Grouting Materials for Ground Treatment: A Practitioner's Guide

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Abstract

Bearing in mind the great variety in grout compositions and chemistries, the authors provide a basic classification of the materials used in contemporary grouting practice. A simple four-fold distinction is drawn between particulate grouts (Binghamian); colloidal solutions (evolutive Newtonian); pure solutions (non-evolutive solutions), and a category termed "miscellaneous" grouts which accounts for more exotic grouts, used less commonly. Typical fluid and set grout parameters are provided for guidance.

1. Introduction

The technical challenges posed to the grouting community appear to grow progressively in difficulty. This reflects not only the increasing complexity of the applications - especially in the urban and environmental markets - but also the growing confidence placed in grouting as a technology capable of providing reliable, engineered solutions even to the most difficult problems. It is therefore timely to review the range of materials available, bearing in mind that new challenges are fostering major advances in the development of new or

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General Manager, ECO Grouting Specialists, Ltd., Cheltenham, Ontario, Canada modified grouts, and leading to our better understanding of fluid and set properties and our ability to control them (Gause and Bruce, 1997a and b)

This paper divides the materials into four categories listed in order of increasing rheological performance and cost:

1. Particulate (suspension or cementitious) grouts, having a Binghamian performance (Figure 1a).
2. Collodial solutions, which are evolutive Newtonian fluids in which viscosity increases with time (Figure 1b).
3. Pure solutions, being nonevolutive Newtonian solutions in which viscosity is essentially constant until setting, within an adjustable period (Figure 1b).
4. “Miscellaneous” materials.

Data are provided for each category to illustrate the range of fluid and set properties that may be expected with change in mix design. This classification reflects and summarizes earlier proposals by various authors including Cambefort (1977), Naudts (1989 and 1996) Karol (1990) and AFTES (1991).

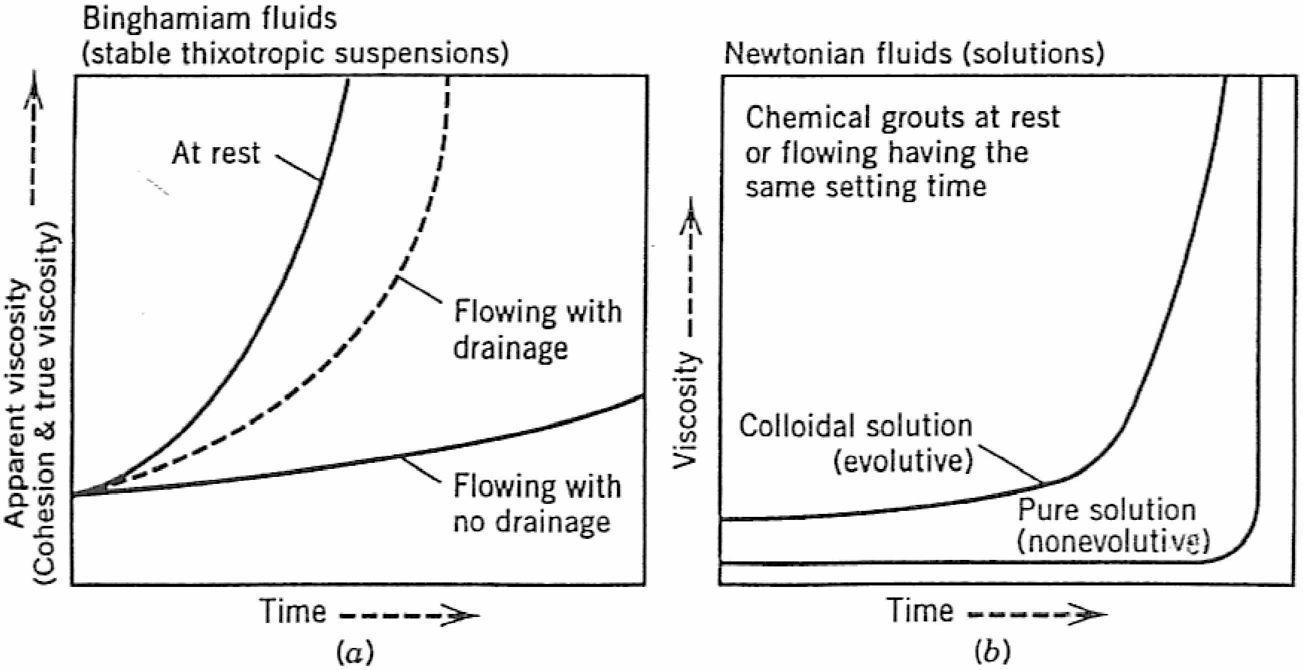


Figure 1. Rheological behavior of typical grouts (Mongilardi and Tornaghi, 1986).

Category 1 comprises mixtures of water and one or several particulate solids such as cement, flyash, clays, or sand. Such mixes, depending on their composition, may prove to be stable (i.e., having minimal bleeding) or unstable, when left at rest. Stable thixotropic grouts have both cohesion and plastic viscosity increasing with time at a rate that may be considerably accelerated under pressure.

Category 2 and 3 grouts are now commonly referred to as solution grouts and are typically subdivided on the basis of their component chemistries, for example, silicate based (Category 2) or resins (Category 3). The outstanding rheological properties of Category 3 grouts, together with their low viscosities, permit permeation of soils as fine as silty sands ($k \leq 10^{-6}$ m/s).

Category 4 comprises a wide range of relatively exotic grout materials, which are used relatively infrequently, and only in certain industries and markets. Nevertheless, their importance and significance is growing due to the high performance standards which can be achieved when they are correctly used.

2. Particulate Grouts

Due to their basic characteristics (including economy) these grouts remain the most commonly used for both waterproofing and ground strengthening. The water to solids ratio is the prime determinant of their properties and basic characteristics such as stability, fluidity, rheology, strength, and durability (Littlejohn, 1982). Five broad subcategories can be identified:

1. Neat cement grouts.
2. Clay/bentonite cement grouts.
3. Grouts with fillers.
4. Grouts for special applications.
5. Grouts with enhanced penetrability.

2.1 Neat Cement Grouts

As illustrated in Figure 2, such grouts are typically unstable, except at water/cement (w/c) ratios less than about 0.4 by weight. Their mode of deposition in intergranular voids or fissures is akin to a hydraulic flushing action and so is controlled by the dimensions of these spaces as well as the grout mix and injection parameters. Typically these grouts are associated with

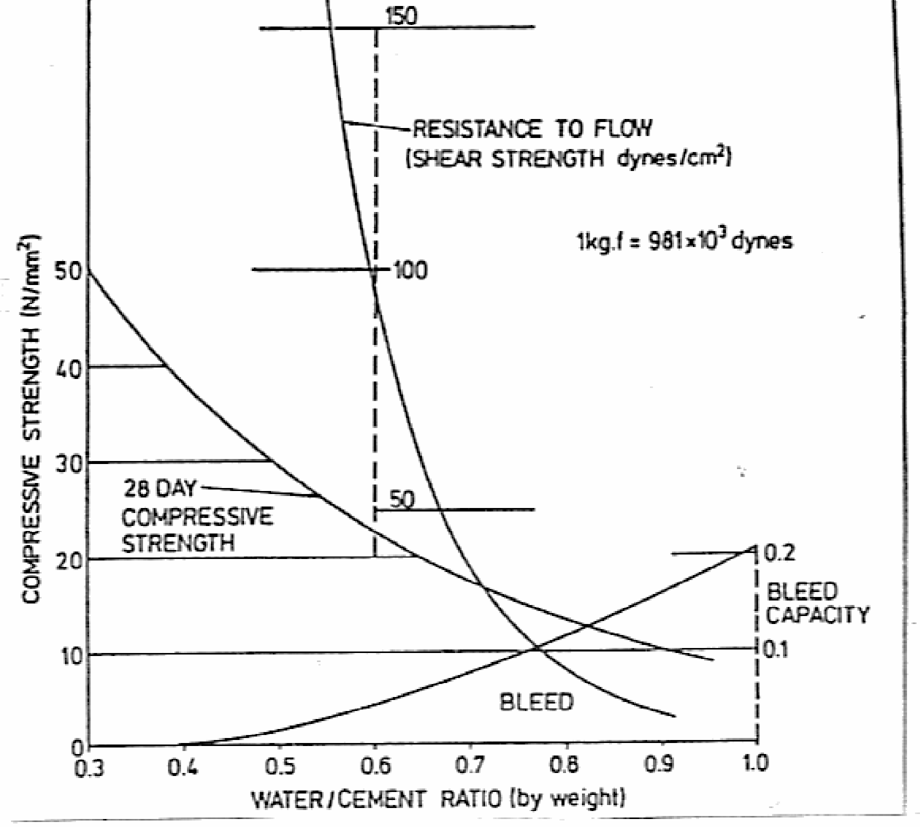


Figure 2. Effect of water content on grout properties (Littlejohn and Bruce, 1977).

high strength and durability, the exact values beir dependent on the water content, and the grain size ar chemistry of the cement. For example, cements ar classified as Type I, II, and so on, or "normal," "rapi hardening," or "sulfate resisting".

