Fundamental Observations on Cement Based Grouts (1): Traditional Materials

B. De Paoli[1], B. Bosco[1], R. Granata[1], and D.A. Bruce[2]

Abstract

Researches have been carried out in recent years to find additives capable of increasing the stability and reducing the cohesion of cement based grouts. In Italy, these studies have led to the development of the MISTRA grouts, a family of stable suspensions with enhanced permeation properties. This paper compares the characteristics of MISTRA grouts with those of conventional cement grouts with and without bentonite.

Introduction

The penetrability of a cement based grout into pores or fissures depends on two main factors: the grain size of the cement used, and the rheologic properties of the suspension.

As is well known, the success of the grout reflects the size of the solid particles of the grout in relation to those of the voids or fissures to be grouted. However, to evaluate the penetrability of a mix by merely studying the size of the single dry grains is misleading: permeation may often be compromised more rapidly than foreseen by the tendency of single grains to agglomerate, thereby producing "flocs" larger than the single dry particles. Therefore, an improvement in penetrability should feature both the use of cements with finer grain size, and a reduction in the tendency for single grains to flocculate in the mix.

Penetrability is also controlled by its rheologic properties, which are normally reflected in three parameters: plastic viscosity, cohesion, and internal

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[1] All of Rodio S.p.A., Casalmaiocco, Milano, Italy

[2] Nicholson Construction of America, P.O. Box 308,
Bridgeville, PA 15017

friction. Figure 1 shows two laws of rheological behaviour: Curve (1) is typical of a purely viscous fluid (Newtonian) like water; Curve (2) represents the behaviour of a Binghamian fluid, characterized not only by viscosity but also by cohesion. Neither of the two liquids in Figure 1 shows internal friction. If they did, and the shear strength depended also on the fluid pressure, the behaviour would be that shown in Figure 2. Cement grouts are not solutions but particulate suspensions in water. If these suspensions are stable

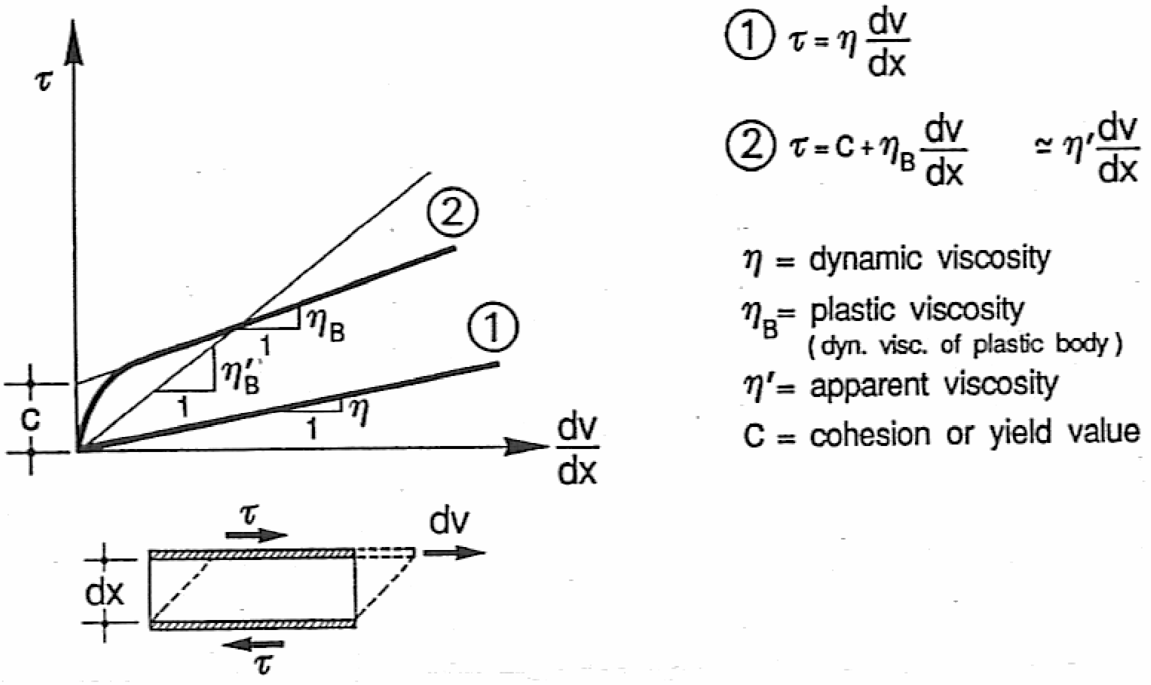
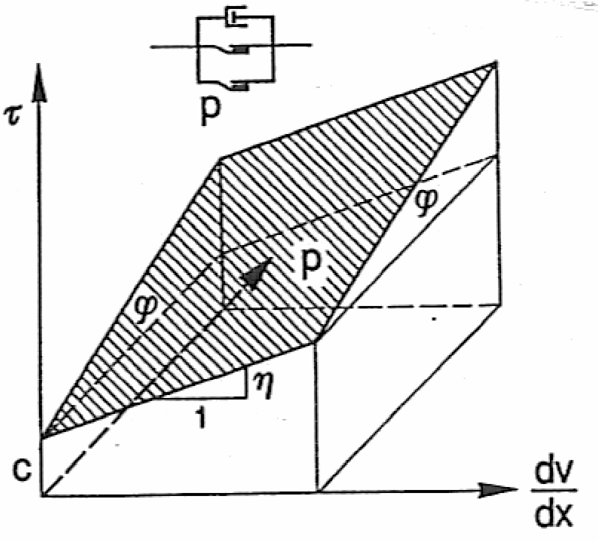


