Equipment for Cement Grouting: An Overview

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Abstract

Contemporary grouting equipment must be capable of accommodating a wide variety of applications, materials and performance parameters. The paper provides an overview of the major features of mixing, storage, pumping, and monitoring equipment. Typical details of modern equipment are provided to illustrate the range available.

1. Introduction

Grouts based on some type of cement remain the most widely used category throughout the world, exceeding in range of applications the other families including colloidal and pure chemical solutions. These Category 1 particulate grouts (Bruce et al., 1997), depending on their composition may 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. They exhibit a Binghamian performance (Figure 1a), compared to the evolutive or non-evolutive Newtonian characteristics of colloidal solutions and pure solutions, respectively (Figure 1b).

The water to solids ratio is the prime determinant of their properties and basic characteristics which in addition to cohesion, viscosity and stability, include durability and strength (Littlejohn, 1982). Five broad subcategories of particulate grouts can be identified:

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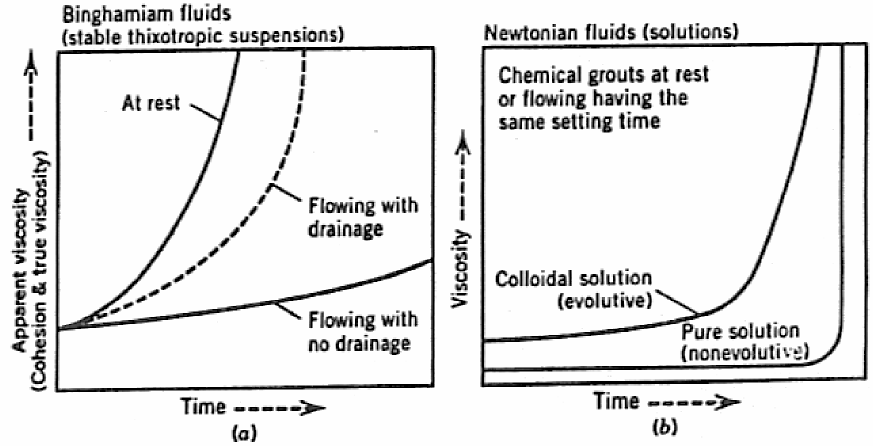

Figure 1. Rheological behavior of typical grouts (Mongilardi and Tornaghi, 1986).

1. Neat Cement Grouts: typically associated with high strength and durability when used either as a ground treatment material per se, or as an integral part of another specialty geotechnical construction process such as anchoring, micropiling, soil nailing or deep mixing.

2. Clay/Bentonite-Cement Grouts: stabilized with a clay mineral to provide specific fluid and set characteristics. Mix designs for water proofing and low strength backfilling applications will have much clay and relatively little cement, while the reverse is true for structural grouts. Jefferis (1982) described how the quality of mixing of such grouts in particular can have a strong influence on the subsequent grout properties especially bleed, penetrability, strength and brittleness.

3. Grouts with Fillers: adding non-cementitious substances substantially modifies the resultant properties and reduces the unit volume cost of the mix. The most common fillers are sands and pulverized flyash (p.f.a.), but other materials have been used depending on local preferences and availability. These are usually fine and inert industrial byproducts including mine tailings, kiln dust, pumice, and silica fume. Major applications include void filling compaction grouting and compensation grouting. Table 1 illustrates the wide range of mix formulations and properties which can be contemplated for p.f.a.-cement grouts alone.

4. Grouts for Special Applications: depending on specific site requirements for the grout in its fluid and/or set condition, there are requirements for grouts with controlled hydration and rheology; foam; enhanced strength; and/or improved resistance to washout. Such grouts will be multicomponent blends of many materials, including typically admixtures and additives (Gause and Bruce, 1997), and are most commonly used in grouting operations in mines, quarries, dams, and tunnels.

5. Grouts with Enhanced Penetrability: to thoroughly and economically fill small pores or fissures while avoiding concerns typical of other categories of grouts, e.g., permanence, toxicity, strength, and cost. Additives are used to improve rheological properties and/or increase pressure-filtration resistance, while the use of microfine cements (Schwarz and Krizek, 1992) is increasing fast.

Table 1. P.f.a.-cement grout properties (Bruce et al., 1997).

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 0.45 0.50	3 6 5	0 2 5	1.765 1.715 1.677	510 >700 >500	17.9 14.0 10.3	22.5 18.0 14.9	31.7 26.0 20.0	49.3 42.9 34.3
2	0.40 0.45 0.50	3 5 7	1 3 6	1.718 1.679 1.648	480 >700 >700	8.7 6.2 5.4	12.2 8.7 7.7	17.5 13.2 12.1	37.9 27.7 25.1
3	0.40 0.45 0.50	6 9 10	4 9 9	1.695 1.650 1.628	460 >700 >700	4.5 3.3 2.7	7.0 5.3 4.4	10.4 8.3 7.2	23.9 18.8 19.1
5	0.40 0.45 0.50	5 8 10	5 8 10	1.675 1.641 1.599	530 >700 >700	2.2 1.6 1.4	3.7 2.7 2.2	5.1 4.4 4.0	15.3 13.4 14.5
7	0.40 0.45 0.50	4 8 11	4 6 9	1.680 1.611 1.587	>700 >700 >700	2.2 1.6 1.4	2.4 2.0 1.8	5.5 4.6 2.9	8.8 6.5 6.0
10	0.40 0.45 0.50	5 8 11	4 6 9	1.643 1.620 1.575	>700 >700 >700	1.5 0.8 0.7	1.9 1.4 1.2	2.3 1.9 1.8	4.9 4.0 2.8
15	0.40 0.45 0.50	6 9 10	6 7 9	1.658 1.608 1.582	>700 >700 >700	1.0 0.6 0.6	1.4 1.0 0.8	2.3 1.7 1.2	3.1 2.2 1.7
20	0.40 0.45 0.50	8 9 10	6 9 9	1.645 1.607 1.580	>700 >700 >700	0.7 0.5 0.5	0.9 0.7 0.6	1.5 1.4 0.8	2.0 2.0 1.3

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

The equipment used to mix, store, pump, and monitor cement based grouts must clearly be compatible with the characteristics of the grouts themselves as well as the project specific parameters, such as anticipated volumes, maximum permissible injection pressures, and access and space restrictions. This paper provides an overview of the various items of equipment in contemporary practice, as well as details of the range of sizes and capacities currently available. It provides an update to the excellent reviews provided in 1990 by Houlsby and in 1991 by Weaver.