2.2 Clay/Bentonite-Cement Grouts

These suspensions are stabilized with a clay mineral to:

- Provide homogeneous colloidal mixes with a wide ranc of viscosities.
- Reduce sedimentation (bleed) and increase resistanc against pressure filtration.
- Decrease the setting time and filtration tendencies
- Increase the cement hydration time.
- Improve penetrability and resistance to washout.
- Permit a wide range of mechanical strengths.
- Reduce permeability.

Common products used include:

- Natural Clay: Economic, and swells when hydrated to as much as six times dry volume.
- Natural Bentonites: Montmorillonitic components predominate. Natural bentonites have remarkable colloidal properties in water and can swell to 18 times their original volume. The sodium bentonites unique to Wyoming give the best performance. Deere (1982) was among the first in the United States to describe the potential of such mixes in routine rock fissure grouting.
- Permuted Bentonites: Natural calcium bentonites that undergo an ion exchange during reaction with sodium carbonate. The volume increase is 10 to 15 times.
- Activated Bentonites: Permuted bentonites with added polymers to increase swelling to 10 to 25 times.

Most types of cements can be used. For a given bentonite dosage, the mechanical performance of slag-based cements is superior to that of Portland cement. For example, Weaver (1989) reported excellent bleed performance at low viscosities, and so a superior performance in contaminated materials. High alumina cement may lead to a long-term decomposition of set grouts and should normally be avoided.

Typical mixes may incorporate

Clay	80 to 400 kg/m^3
Bentonite	20 to 80 kg/m^3
Cement	100 to 800 kg/m^3

Since clay minerals are insoluble, they tend to form a protective environment around cement particles, thus preventing (or inhibiting) dissolution by aggressive waters. These grouts are thus relatively durable.

Grout mix designs reflect the result required: grouts for waterproofing and low strength backfilling applications will have much clay and relatively little cement, while the reverse is true for strengthening grouts. Water-cement ratios may vary from 1 to 8, "Marsh" viscosity from 35 to 60 s, bleed from 0 to 10%, and permeability to 10^{-8} m/s. With the further addition of stability enhancing additives, bleed can be completely eliminated, if so desired.

For w/c ratios of 1 to 3 (by weight), cement-bentonite grouts may be used to permeate soils for strengthening or waterproofing. Water/cement ratios of 2 to 3 are particularly popular in forming cut-offs in alluvium. At higher w/c ratios of 4 to 5, cement-bentonite grouts have been used for compensation grouting, and for encasing instrumentation in soils, where the grout characteristics match those of the soils e.g., stiff to hard clay. Typical rheological and strength development properties are shown in Table 1.

As a final point, Jefferis (1982) described how the quality of mixing such grouts has a strong influence on the subsequent grout properties, especially bleed, penetrability, strength, and brittleness. This practical factor is extremely important and should also be addressed when attempting to compare results from various sources. Such grouts may be regarded as the "all-purpose, cheap, and basic" mix for ground treatment.

2.3 Grouts with Fillers

Adding noncementitious substances substantially modifies the properties and reduces the cost of the mix. The most commonly used are sands and pulverized flyash (p.f.a.) both Type C and Type F, but other materials have been used depending on local availability. These are usually fine and inert industrial byproducts, and include mine tailings, pumice, and silica fume. Tosca and Evans (1992) detail the influence of fillers on the ability to penetrate large fissures.

Sand can account for as much as 750 to 900 kg/m^3 of the grout. For treating large voids, the filler-cement ratio can reach 10. Fillers generally reduce penetrability, while the w/c ratio again controls strength (0.4 to 30 MPa), depending on application.

Pulverized flyash-cement grouts are typically used to fill large cavities, such as karstic features in limestone or old mine workings. Mix designs are geared to meet specified strengths although unconfined compressive strengths in excess of 5 MPa are seldom required. For efficient void filling, a minimal bleed capacity is recommended, and for permanent applications where durability is important a minimum cement content of 50 to 75 kg/m^3 may be applied. Table 2 illustrates typical rheological and strength development properties for the p.f.a.-cement grouts used for void filling.

Table 1. Cement-Bentonite Grout Properties

Water/ Cement ratio by weight	Bentonite by weight of water (%)	Bleed % at		Wet Density (Mg/m³)	Flow Cone (sec) (water= 10 sec)	HAAKE Viscometer RV20-MV2 (1Pa/s = 1000cP)		Unconfined Compressive Strength of 100 mm Cubes			
		3 hrs	24 hrs			Yield Stress (Pa)	Plastic Viscosity (Pa/s)	3 Days (MPa)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
1	2	5	2	1.514	15	31	0.020	3.6	5.2	6.9	9.4
1.2	3	3	0	1.434	20	80	0.025	1.8	4.9	6.7	7.6
1.25	2.5	5	3	1.427	14	50	0.023	1.6	4.0	4.9	6.3
1.5	3	7	2	1.340	13	30	0.025	0.9	1.7	2.3	2.8
2	4	2	2	1.250	15	48	0.028	0.5	1.2	1.5	2.0
2	5	1	0	1.290	16	54	0.020	0.6	1.4	1.9	2.2
2	6	1	0	1.290	20	75	0.025	0.8	1.4	1.9	2.3
3	4	4	0	1.189	22	60	0.023	0.3	1.4	0.61	0.71
4	5	2	1	1.170	12	25	0.017	0.09	0.51	0.22	0.27
5	6	1	0	1.120	18	32	0.023	0.03	0.14	0.06	0.08

All the grouts were mixed in a colloidal mill mixer. Firstly 60kg water was put in the mixer and the bentonite was sprinkled into the water over a period of about 30 seconds. This slurry was mixed for 2 minutes and then discharged to an agitation tank. Temperatures: °C - Ambient 16 to 19, Grout 17 to 22.

Table 2. P.f.a.-Cement Grout Properties

P.f.a.-Cement ratio by weight	Water/solids ratio by weight	Bleed % at		Wet Density (Mg/m³)	Colcrete flowmeter (mm)	Unconfined Compressive Strength of 100 mm Cubes			
		3 hrs	24 hrs			7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	90 Days (MPa)
1	0.40	3	0	1.765	510	17.9	22.5	31.7	49.3
	0.45	6	2	1.715	>700	14.0	18.0	26.0	42.9
	0.50	5	5	1.677	>500	10.3	14.9	20.0	34.3
2	0.40	3	1	1.718	480	8.7	12.2	17.5	37.9
	0.45	5	3	1.679	>700	6.2	8.7	13.2	27.7
	0.50	7	6	1.648	>700	5.4	7.7	12.1	25.1
3	0.40	6	4	1.695	460	4.5	7.0	10.4	23.9
	0.45	9	9	1.650	>700	3.3	5.3	8.3	18.8
	0.50	10	9	1.628	>700	2.7	4.4	7.2	19.1
5	0.40	5	5	1.675	530	2.2	3.7	5.1	15.3
	0.45	8	8	1.641	>700	1.6	2.7	4.4	13.4
	0.50	10	10	1.599	>700	1.4	2.2	4.0	14.5
7	0.40	4	4	1.680	>700	2.2	2.4	5.5	8.8
	0.45	8	6	1.611	>700	1.6	2.0	4.6	6.5
	0.50	11	9	1.587	>700	1.4	1.8	2.9	6.0
10	0.40	5	4	1.643	>700	1.5	1.9	2.3	4.9
	0.45	8	6	1.620	>700	0.8	1.4	1.9	4.0
	0.50	11	9	1.575	>700	0.7	1.2	1.8	2.8
15	0.40	6	6	1.658	>700	1.0	1.4	2.3	3.1
	0.45	9	7	1.608	>700	0.6	1.0	1.7	2.2
	0.50	10	9	1.582	>700	0.6	0.8	1.2	1.7
20	0.40	8	6	1.645	>700	0.7	0.9	1.5	2.0
	0.45	9	9	1.607	>700	0.5	0.7	1.4	2.0
	0.50	10	9	1.580	>700	0.5	0.6	0.8	1.3

All the grouts were mixed in a colloidal mill mixer for a period of not less than 2 minutes.