Figure 1. Rheological laws: 1) Newtonian fluid
2) Binghamian body



$$\tau = c + \eta \frac{dv}{dx} + p \cdot tg\varphi$$

Figure 2. Rheological surface of a Binghamian body with internal friction (Lombardi, 1985).

(i.e. during the grouting process the water does not separate from the cement) they behave like a Binghamian fluid. If, however, the mix is unstable, it will separate into components and its behaviour will become unpredictable, being alternatively a Newtonian or Binghamian fluid with internal friction. Simple theoretical considerations and elementary experimental evidence show that, as soon as internal friction appears in the mix, grouting is no longer possible. For instance, in a very dense grout the cement grains come into contact and so develop friction that can arrest the grouting process. This phenomenon is particularly important since, during the grouting process, the initial C/W* ratio of the grout may decrease, due to loss of water under the applied pressure (i.e. pressure filtration) or simply due to gravity (i.e. bleed).

All suspensions tend to decant by gravity, but this phenomenon affects more the effective yield of the grout than its penetrability: due to this bleeding, part of the grouted voids will remain full of water. The influence on penetrability of the loss of water due to pressure filtration is, however, much greater. Injected under pressure, the mix, even if stable with respect to bleed, may lose water through the soil matrix or the rock fissure walls, which are permeable to water but not to cement particles. This loss of water causes a rapid thickening of the mix, with a consequential increase of viscosity and rigidity and formation of a dense, dry cake. These phenomena block the flow and will initiate hydrofracturing if the pressure is increased. To improve mix penetrability it is therefore necessary to increase its stability under pressure, thereby reducing water loss and filter cake growth.

Assuming a stable, perfectly viscoplastic mix, Lombardi (1985) analyzed the flow conditions of a mix through a smooth rock fissure in an excellent parametric study. He concluded: a) the cohesion determines the maximum distance the grout can reach; b) the viscosity determines the flow rate and therefore the time necessary to complete the injection. Therefore, a significant improvement in penetrability may be obtained by reducing the initial cohesion of the mix and delaying its increase with time.

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* It is common practice in parts of Europe to express grout composition in relation to the cement to water ratio: the inverse of W/C. These ratios are expressed by weight.

To summarize, there are two main ways of improving grout penetrability: a) by reducing the size of the cement grains and preventing their flocculation; and b) by improving the grout's rheological properties, increasing the stability under pressure filtration and reducing the cohesion values. The former approach is described by De Paoli et al. (1992), while the latter topic is addressed in this paper.

Controlling Mix Properties with Additives

A water-cement grout tends to be unstable with respect to both bleeding and pressure filtration for the C/W ratios normally used in soils (C/W = 0.2 to 0.6) and in rocks (C/W = 0.4 to 1.4). To stabilize it, the additive most commonly used is bentonite, in weight ratio to water normally between 1 and 6%. The addition of bentonite, however, strongly increases cohesion and, to a lesser extent, viscosity. Nevertheless, the addition of a colloidal additive has been sanctioned for decades as a necessary evil, particularly for grouting soils. In more recent years, additives have been sought to act on the cement and bentonite, to strongly limit the cohesion increase, to improve stability to pressure filtration and to reduce the rate of filtercake formation.