2. *Mixing*

The two basic principles are mixing by agitation, and mixing by creating high shear.

2.1 Mixing by Agitation

This group includes the simple paddle mixer (Figure 2) and the continuous screw mixer (Figure 3). The mix components are stirred or blended together until they slowly intermix. However, the shearing forces are very small, and unmixed cementitious lumps are typically illustrative of an unstable, heterogeneous product.

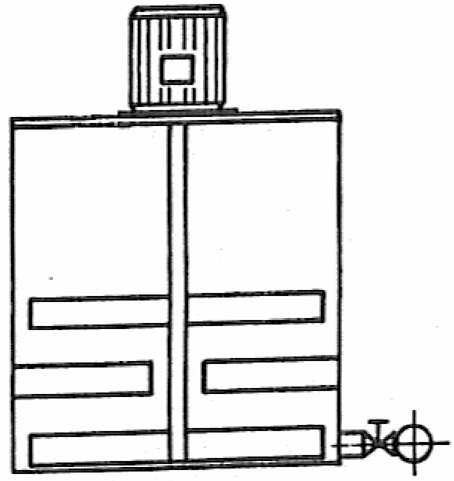

Figure 2. Schematic of a paddle mixer.

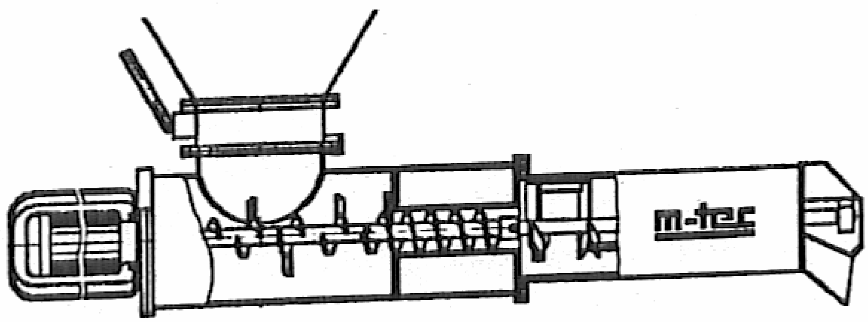

Figure 3. Schematic of a continuous screw mixer.

Such lumps are often orders larger than the pore or fissures which are intended to be penetrated, while the grout instability is also reflected in blockages in grout hoses, pumps, and valves. The unstable mix is also susceptible to dilution with groundwater. The paddle mixer is a "batch" mixer wherein the water/cement ratio can be closely controlled. In contrast, the continuous mixer is subject to grout variation due to fluctuations in the pressure of the water and/or the flow of cement. From both mixers the grout must be gravity fed into a holding tank (agitator), which can be mounted below or beside the mixer (Figures 4a and 4b).

2.2 Mixing by Creating High Shear

High speed, high shear mixers are often referred to as colloidal mixers in recognition of the nature of the suspension created although the suspension more correctly remains "mechanical" rather than "colloidal". These mixers most commonly comprise a mixing tank and a mixing/circulation pump (Figure 5). The pump circulates the water from the bottom to the top of the tank while the other mix components are added and pre-wetted. The cement particles are then individually mixed by the high shearing action of the pump so preventing coagulations or lumps and so ensuring the homogeneity and enhancing the stability of the grout.

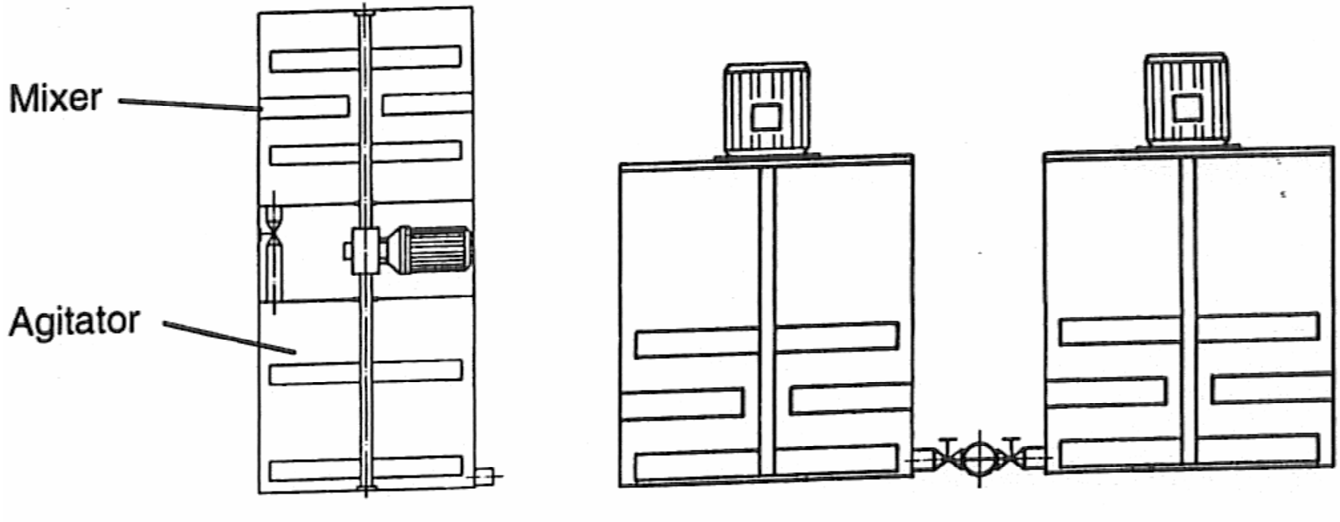

Figure 4. Schematics of a paddle mixer and agitator setups for continuous grouting.

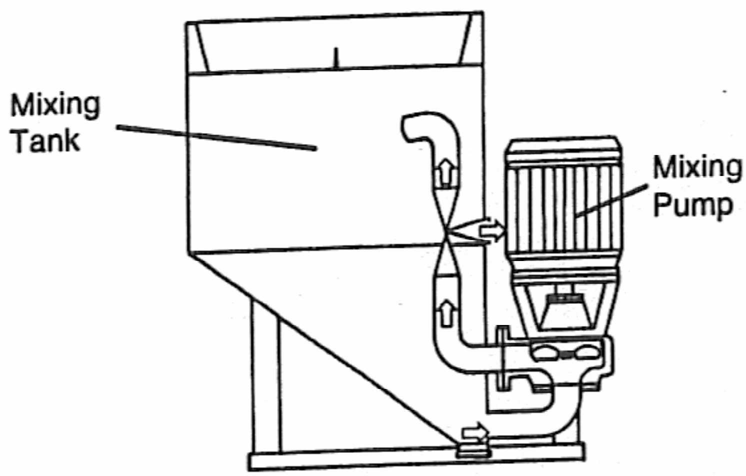

Figure 5. Schematic of a high shear mixer.