Over the past three years, a wide range of Type F p.f.a.-cement-bentonite mixes have been developed for compensation grouting in clays via the sleeve port pipe system, at the Jubilee Line Extension in London, England. Such grouts can generate thick lenses or wedges (10 to 30 mm thick) when injected into stiff to hard clay. A typical mix is 20:1 p.f.a./cement with a w/c ratio of 10, and 6 % bentonite by weight of water. This exhibits a concrete slump of 210 mm, vane strength of 2.1 kPa and a strength development of 0.10 MPa (3 days), 0.30 (7 days), 0.50 MPa (14 days) and 0.80 MPa (28 days).

It is important to note that grouts with more than 15% Type C ash (by weight of cement) can exhibit major durability problems within 6 months of injection. This is attributable to the reaction between the liberated calcium hydroxide and the artificial pozzolans in this type of ash.

With respect to other fillers:

- Pumice (clay phillosilicate) is used to increase grout durability, especially in environmental applications. For example, Huff et al. (1996) report on the use of finely ground pumice in both microfine and regular particulate grouts used for the stabilization of low grade radioactive nuclear waste at Oak Ridge National Laboratories, Tennessee.
- Silica fume is incorporated to enhance penetrability, durability, and where necessary, interfacial bond. In Canada, for example, it is routinely used in geotechnical and structural grouting projects, with both regular and microfine grouts.
- Cement (kiln) dust is used to create inexpensive grouts in the mining industry for void filling and backfilling.
- Mine tailings are often used for grout curtains in mining environments, although their compatibility with other additives, and cement, must be always evaluated initially.

2.4 Grouts For Special Applications

<u>Grouts with Controlled Hydration and Rheology</u>. Traditionally, sodium silicate and calcium chloride (for neat cement grouts only) have been the two most common additives (e.g., Reifsnyder and Peters, 1989). In cement-bentonite grouts, the cement proportion must be a minimum of 250 kg/m^3 of grout. For premixing, the silicate can vary

from 10 to 20 percent of cement weight, greater in the case of separate injection (Bruce and Croxall, 1989). Set times can be varied from "flash" to several minutes although these are practically very difficult to control with precision.

Gause and Bruce (1997a) describe recent developments in control over hydration and rheology characteristics. These involve the use of admixtures which can, for example, "put to sleep" cement-based grouts after mixing, for periods of days, before allowing them to resume normal (or accelerated) chemical reactions when they are to be actually injected. The benefits of such developments, especially in mining and tunneling applications, are described by Gause and Bruce (1997b), while research continues in their exploitation for other applications, principally in soft ground treatment by the Deep Mixing Method.

<u>Cement-Foam Grouts</u>. Two categories may be delineated. The first involves the creation of a stable foam (based on organic and/or inorganic proprietary additives) in a foam generator, followed by its mixing with the cement-based particulate grout in a horizontal paddle mixer. The ratio of foam to grout determines the density (400 to 1000 kg/m^3) and the strength of the expanded mix. This group is characterized by high levels of repeatability, and quality control and assurance. The second category involves the use of expanding or swelling grouts. These increase in volume (generally over 100 percent without restraint) by the <u>release of gas</u> inside the grout. Typically this gas is hydrogen-generated by the chemical reaction of the lime in the cement with aluminum powder, the basis of such additives (up to 2 kg/m^3 of grout). Such measures are for filling large cavities only: they cannot be entertained in the vicinity of steel structures or elements such as ground anchorages due to the potential for loss of bond, and long-term hydrogen embrittlement of the steel. Cellular type grouts can also be produced by <u>air entraining additives</u>. These additives can increase volume by 30 to 50 percent before injection and, by exerting residual pressure during setting, can ensure full filling of large voids. Typical additive dosages begin at 0.1 percent of total initial grout volume.

<u>Grouts with Enhanced Strength</u>. These grouts can be produced by: (1) adding a dispersant to permit the mixing and pumping of low w/c ratio grouts; or (2) modifying the

lime/silica ratio of the cement, by adding reactive siliceous products that give a pozzolanic-like compound with the lime of the cement. In some cases and for certain cement chemistries, these additions will be supplemented with activators such as caustic soda or sodium carbonate.

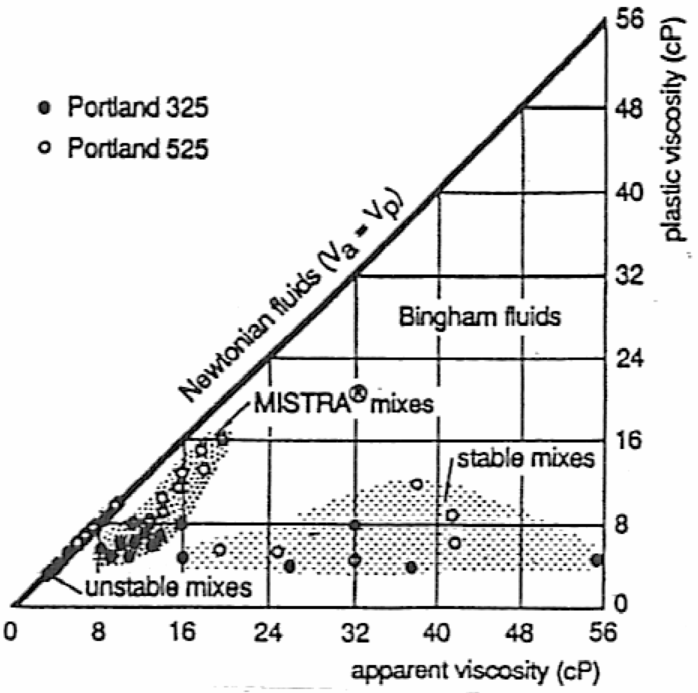
Grouts with Improved Resistance to Washout. These grouts can be achieved by adding accelerating additives, or by adding flocculating, coagulating, or thickening types of organic materials (Gause and Bruce, 1997a and b). These increase both viscosity and cohesion, which in turn modify grout rheology as well as the behavior at the grout/water interface.