This research has led in Italy to the development of mixes with special additives (Na-metacrylates) which have provided considerable improvements in the penetrability of grouts prepared with traditional cements and made stable with the use of bentonite*. These additives produce a triple effect: a) they reduce the attraction between the single solid particles (and consequently reduce grain agglomeration); b) they reduce the apparent viscosity and cohesion; and c) they increase mix stability (by lowering the cake permeability which in turn limits the loss of pressure filtered water and consequently the rate of filtercake growth).

The properties of each mix obviously depend on the characteristics of the products (cement, water and bentonite) used locally and their relative compatibility. The following comparisons are made between the characteristics of various mixes, prepared with Italian materials in a laboratory study whose aim was to analyze the behavioural variations caused by the addition of bentonite and additives.

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* Commercially these mixes have the MISTRA^R (Rodio Stable Additivated Mixes) trademark. This terminology will be used in the text.

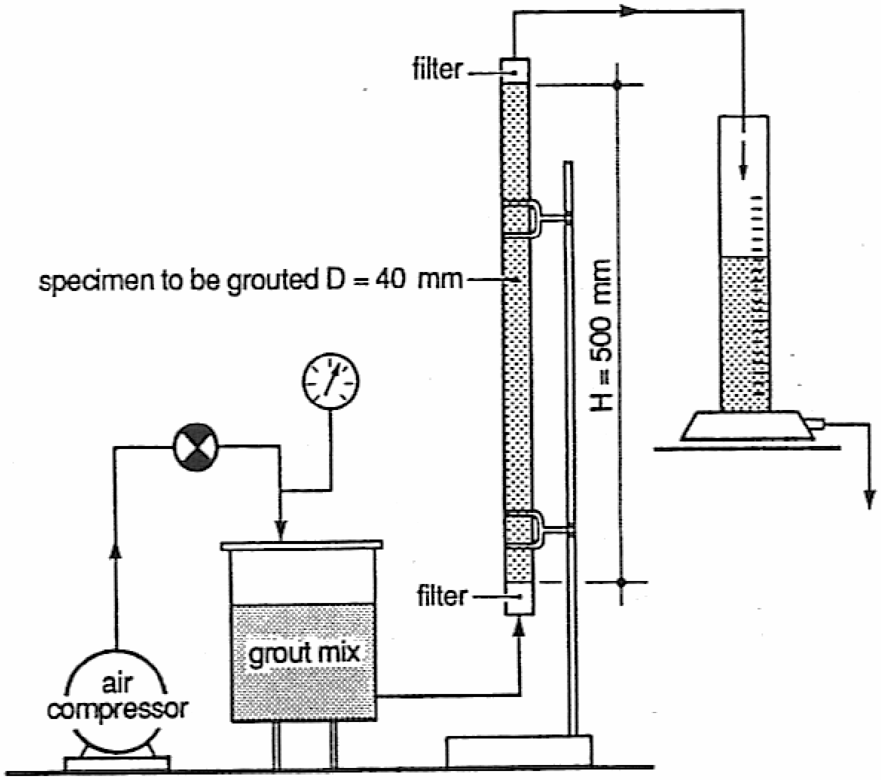


Figure 3. Mould grouting apparatus.

Experimental Methods of Study

Modelling the "penetrability" parameter in the laboratory is not easy. For soils, there is the tendency to check grout behaviour directly using an apparatus of the type illustrated in Figure 3, which uses a sample of saturated, compacted sand. However, due to the variability inherent in sample preparation, this procedure leaves a wide margin of doubt. Rarer, and even less reliable, are the procedures proposed to model the grouting of fissured rocks. Considering the large number of possible experimental parameters, we decided against studying these soil/grout or rock/grout interactions, preferring to analyze, through standard equipment and procedures, the properties of the mixes themselves.