Contemporary high shear mixers have the following features:

- Mixing pump speed of 1500 to 2000 rpm.
- Mixing pump capacity such that the whole tank content is circulated a minimum of three times per minute. The pressure generated by the pump is of little importance but is typically up to 0.2 MPa.
- The mixing pump should create high shear either through close tolerances between impeller and casing (e.g., Figure 6) or by creating high turbulence in the pump housing (Figure 7). The latter must have recessed vortex type impellers to ensure adequate turbulence. High turbulence pumps have much less wear than those of the close tolerance types, and are less prone to damage by larger grout particles. They are also suitable for mixing sanded grouts without the need for a separate sand-mixing drum (Figure 8).

- The shape of the mixing tank should be such that the grout vortex in the tank is broken up, near the base, to avoid the intake of air. Peripheral baffles are not suitable as they lead to a buildup of grout and are difficult to keep clean.

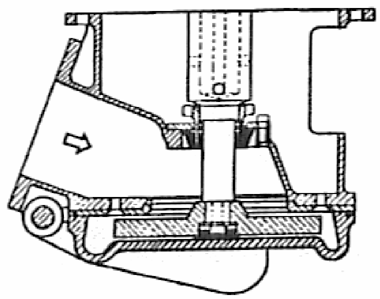

Figure 6. Schematic of a Craelius system mixer.

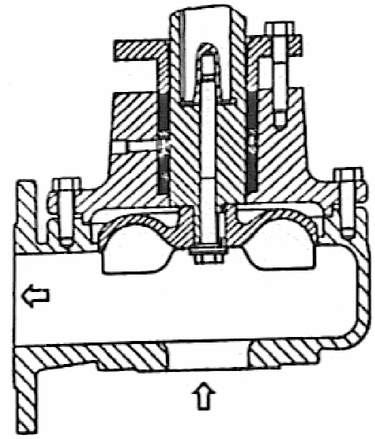

Figure 7. Schematic of a Häny system mixer

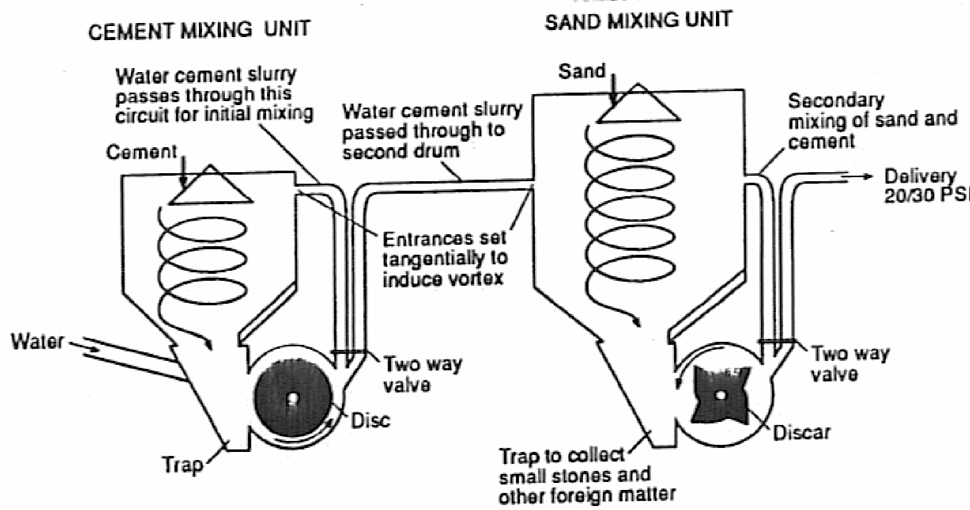

Figure 8. Schematic of a Colcrete double drum mixer for sanded grouts (Weaver, 1991).

High shear mixers can regularly produce neat cement grouts of water/cement ratio as low as 0.4, and even lower when dispersing admixtures are employed. Only 30 to 60 seconds are needed for complete mixing after the addition of the last portion of cement. Longer circulation is unnecessary and may be deleterious to the grout properties due to excessive heat generation resulting from the very efficient mixing action. The mix should therefore be transferred as quickly as possible to the agitator/holding tank, using the natural pump pressure.

Such mixers are batch mixers, which means that a full mixing cycle has to be completed before the mix can be used. This makes the use of a holding tank or a second mixer essential if a continuous grouting operation is required, but does allow the water/cement ratio and the various filler and admixture portions to be precisely controlled. In this regard, water is monitored via a calibrated holding tank, or a water flow meter, usually equipped with a preset cutoff control. Other components are measured by discrete pre-measured volumes (e.g., bags of cement; packets of admixture) or by bulk delivery systems (e.g., bulk delivered materials and screw feed, weigh or volume batching equipment). It has been found that if the mixers themselves are mounted on load cells, the weight of all components *actually placed in the mixer*, can be precisely known. This feature also saves space and allows for easy transportation without dismounting the scale. Most mixers have rated outputs in the range of 2 to 40 m^3/hr, with usable drum volumes of 100 to 2500 liters. These require motors of 3 to 52 kW power. A typical range of mixers from one manufacturer is shown in Table 2.

It should also be noted that a high shear action can also be provided by "jet mixers", which have no moving parts. They use the venturi principle to make a vacuum: a strong jet of water discharging into an enlarged chamber accomplishes this. The cement is sucked into the vacuum and then mixes with the water jet. Such mixers are best suited to high volume outputs of relatively fluid mixes. The water/cement ratio can be controlled by varying the rate of water flow in response to readings from a nuclear density meter mounted on the discharge line (Houlsby, 1990).

Table 2. Details of Hány high shear mixers.