2.5 Grouts with Enhanced Penetrability

Such grouts are used to thoroughly and economically fill small pores or fissures while avoiding typical concerns associated with Category 2 or 3 grouts (e.g., permanence, toxicity, strength, and cost). As described by DePaoli et al. (1992a and b) significant investigations have proceeded along three major tracks:

a) By improving the rheological properties. Plastic viscosity, cohesion, and internal friction may be decreased by using deflocculating dispersive additives such as derived from natural organic (polyacrylates, melamines, lignosulfonates, naphthalene sulfonates) or mineral products. Adding 0.5 to a few percent of such fluidifiers will alone reduce Marsh viscosity from the 55 - 60 s range to 32 - 35 s.

b) By increasing stability. While rheological properties can be improved by simply increasing the water content, both bleed, and pressure filtration will increase, thus negating any real advantage during injection. Therefore, additives such as dispersants or water retaining polymers are used. The former typically comprise 0.4 to 2.5 kg/m^3 of grout in cement-bentonite mixes, while polymers vary from 0.1 to 5 kg/m^3 of neat cement, or cement-bentonite mixes. The advantages of one particular type of stabilized modified grout, (MISTRA:DePaoli, 1992a, b) are shown in Figures 3 and 4, and typical properties are summarized in Table 3. A more recent development by one of the authors involves the use of minute quantities (0.1% by weight of cement) of a starch-based additive to such modified grouts to reduce the



ure 3. Relationship between plastic and apparent viscosi for different types of mixes (DePaoli et al., 199

Composition	Cement/water ratio	0.35
	Additives/water ratio	0.04-0.05
Bleed capacity (%)		0-2
Marsh viscosity (sec)		33-37
Rheometer parameters	Apparent viscosity (cP)	8-12
	Plastic viscosity (cP)	5-8
	Yield strength (Pa)	1.5-5
Filter press test at 0.7 MPa	Filtrate (cm^3) after 30 min.	36-72
	Filtration rate ($min^{-1/2}$)	0.016-0.032
UCS (MPa) of grouted sand after 28 days		1.2-1.8

Table 3. Composition and characteristics of Mistra grout, Lot 1PB, Passante Ferroviario, Milan, Italy (Mongilardi and Tornagi, 1986).

pressure filtration coefficient to less than 0.02 $min^{-1/2}$. There is a slight increase in cohesion, but this is strongly influenced by the shear rate during testing.

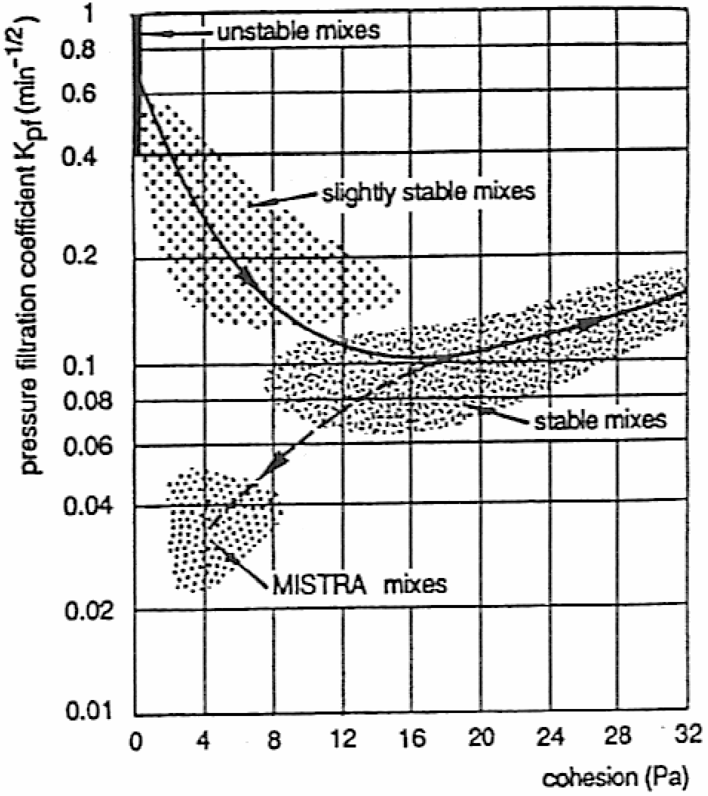
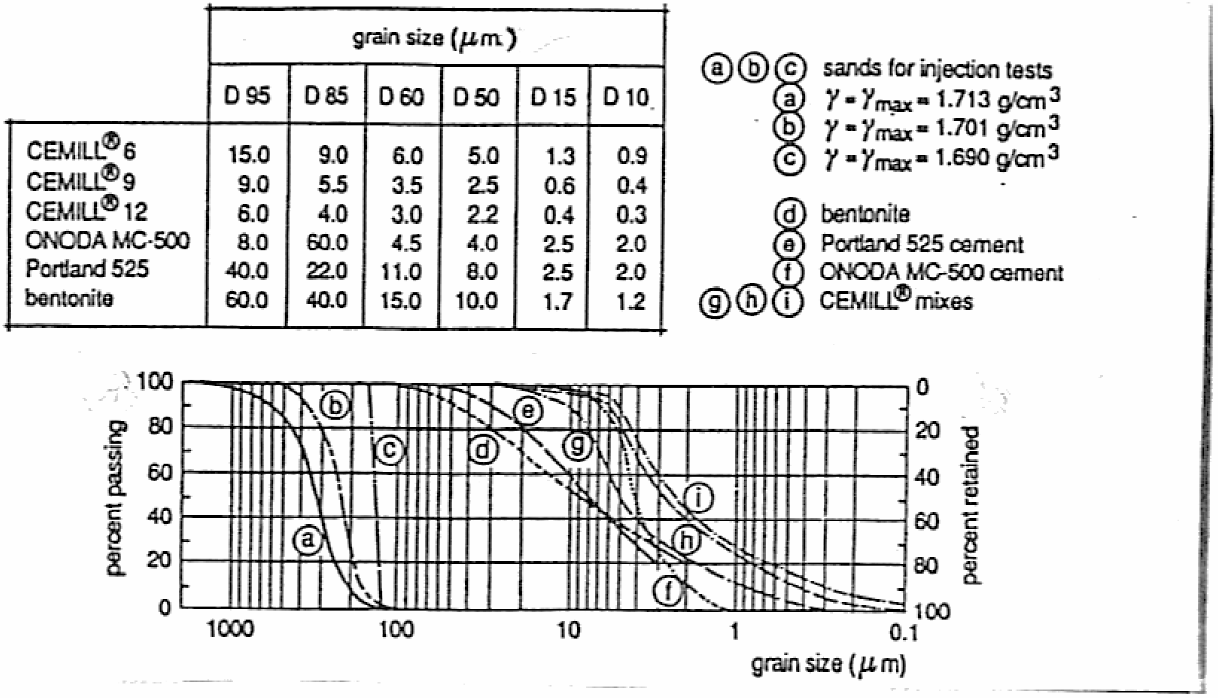


Figure 4. Relationship between stability under pressure and cohesion for different types of mixes (DePaoli et al., 1992a).

c) By reducing grain size. Until recently, the concept solely revolved around manufacturing microfine cements, materials with a mean grain size of 4 microns, and a maximum of 10 to 12 microns, capable of permeating fine sands ($k=10^{-5}$ to 10^{-6} m/s). Regrinding reduces, by a factor of two or three times, the size of normal Portland cement particles (Figure 5). This corresponds to an increase in Blaine specific surface of 350 to 800 m^2/kg. In producing reground dry cements, care must be taken to prevent the selective elimination of certain components and so changes in chemistry. In addition, microfine cements are hygroscopic, may prove awkward to store and handle, and unless mixed correctly, may agglomerate to form undesirably large "lumps" in the grout, or create flash setting. These problems can be resolved with the newer development of wet grinding the *mixed normal grout*, as in the CEMILL® process described by DePaoli et al. (1992a).

Comprehensive data on microfines are provided by Schwarz and Krizek (1992). Hakansson et al. (1992) detailed the rheological properties of microfine cement grouts with additives, while the effect of reacting such grouts with sodium silicate has been reported by Krizek et al. (1992)



	grain size (μm)					
	D 95	D 85	D 60	D 50	D 15	D 10
CEMILL® 6	15.0	9.0	6.0	5.0	1.3	0.9
CEMILL® 9	9.0	5.5	3.5	2.5	0.6	0.4
CEMILL® 12	6.0	4.0	3.0	2.2	0.4	0.3
ONODA MC-500	8.0	60.0	4.5	4.0	2.5	2.0
Portland 525	40.0	22.0	11.0	8.0	2.5	2.0
bentonite	60.0	40.0	15.0	10.0	1.7	1.2

igure 5. Grain size distribution curves for sands, dry grou materials, and grouts (DePaoli et al., 1992b).

and Liao et al. (1992). Again it may be noted that the use of appropriate additives will permit the formulation of microfine based grouts of low solids content (w/s = 1.25) having no bleed, and a pressure filtration coefficient less than 0.05 min$^{-1/2}$.

