samples: ASTM 4609 (Screening Chemicals for Soil Stabilization), ASTM 4320 (Laboratory Preparation of Chemically Grouted Soil Specimens for Obtaining Design Strength Parameters), ASTM 4219 (Unconfined Compressive Strength Index of Chemical-Grouted Soils), ASTM 4016 (Viscosity of Chemical Grouts by Brookfield Viscometer (Laboratory Method)).

>> end of page 20

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