MODEL	UNITS	HCM 100	HCM 300	HCM 300	HCM 600	HCM 800	HCM 2500
Production approx. (w/c ratio = 1)	m^3/hr	2	5	5	8	20	40
Circulation capacity	l/min	540	1100	1400	1400	2400	4800
Usable volume	Liter	100	260	260	550	800	2500
Max. particle size	mm	5	8	8	8	3	-
Electric motor							
50 Hz	kW	3	5.5	9	9	22	45
60 Hz	kW	3.6	-	11	11	25	52
Water connection		¾"	1"	1"	1½"	-	-
Length	mm	800	1150	1150	1360	1650	2600
Width	mm	640	820	820	1010	1400	2220
Total height	mm	1075	1140	1140	1500	2000	2040
Batching height	mm	870	1000	1000	1360	2000	1900
Weight	kg	115	250	275	320	1150	2350

2.3 Agitators/Holding Tanks

Batch mixers (either paddle or high shear) must be complemented by a holding tank to allow uninterrupted pumping . Such tanks should have a capacity at least 30 percent bigger than the usable capacity of the mixer to prevent the pump running dry. A slowly revolving agitator paddle mounted at an angle to the axis of the tank prevents the mix tending to segregate, and relieves any air bubbles which may have been entrained during the mixing and transfer processes. A sieve at the inlet intercepts any large particles or debris. Agitators can be equipped with level probes to control automatic mixing cycles based on consumption rates.

As is the case for all the grouting equipment reviewed in this paper, the actual power source can be varied to suit local conditions. Thus, although electric drive is most common (either directly or electro-hydraulic), diesel engines or compressed air are also common choices.

Agitators are typically of useful capacity 160 to 3000 liters, requiring motors of 0.75 to 3.6 kW (Table 3).

Table 3. Details of Häny agitators.

MODEL	UNITS	HRW 160	HRW 350	HRW 800	HRW 1200	HRW 3000
Usable volume	Liter	160	350	800	1050	3000
Electric motor 50 Hz 60 Hz	 kW kW	 0.75 0.90	 0.55 0.66	 0.55 0.66	 1.5 1.8	 3 3.6
Paddle speed 50 Hz 60 Hz	 min^{-1} min^{-1}	 36 43	 47 56	 47 56	 34 40	 32 38
Length	mm	1100	810	1000	1200	2000
Width	mm	1100	810	1000	1200	1950
Height	mm	1280	1230	1550	2300	2350
Weight	kg	150	155	230	450	1025

3. *Pumps*

3.1 Basic Considerations

The key choices to be made relate to the required flow rates and pressures. Flow rates must be compatible with the nature of the grouts and the ground being injected, the purpose of the injection program, as well as logistical and economic factors.

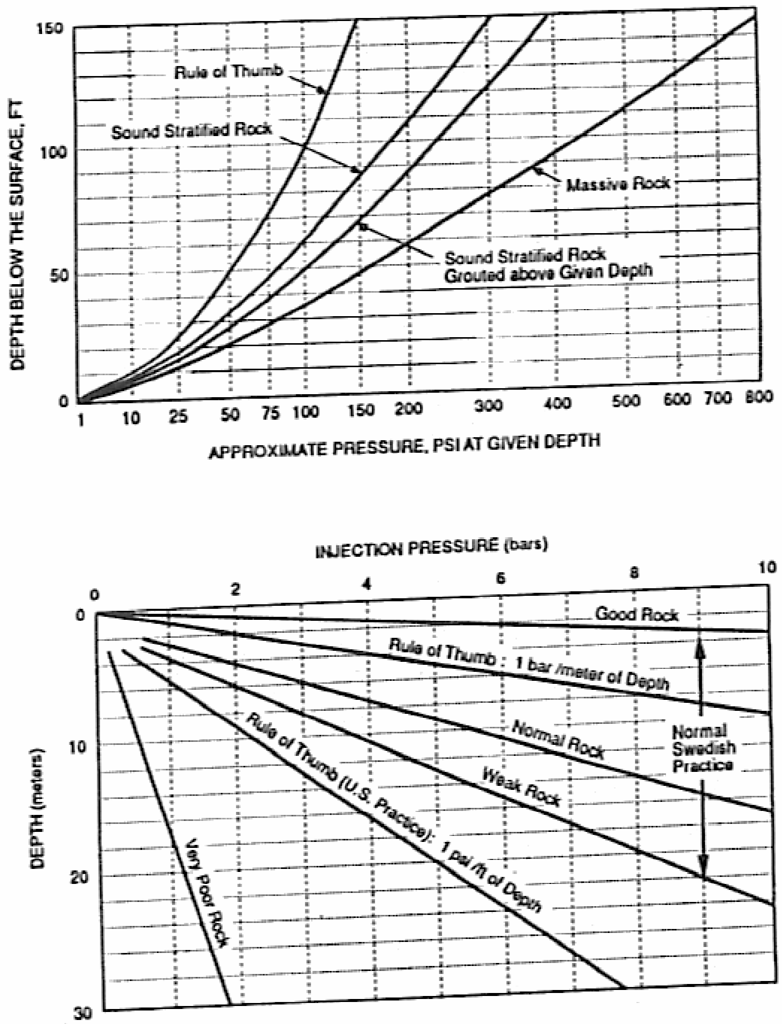

Figure 9. Injection pressures used in U.S. (above), and Swedish (below) grouting practices (Weaver, 1991).

Even more important is the selection and control of grouting pressures: excessive pressures may lift structures or damage formations whereas insufficient pressure may lead to inefficient grout placement. For certain grouting applications (e.g., tunnel backfilling) the maximum grout pressure can be readily calculated, based on structural strength parameters, and various safeguards put in place during injection (e.g., "vent" holes). However, for rock and soil grouting it is more difficult to agree appropriate safe maximum pressures, due to the inherent variability of the ground (and the properties of the grouts), as well as fundamental differences in philosophy. Thus the "European" philosophy calls for higher pressures (e.g., 0.1 MPa/m depth) to break through weak formations and encourage penetration into adjacent spaces, while the "North American" philosophy calls for low pressures to preserve the virgin structure as much as possible (0.022 MPa/m). This argument has been discussed widely, but it clearly illustrated by Weaver (1991), as shown on Figure 9.

Another controversial point is whether the injection should be at a constant pressure or whether fluctuations can be accommodated. While it is obvious that any pressure peaks cannot exceed the maximum allowable pressure (Figure 10), the authors believe that short pressure drops within the specified pressure range may not only be acceptable, but may actually help to move the grout particles into finer fissures and voids: the short and frequent relaxation of pressure allows the particles to reorient and adapt to the restraints of the fissure whereas constant pressure will cause bridging and initiate pressure filtration (Figure 11). This latter phenomenon is only acerbated by raising the (constant) pressure. The authors therefore consider it advantageous to use plunger or piston pumps, as long as they are equipped with precise pressure control valves. They also allow the use of single line grouting and permit the holding of a specified maximum pressure to encourage proper refusal (assuming appropriately formulated grouts are being injected).