3. Colloidal Solutions

These comprise a mixture of sodium silicate and reagent solutions, which change in viscosity over time to produce a gel. Sodium silicate is an alkaline, colloidal aqueous solution. It is characterized by the molecular ratio R_p, and its specific density, expressed in degrees Baumé (° Bé). Typically R_p is in the range 3 to 4, while specific density varies from 30 to 42 ° Bé. Reagents may be organic or inorganic (mineral). The former cause a saponification hydraulic reaction that frees acids, and can produce either soft or hard gels depending on silicate and reagent concentrations. Common types include monoesters, diesters, triesters, and aldehydes, while organic acids (e.g., citric) and esters are now much less common. Inorganic reagents contain cations capable of neutralizing silicate alkalinity. In order to obtain a satisfactory hardening time, the silicate must be strongly diluted, and so these gels are typically soft and therefore of use only for waterproofing. Typical inorganic reagents are sodium bicarbonate and sodium aluminate.

The relative proportions of silicate and reagent will reflect in their own chemistry and concentration the desired short- and long-term properties including gel setting time, viscosity, strength, syneresis, and durability, as well as cost and enviromental acceptability.

Typical grout compositions are:

- With organic reagent:

Sodium silicate ($R_p = 3.3$)	180 to 800 liters/m^3
Reagent	40 to 150 liters/m^3
Water	To make up 1 m^3 of grout

- With inorganic reagent:

Sodium silicate ($R_p = 3.3$)	100 to 300 liters/m^3
Reagent	10 to 30 liters/m^3
Water	To make up 1 m^3 of grout

The main characteristics of a silicate grout in its pre-gel state are:

- Density: Linked to the silicate composition and relative amount.
- Initial Viscosity: Depends mainly on the silicate R_p and concentration.
- Evolutive Viscosity: Changes until gel point, and strongly influences injection time (Figure 6).
- Setting Time (Gel Point): Defined when the grout becomes hard enough that it cannot be poured. Depends on the quality and/or quantity of reagent and varies inversely with temperature. Can vary from a few to 120 minutes and clearly influences the period of injectability.

In its hardened state, the main characteristics are:

- Mechanical strength: Rarely measured on gels, due its irrelevance, but rather on permeated soil samples. It varies with reagent and silicate concentrations, chemistries, and degree of neutralization (Table 4).
- Syneresis: The expulsion of water (usually alkaline) from the gel, accompanied by gel contraction. This may continue for 30 to 40 days after gel setting.

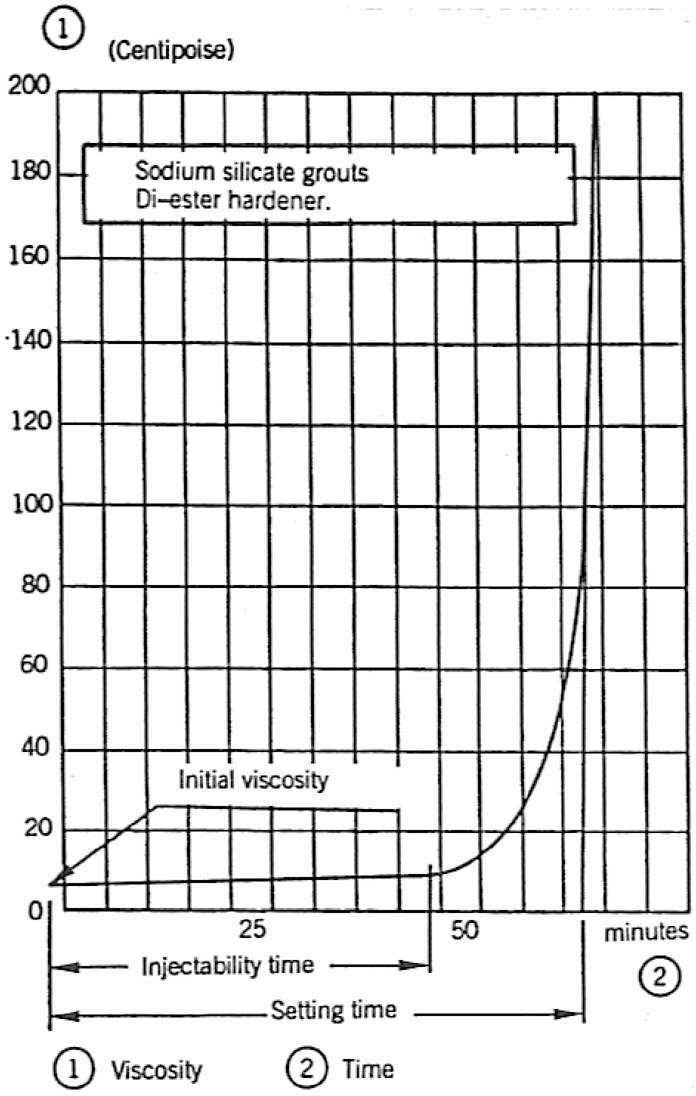
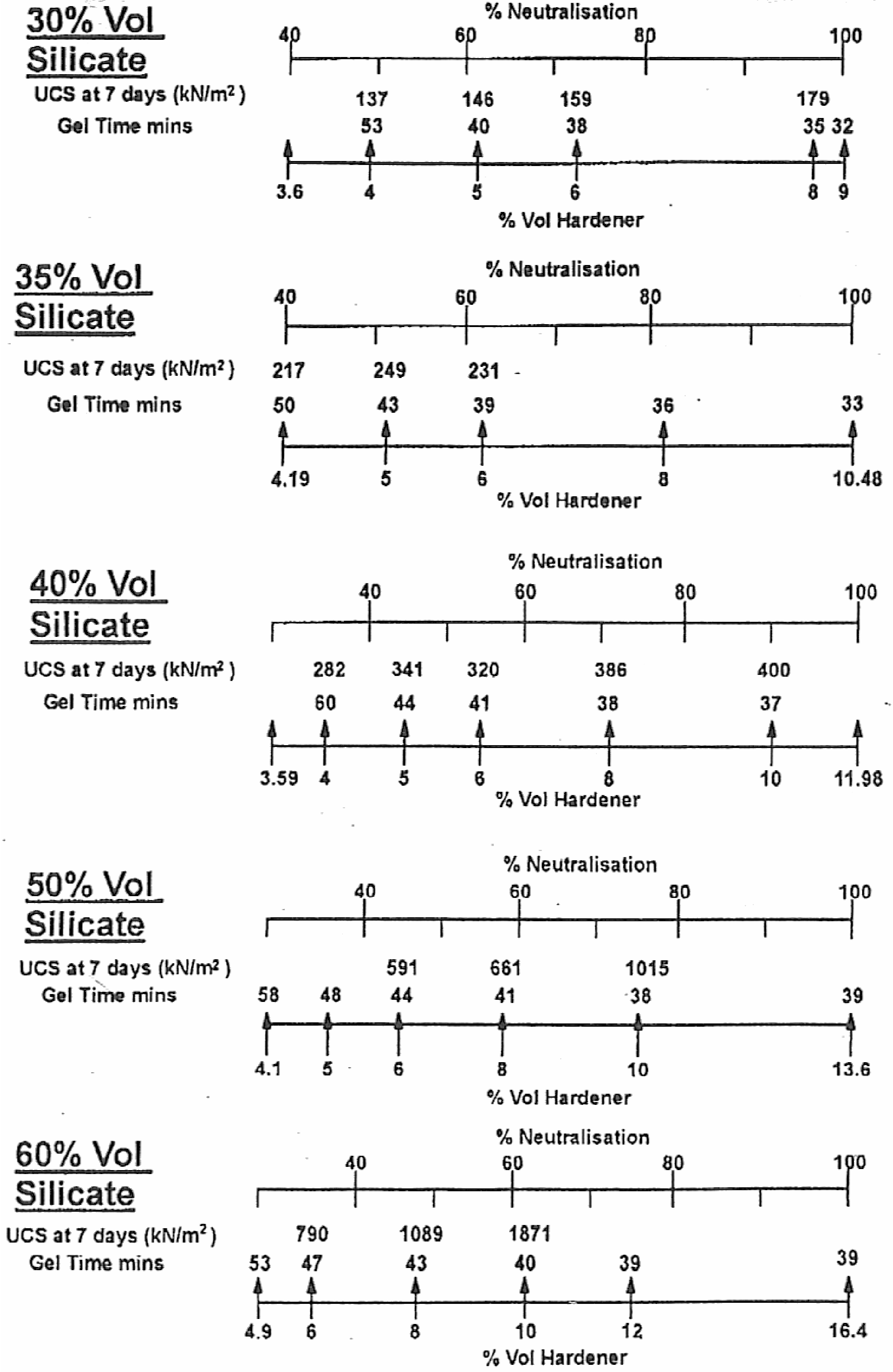


Figure 6. Example of viscosity evolution with time (AFTES, 1991).

Varies with the nature and concentration of the components and on the granulometry and pH of the soil (progressively less in finer soils).

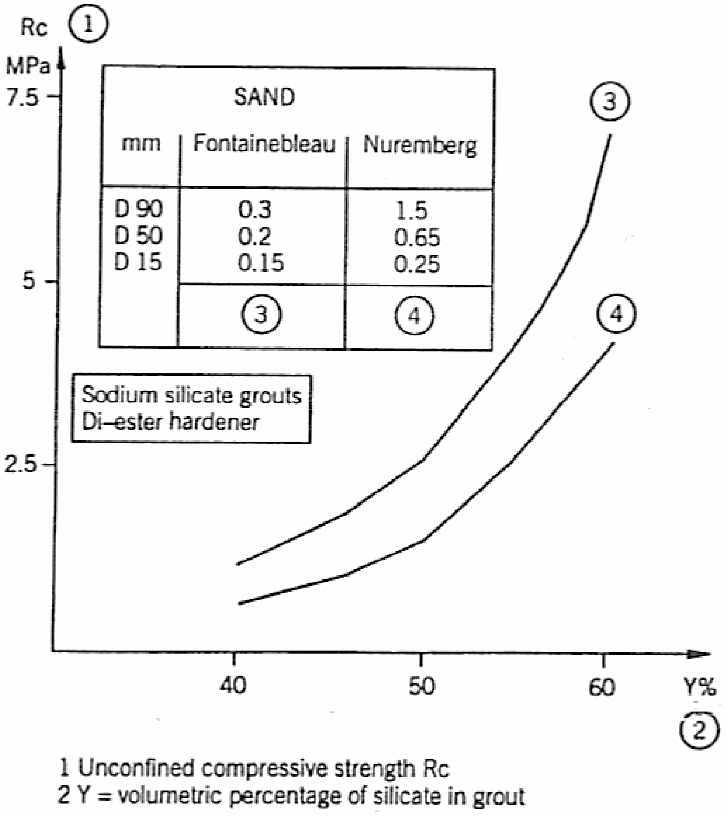
- Resistance to washout: Along with gel dissolution, depends on silicate concentration and on the stage reached in the gelation reaction (itself linked to the reagent concentration).

Regarding gel types, *soft gels* have low silicate concentrations and usually an inorganic reagent. They have very low viscosity (less than 10 cP)and so are used for sealing fine sands or very fine rock fissures. *Hard gels* have higher silicate concentrations and organic reagents, the proportion of which is selected to achieve the best possible neutralization rate. Initial viscosities can reach 30 cP, and strengths can vary from 0.2 to 6 MPa.



ble 4. Percent neutralizations, 7-day UCS values for permeated Leighton Buzzard sand and gel times for silicate-R100 ester grout formulations.

Soils treated by soft gels can have permeabilities as low as 10^{-7} m/s, strengths of 0.2 MPa, and durabilities that vary greatly with soil grain size. In this context, grouts with sodium bicarbonate - which produces higher syneresis - are acceptably durable only in fine to very fine sands. The main purpose of hard gels is to impart strength, although waterproofing is also provided. Strength is controlled by the soil, as well as the grout: higher strengths are found in finer soils (Figure 7), while increasing density has a similar effect. Clearly, the silicate R_p and concentration, and the nature and concentration of the reagent, also control the strength, while the efficiency of pore filling and the grouting pressure also influence the strength of the grouted soil.



1 Unconfined compressive strength Rc
2 Y = volumetric percentage of silicate in grout

gure 7. Unconfined compressive strength of grouted sands (AFTES, 1991).

Strengthening in soils appears to be due primarily to an increase in cohesion as opposed to a change in the internal friction angle. The test stress rate also is significant in determining strength, although this has less influence in triaxial testing. Immediate strength and resistance to creep increase with reagent content, and sensitivity to creep varies with the silicate concentration rate (Littlejohn and Mollamahmutoglu, 1994).

It must be noted that many specialists (and suppliers) believe that there are serious longevity issues associated with the use of sodium silicate grouts (Hewlett and Hutchinson, 1983). This stems from the fact that only in particular environments (high pH soil) is the neutralization of the sodium silicate not reversed, and so syneresis becomes a major factor. In reviewing this problem, Naudts (1996) writes "for the sake of the credibility of the grouting industry, grouting contractors should pay far more attention to the (long-term) durability problems associated with this family of products." It is therefore significant that progress appears to have been made in Japan (Shimada et al., 1992) using carbon dioxide as a reagent, in the "Carbo rock" method. The gas efficiently neutralizes the alkalis, thus preventing environmental contamination during the precipitation of the silica gel and encouraging improved durability. Depending on concentrations, gel times can be substantially varied. Treated soil unconfined strengths of 0.6 to 1.2 MPa are obtained, with residual permeabilities of 1.5 to 2.1 x 10^{-7} m/s.

4. Pure Solutions

Resins are solutions of organic products in water, or a nonaqueous solvent, capable of causing the formation of a gel with specific mechanical properties under normal temperature conditions and in a closed environment. They exist in different forms characterized by their mode of reaction or hardening:

- Polymerization: activated by the addition of a catalyzing element (e.g., poly-acrylamide resins).
- Polymerization and Polycondensation: arising from the combination of two components (e.g., epoxies, aminoplasts).

In general, setting time is controlled by varying the proportions of reagents or components. Resins are used when cement or silicate grouts prove inadequate. Examples of such situations would include the following requirements:

- particularly low grout viscosity.
- high rapid gain of strength (a few hours).

- variable setting time (few seconds to several hours).
- superior chemical resistance.
- special rheological properties (pseudoplastic).
- resistance to high groundwater flows.

Resins are used for both strengthening and waterproofing in cases where durability is essential, and the above characteristics must be provided. Four categories can be recognized: acrylic, phenolic, aminoplastic, and polyurethane. Applications are summarized in Table 5. Chrome lignosulfonates are not discussed, being, according to Naudts (1996), "a reminder of the dark, pioneering days of solution grouting" on account of the environmental damage caused by the highly toxic and dermatitic components.

Acrylic Resins. Acrylic resins are monomers in aqueous solution. A polyerization and reticulization interaction is obtained by adding catalyzers (0.1 to 5 %) (redox system). Accelerators can also be used in the same range of dosages to adjust setting. Viscosities almost as low as water can be achieved (1.2 cP). The set gel, depending on the degree of reticulation, will be more elastic or more plastic in place and will swell accordingly in the presence of water. Unconfined compressive strengths of pure gels are low, but testing of grouted sand samples may yield up to 1.5 MPa. Modified acrylic resins can be produced with: a) sodium silicate, to have low viscosity (2 cP), good mechanical properties, and expansion in water; or b) latex polymers, to have moderate viscosity (15 cP), good adherence, elasticity, and high resistance to extrusion under water pressure.

Type of Resin	**Nature of Ground**	**Use/Application**
Acrylic	Granular, very fine soils	Waterproofing by mass treatment
	Finely fissured rock	Gas tightening (mines, storage) Strengthening up to 1.5 MPa Strengthening of a granular medium subjected to vibrations
Phenol	Granular, very fine soils	Strengthening
Aminoplast	Schists and coals	Strengthening (by adherence to materials of organic origin)
Polyurethane	Large voids	Formation of a foam that forms a barrier against running water (using water-reactive resins) Stabilization or localized filling (using two-component resins)

Table 5. Uses and Applications of Resins (AFTES, 1991).