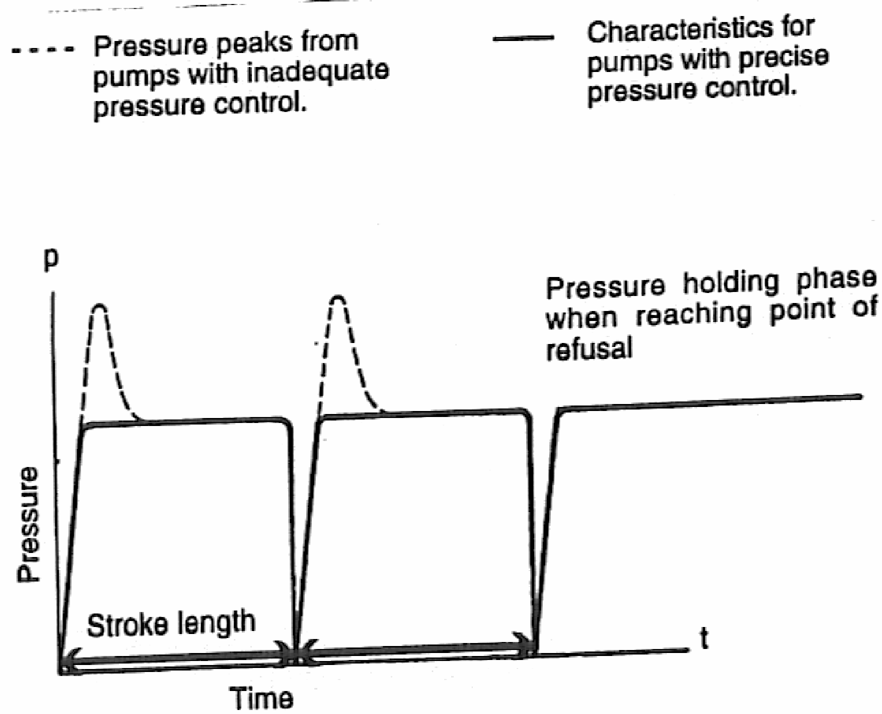

Figure 10. Output pressure characteristics of piston and plunger pumps.

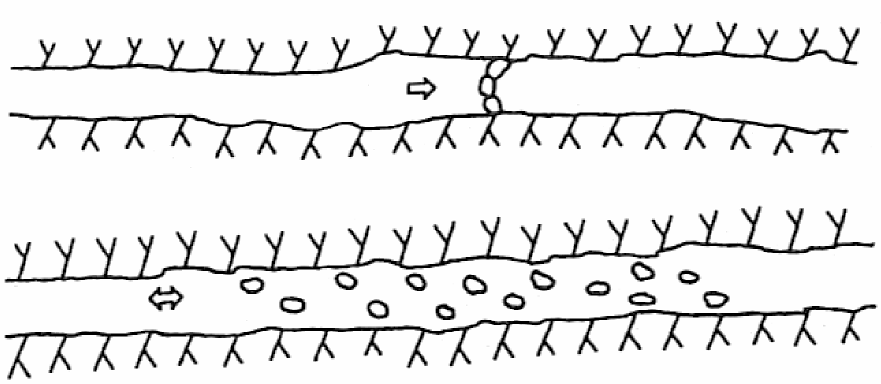

Figure 11. Fissure grouting showing particle bridging effect at constant pressure (above), and reorientation of particles under short pressure fluctuations (below).

3.2 Pump Selection Criteria

Attention should be paid to the following factors:

- The maximum injection pressure should be adjustable on the pump. All the controls must be on the drive ("dry") side and not on the grout ("wet") side where valves do not function as reliably or as long. The control valves should allow a predetermined maximum pressure to be held over a preset period of time. Pressure control devices with an ON-OFF function should be avoided as they cause the pump to cut in and out very frequently and no pressure holding effect can be achieved near refusal.
- Fully adjustable output.
- Piston or plunger pumps with direct drives do not allow pressure and flow to be controlled adequately.
- Abrasive grouts call for a low wear pump system (e.g., plunger).
- Must be easily cleaned and maintained.
- Must have non-clog type, full area valves to handle viscous or sanded grouts.

3.3 Common Pump Types

There are three types of pumps which remain in common contemporary use worldwide:

- Progressive Cavity Pumps (Figure 12): these are also known as helical screw, progressive helical cavity, worm, Mono or Moyno pumps and are widely used in rock grouting and associated geotechnical process grouting. Although they are relatively inexpensive to purchase and mechanically simple, their maintenance costs may be higher due to high wear rates on the rubber stator and the steel rotor, especially when sanded grouts are used. Maximum pressure is moderate (2 MPa) for a 4-stage pump although injection rates can be high (4 m^3/hr). Pressure and output controls may not be closely adjustable for most models and so a valve system at the injection point is required, in conjunction with a return line system. Both add cost. Such pumps provide an essentially constant pressure output.
- Piston Pumps (Figure 13): most are double-acting reciprocating pumps, and have a higher initial capital cost but lower maintenance costs. High pressure (over 7 MPa) and moderate flow characteristics are allied to close pressure and flow rate controls especially on electro-hydraulic units. Grouts with fine sands can be accommodated readily, although the tight fit between piston seal and lining results in increased wear. Another potential disadvantage is that the gravity type valves may clog when pumping more viscous grouts over prolonged periods.
- Plunger Pumps (Figures 14, 15, and 16): are probably the most versatile grout pumps and most commonly used worldwide. Initial costs are similar to piston

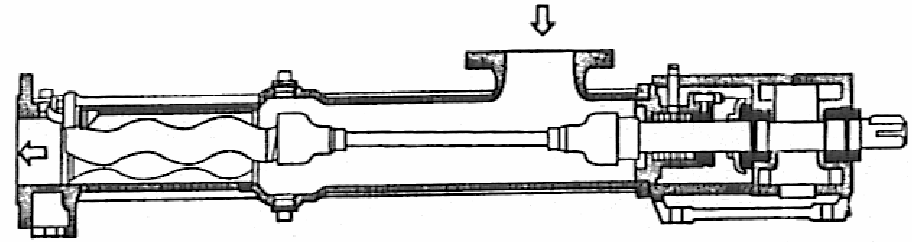

Figure 12. Schematic of a progressive cavity pump.

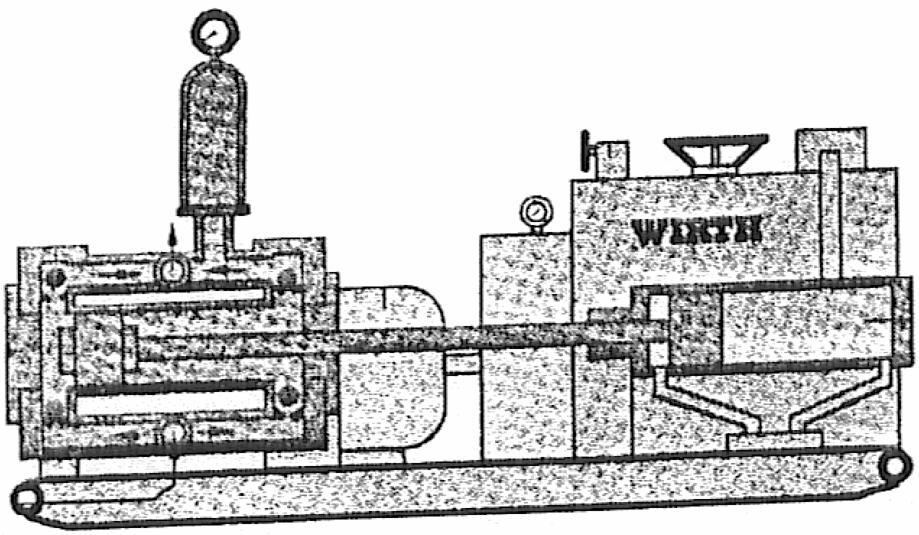

Figure 13. Schematic of a piston pump.

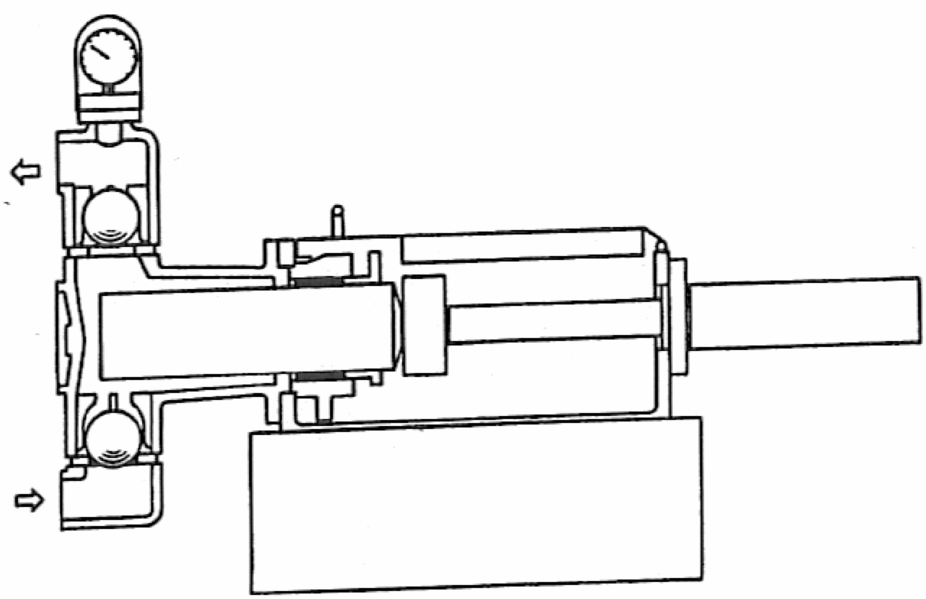

Figure 14. Schematic of a plunger pump.

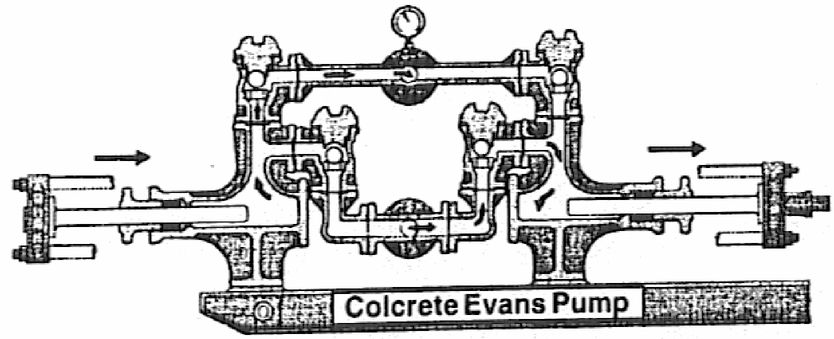

Figure 15. Schematic of a double acting, reciprocating plunger pump.

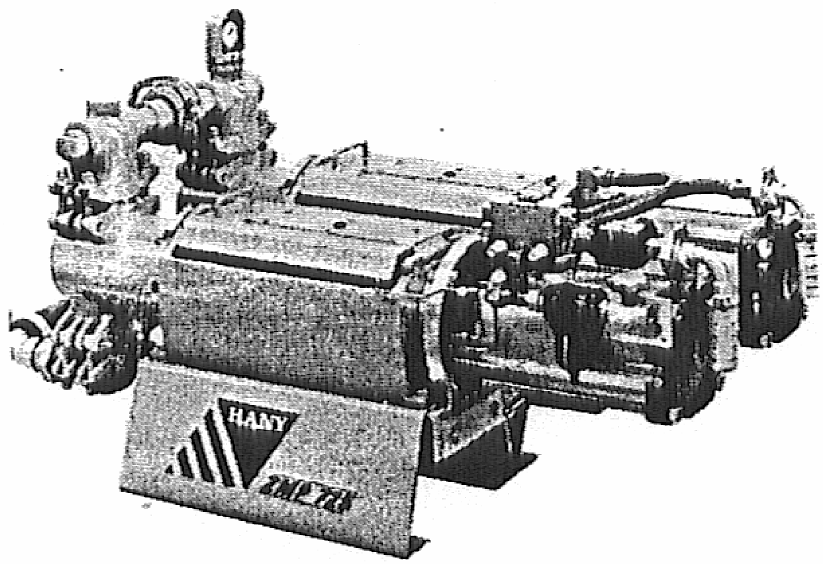

Figure 16. Photo of a double acting plunger pump ("side by side").

pumps, while the pressure and flow ranges cover all usual grouting requirements. Some manufacturers provide very precise pressure and flow control features on their hydraulic or pneumatic drive systems. They have low wear characteristics, and, by virtue of being able to quickly change plungers, can significantly reduce the number of pump sizes which have to be carried by the contractor faced with a wide range of applications. The fast suction stroke creates a high grout velocity which flushes the suction valve on every stroke thus eliminating clogging or " floating" of the valves when injecting at high pressure or low flow rates. Heavily sanded grouts, with particle sizes up to 8 mm can be pumped without the risk of blockage. Rates of injection of 1 to 13 m^3/hr can be provided, at pressures up to 10 MPa.