Phenolic Resins. Powders dissolved in water undergo a phenol-formaldehyde polycondensation by adding an alkaline reagent. Empirically, the gel time is halved for every 8 degrees C increase in temperature. Typical of this category are the tannin formaldehyde grouts which provide the time-viscosity-concentration characteristics illustrated in Figure 8. Depending on the concentration of the active components (typically 12.5 to 25%), unconfined compressive strengths of grouted uniform fine-medium dry sand will be in the range 0.1 to 1 MPa at 7 days. Gelation time also depends on component concentration Figure 9). Particular care should be taken when using certain formaldehyde grouts given the nature of their components. Incorrect batching will result in an unreacted excess of one of these components, thus creating an environmental hazard. Of the three typical components, resorcinol is toxic and caustic, formaldehyde causes respiratory illnesses, and sodium hydroxide is caustic.

Aminoplastic Resins. Aminoplasts also require an acid environment to complete the endothermic polycondensation reaction between a urea and a formaldehyde. Viscosities range from 10 to 100 cP, depending on resin quality, and unconfined strengths vary from 3 to 10 MPa. The foams or gels are inert, but generally contain small amounts of unreacted formaldehyde, and care must be taken with their application.

Polyurethane Resins. Polyurethane resins have two basic classes:

- Water-reactive: Liquid resin, often in solution with a solvent or in a plasticizing agent, possibly with added accelerator, reacts with groundwater to provide either a flexible (elastomeric) or rigid foam. Viscosities range from 50 to 100 cP. These resins have two subdivisions:

    1) Hydrophobic - react with water but repel it after the final (cured) product has been formed.
    2) Hydrophillic - react with water but continue to physically absorb it after the chemical reaction has been completed.

- Two Components: Two compounds in liquid form react to provide either a rigid foam or an elastic gel due to multiple supplementing with a polyisocyanate and a polyol. Such resins have viscosities from 100 to 1,000 cP and strengths as high as 2 MPa. Thorough

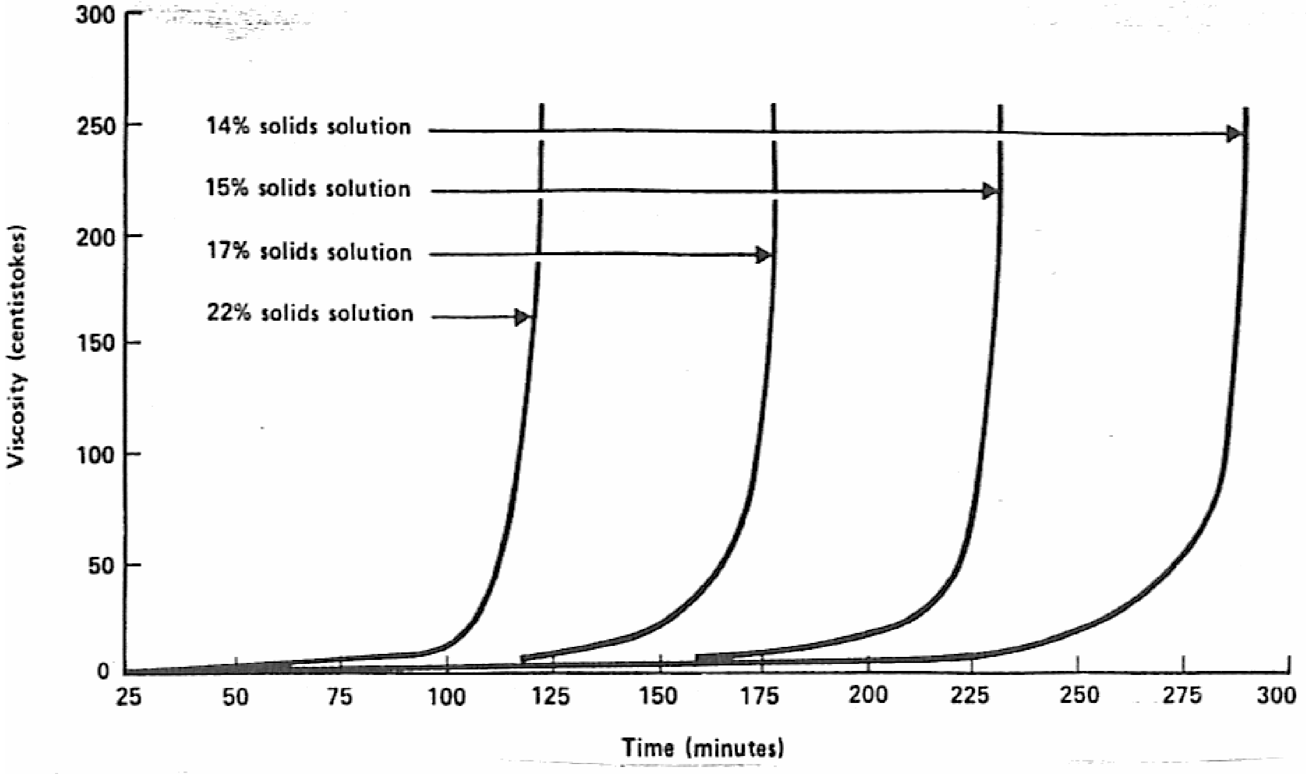


Figure 8. Graph showing typical viscosity/time curves for various grout concentrations. Temperature of solutions held at 10°C.

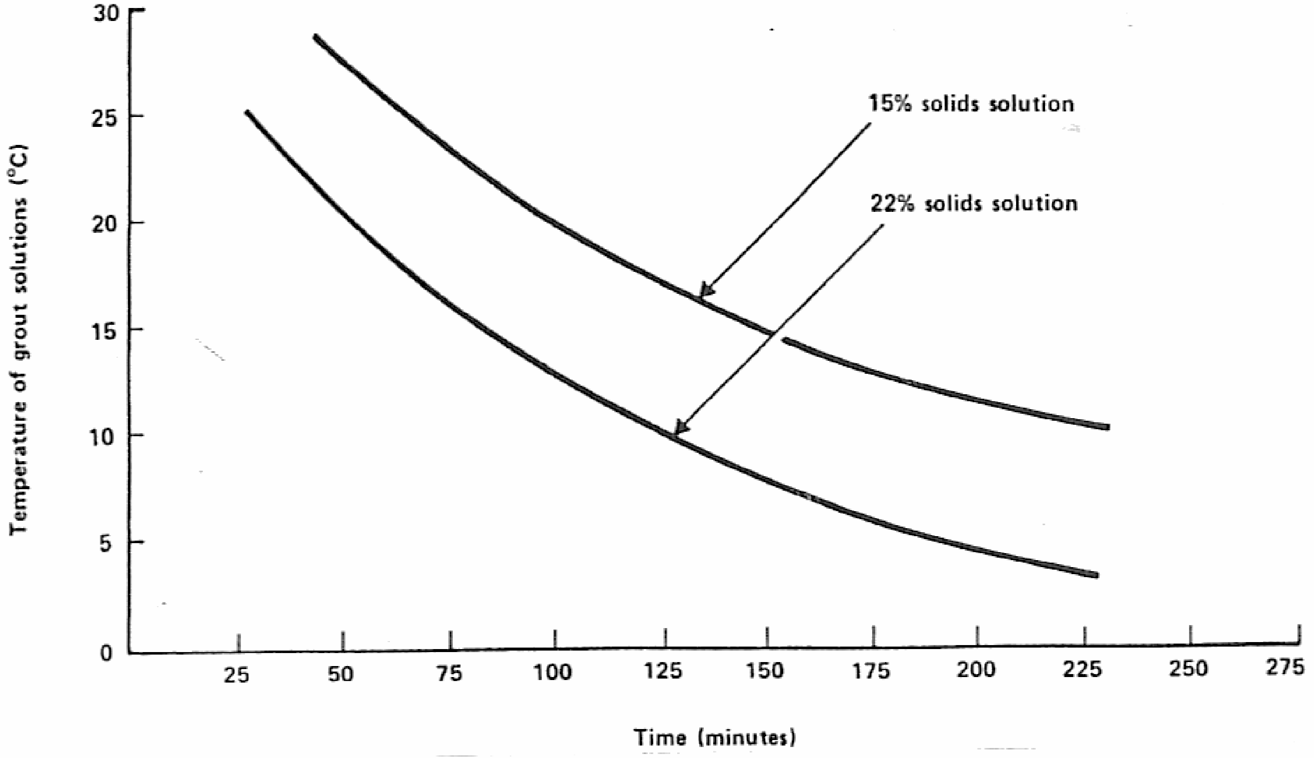


Figure 9. Graph showing effect of temperature on the gelation time of typical solutions.

description of these grouts is provided by Naudts (1990), while a particularly illustrative case history of application was provided by Jiacai et al. (1982).