4. *Injection Parameter Recording*

The accurate recording and informative presentation of all the mixing and injection parameters are essential elements in the grouting QA/QC and verification process. In particular, such data can be used in real time to allow the grouting engineer to make informed decisions as to the progress and efficiency of the grouting of each stage. There are various steps in this process.

- Mix batching verification: the accuracy of mix batching when manually conducted is dependent on the skill and care of the operators, and verified by systematic testing of the mix, by the quality control inspectors, in its fluid form (e.g., specific gravity, bleed, flow time, setting and stiffening times). When an automatic mixing plant is used, the computer generated records of the weight components of the components in each batch constitute the prime record, supported, as for manual batching, by fluid mix test data.
- Data Acquisition of Pressure and Flow Rates: pressure transducers should be located close to the point of injection to minimize friction loss implications. Such transducers must be separated physically from the grout by a diaphragm. It is now common to have the output directly transferred to the grouting engineer's computer display via telemetry or hardwire. Flow rates are preferably recorded by an inductive flow meter, which has no obstructed passage or moving parts. Sensitivities should reflect the full range of flow rates anticipated, but should typically be in the range of 1 to 5 liters/min. The meter must also be able to accommodate quick velocity changes, especially important when piston or plunger pumps are to be used. Generally, the accuracy should be within 1% for flow rates down to 5% of the full scale and at 1% of full scale, the accuracy should still be within 5%. The composition of the grout has no influence on the measurement accuracy provided the grout has a minimum conductivity of about 5µs. Chemical additives or admixtures are generally compatible with the use of these meters. Recent developments have made it possible to record flow rates and quantities by stroke impulses from piston or plunger pumps. The value of an impulse can be easily calibrated to within 5%. Prime advantages of stroke recording are the simplicity of the system and its low costs relative to inductive flow meters.
- Recording, Display and Analysis Equipment: the most commonly used recorders incorporate electro-magnetic (inductive) flow meters and electronic pressure transducers. Pressure and flow rate are continuously recorded and displayed on a chart recorder (Figure 17), the total quantities being accumulated by a resettable counter. Water test data and grout location injection information can be provided. Contemporary computer technology permits an almost unlimited variety of data output to be displayed, and processed, and when used by knowledgeable and understanding grouting engineers can be a very powerful tool for significantly improving the quality and efficiency of the grouting program (Wilson and Dreese, 1998). In addition, such records constitute an invaluable source of data when planning a similar program in comparable conditions. All

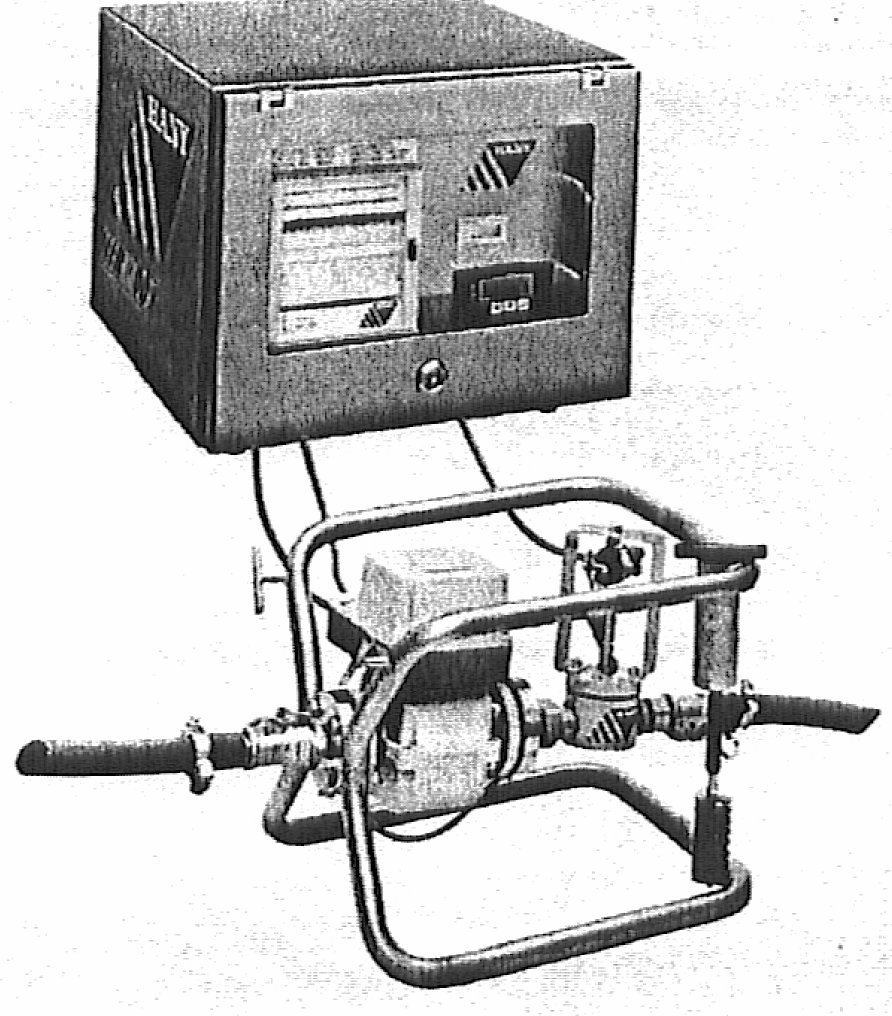

Figure 17. Simple pressure and flow recording unit.

monitoring equipment must be designed to cope with typical site conditions, and must be operated and maintained by skilled operators as opposed to computer specialists. New units are capable of recording pressure and flow data from up to six grout lines simultaneously. Signals from flow meters and/or stroke impulses are collected, and limits on grout volume pressure and flow rate can be preset for each group pump. Data are recorded on standard memory cards and later processed under a Windows-based program or can be processed and displayed in real time.

Weaver (1991) described proprietary automated injection systems wherein the outputs from drilling parameter recorders are "married" to automated plants to cause "the proper grout mix to be injected at the proper pressure for a given soil condition". Similar electronic recording and analytical equipment can also

- Obtain, record, and interpret in situ permeability tests.
- Design grout patterns and quantities.
- Identify anomalies and produce various tables, graphs, and documents.
- Record and display surface movement data in relation to the grouting progress (for compensation grouting).

5. Combined Units

Depending on the application for the grouting, and the project requirements and constraints, it is often found that all the equipment components are combined into one portable unit. Thus for anchor, micropile, soil nail, or tunnel contact grouting, compact integrated units are available, comprising a high shear mixer, holding tank, grout pump and power pack. In addition, a water flow meter or grout injection parameter instrumentation is usually mounted on the same steel frame. Outputs of 1 to 8 m^3/hr are commonly available, with the pump capacities, depending also on choice, rated at 2 to 10 MPa. For projects such as deep mixing or diaphragm walling where large volumes of slurry are required, larger, containerized units are produced, usually fed by screw conveyors. Figure 18 provides a view of a typical 2-pump set up. Such plants can produce 12 to 45 m^3/hr depending on the type and composition of the mix, have a weigh batch accuracy of ± 3% and can weigh up to 8500 kg.

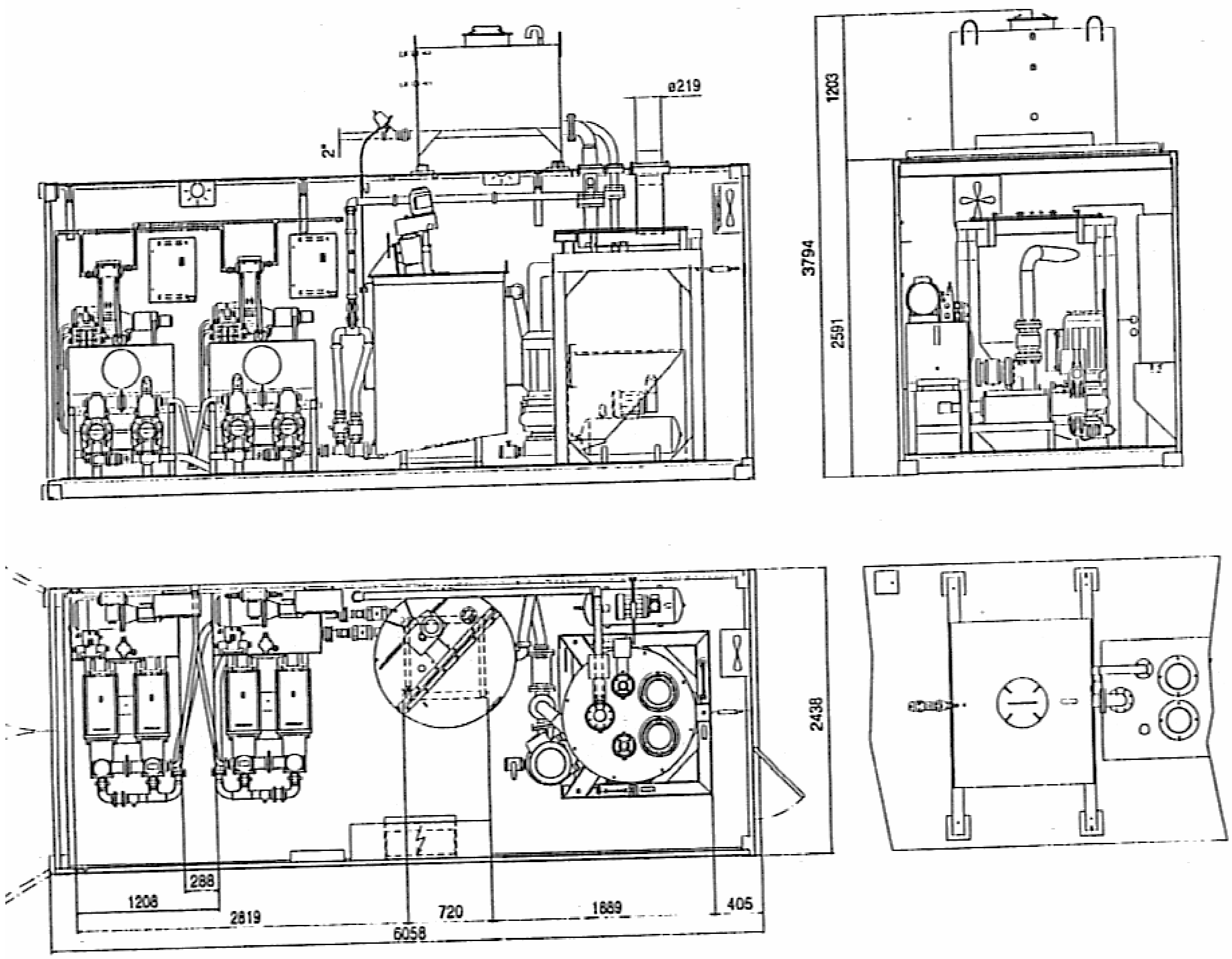

Figure 18. Plan of a typical containerized combined unit.

6. *Final Remarks*

Practice in cement grouting technology is spread across a wide variety of applications, and employs a similarly extensive range of materials, grouts, and parameters. The correct choice of the most appropriate batching, mixing, pumping, and recording systems plays a vital role in the potential success of any grouting project. The growing use of multicomponent grout formulations, often using microfine cements, requires equipment that can accurately batch and efficiently mix the components so that the intrinsic benefits of these materials can be fully exploited: the use of high shear mixing equipment is therefore essential to produce fully hydrated, homogeneous "colloidal" suspensions. Pumps are available which are capable of pumping grouts with a wide range of rheological properties under closely controllable pressure and flow rate limits, and which can satisfy the different national injection philosophies. Regarding data recording and display, the ability to view and process such information in real time is integral to the management of a successful project. Aided by modern computer technology this goal is readily and economically achievable.

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