It may be remarked that the polyurethane grouts provide an extremely useful and wide range of properties, and are enjoying an excellent reputation in "difficult" grouting jobs typically involving high flow rates and excessive heads.

5. Other Grouts

The following grouts are essentially composed of organic compounds or resins. In addition to waterproofing and strengthening, they also provide very specific qualities such as resistance to erosion or corrosion, and flexibility. Their use may be limited by specific concerns such as toxicity, injection and handling difficulties, and cost. Categories include hot melts, latex, polyesters, epoxies, furanic resins, silicones, and silacsols. Some of these (e.g., polyesters and epoxies) have little or no application for ground treatment. Others such as latex and furanic resins are even more obscure and are not described below.

Hot Melts. Bitumens are composed of hydrocarbons of very high molecular weights, usually obtained from the residues of petroleum distillation. Bitumen may be viscous to hard at room temperature, may have low viscosity (15 to 100 cP) when hot (say 200 degrees C plus). They are used in particularly challenging water-stopping applications (Bruce, 1990a and b), remain stable with time, and have good chemical resistance. Simultaneous penetration by stable particulate grouts is necessary to ensure good long-term behavior (Naudts, 1996).

Polyesters. These contain prepolymers in a reactant solution and can be polymerized by adding catalysts.

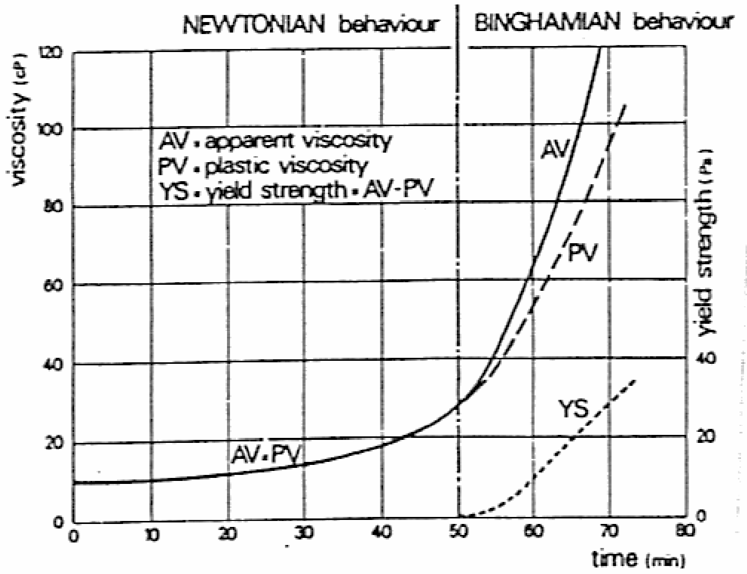
Epoxies. These are liquid pure polymers (Bisphenol A and F), cross linkable by reaction (poly addition) with a hardening agent (amide, amine). Like polyesters, epoxies are used for their high mechanical strength and good adhesive qualities (e.g., Bruce and DePorcellinis, 1991). They also have excellent chemical resistance.

Montan wax. This is a recent German development and is a resin produced from lignite. It has great potential for permanent environmental barriers, either on its own or together with other grouts.

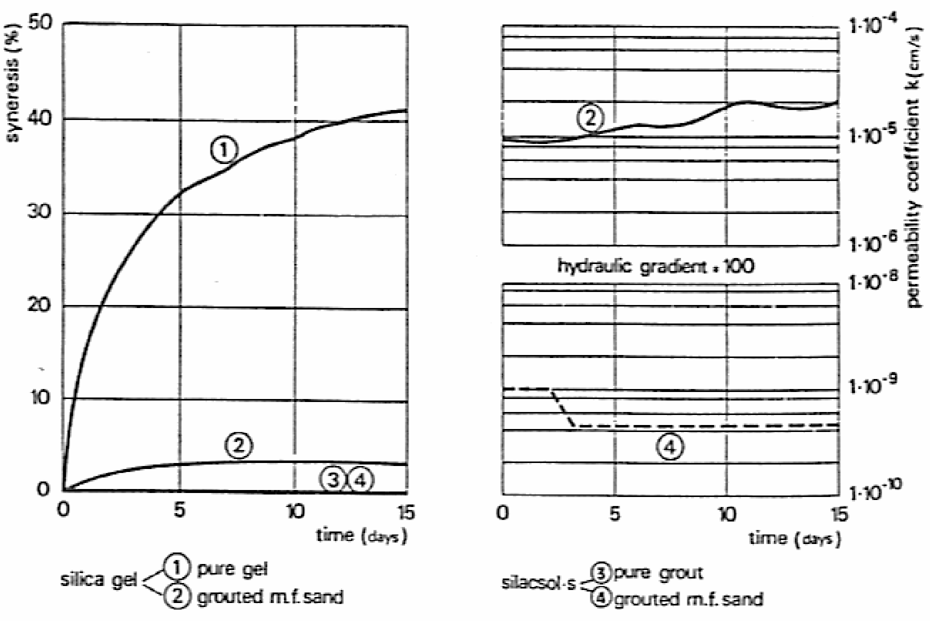
Silicones. Silicones are solution grouts prepolymers that may be hardened (by polycondensation) with cross linking or catalyzing agents. The grouts have great flexibility and excellent chemical resistance. They can be used as a water repellent.

Silacsols. Silacsols are solution grouts formed by reaction between an activated silica liquor and a calcium-based inorganic reagent. Unlike the sodium silicates discussed in Section 3 - aqueous solutions of colloidal silica particles dispersed in soda - the silica liquor is a true solution of activated silica. The reaction products are calcium hydrosilicates with a crystalline structure similar to that obtained by the hydration and setting of Portland cement: a complex of permanently stable crystals. This reaction is not therefore an evolutive gelation involving the formation of macromolecular aggregates (Figure 10), but is a direct reaction on the molecular scale, free of syneresis potential (Figure 11). This concept has been employed in Europe since the mid-1980s (Bruce, 1988) with consistent success in fine-medium sands. The grout is stable, permanent, and environmentally compatible. Other important features, relative to silica gels of similar rheological properties, are:

- their far lower permeability (Figure 11);
- their far superior creep behavior of treated sands for grouts of similar strength (2 MPa);
- even if an unusually large pore space is encountered, or a large hydrofracture fissure is created, a permanent durable filling is assured.



ure 10. Typical viscosity-time behavior of Silacsol-S grc
(Tornaghi et al., 1988).



gure 11. Effect of time on syneresis and permeability of typical chemical grouts (Tornaghi et al., 1988).

Precipitation Grouts. These constitute a relatively unknown family of grouts, despite the fact that arguably the largest grouting project ever conducted used the principle. In essence, a solution (which on its own does not harden) is injected into the groundwater flow, and precipitates crystals or forms complex molecules to fill fissures and pore spaces. At the Esterhazy potash mine in Saskatchewan, saturated calcium chloride solution was injected into fast flowing saturated brine, quickly creating massive crystals of sodium chloride, so effectively reducing flow through the karstic erosional features.

6. Final Remarks

The world of grout materials is in a constant state of evolution, as manufacturers and specialists react to the ever changing demands and restrictions of geotechnical grouting, while benefiting from the growing bank of long-term performance studies. For example, durability and environmental concerns in some countries are arguing against the use of classic sodium silicate grouts, and phenols and aminoplasts. On the other hand, finely ground, modified cement-based grouts, polyurethanes and silacsols appear to offer excellent scope to the practitioner. This overview encapsulates what the authors believe to be the essence of our practice in the late 1990s. The reader is encouraged to pursue the references, and to constantly challenge the validity of the structure and details contained herein, as the years and the developments unfold.

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