The viscosity and cohesion parameters were measured with a Marsh Cone and Baroid Rheometer following the API standard procedure (American Petroleum Institute 1988). Bleed was measured in 0.5 liter graduated cylinders. The stability under pressure was determined using the API filter press. The test is performed by placing a volume V_i of mix in the cup of the apparatus, then measuring the quantity of water V_f separated from cement through a filter paper, under a 7 bar pressure, in time t (American Petroleum Institute standard procedure, 1988). A cake with high density and high angle of friction forms on top of the filter paper, simulating in the laboratory what takes place along the grouted surfaces. From this test, the volume of pressure filtered water and the thickness (h) of the cake are found and the pressure filtration coefficient K_{pf} and cake growth coefficient K_{pc} can be calculated:

$$K_{pf} = V_f/V_i \cdot t^{-1/2} \quad (\text{min}^{-1/2}), \text{ and } K_{pc} = h \cdot t^{-1/2} \quad (\text{mm.min}^{-1/2})$$

Obviously, the lower the coefficients K_{pf} and K_{pc}, the higher the stability under pressure.

The medium-long term strength characteristics were measured by means of unconfined compressive tests on cylindrical samples following the ASTM C39 method. The permeability of the mixes was measured in a triaxial cell, with a confining pressure one fifth of the expected compressive strength.

The test program was executed to compare the behaviour of the following three categories of grouts:

I- Unstable mixes, prepared by mixing (2 minutes) neat cement with drinking water;

II- Ordinary Stable mixes, prepared by mixing (2 minutes) cement with bentonite slurry;

III- Additivated Stable mixes, made by mixing (2 minutes) cement with bentonite slurry, and additive (4 g/1).

The mixes were prepared in a RE166-Pabbish mixer operating at 3000 rpm. For the stable mixes the bentonite slurry was hydrated for 24 hours before adding the additive (if any) and the cement.

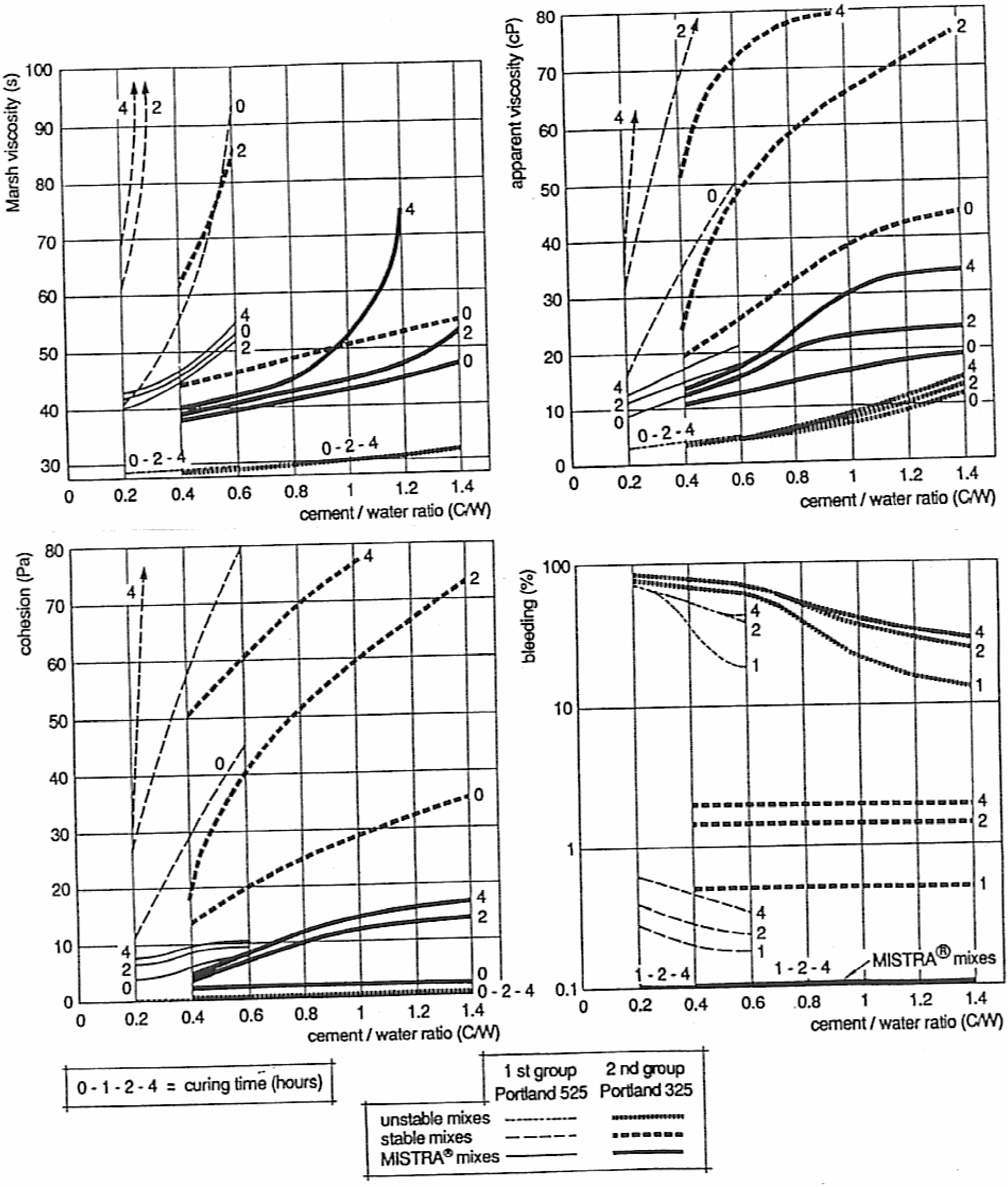
Within each category, two groups of mixes were studied:

a) for the first group, Portland 525 (5100 Blaine) cement was used, with C/W ratios from 0.2 to 0.6, such as typically used for soil treatment. The bentonite content, when used, was maintained constant at 5% by weight of water.

b) for the second group, Portland 325 (2960 Blaine) cement was used, with C/W ratios from 0.4 to 1.4, as often used for rock grouting. The bentonite content, in stable mixes, varied between 3.7 and 5%, in reverse proportion to the cement content, to ensure a bleed of less than 2%, while still limiting the Marsh viscosity to acceptable values.

Summary of Results

The measurements of viscosity (Marsh and apparent) and cohesion were made on fresh mixes and were



<u>Figure 4.</u> Grout rheology and stability, as related to cement content.

repeated after a further 2 and 4 hours. The results are summarized in the graphs of <u>Figure 4</u>:

- <u>Unstable mixes</u>: the value of the initial apparent viscosity was, for the two groups of mixes examined,

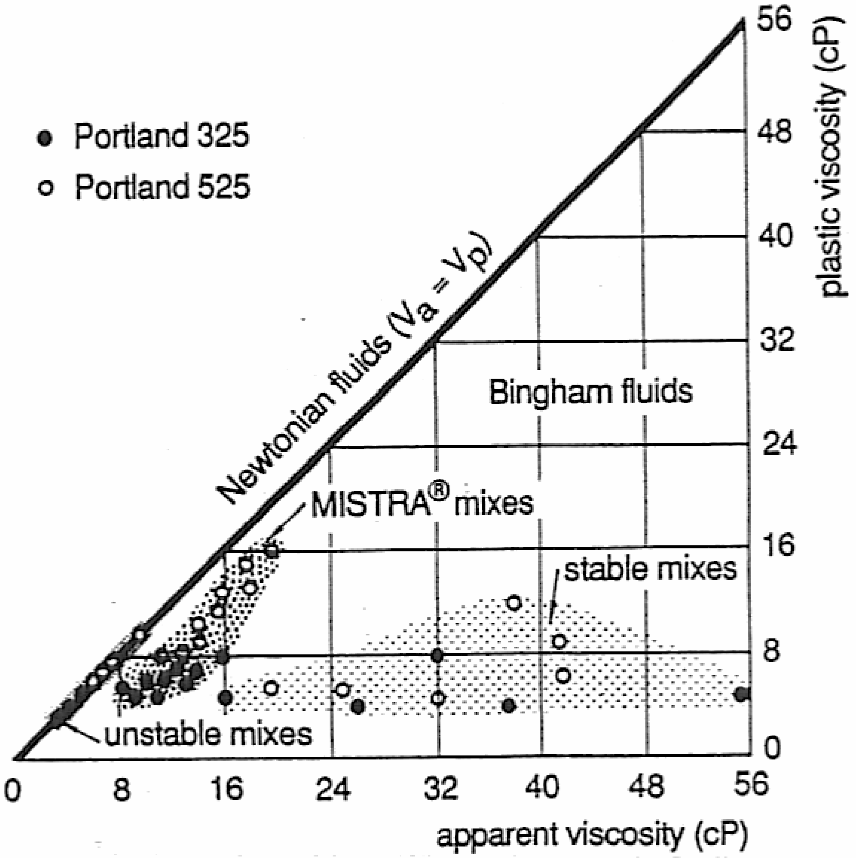


Figure 5. Relationship between plastic and apparent viscosities for the different types of mixes.

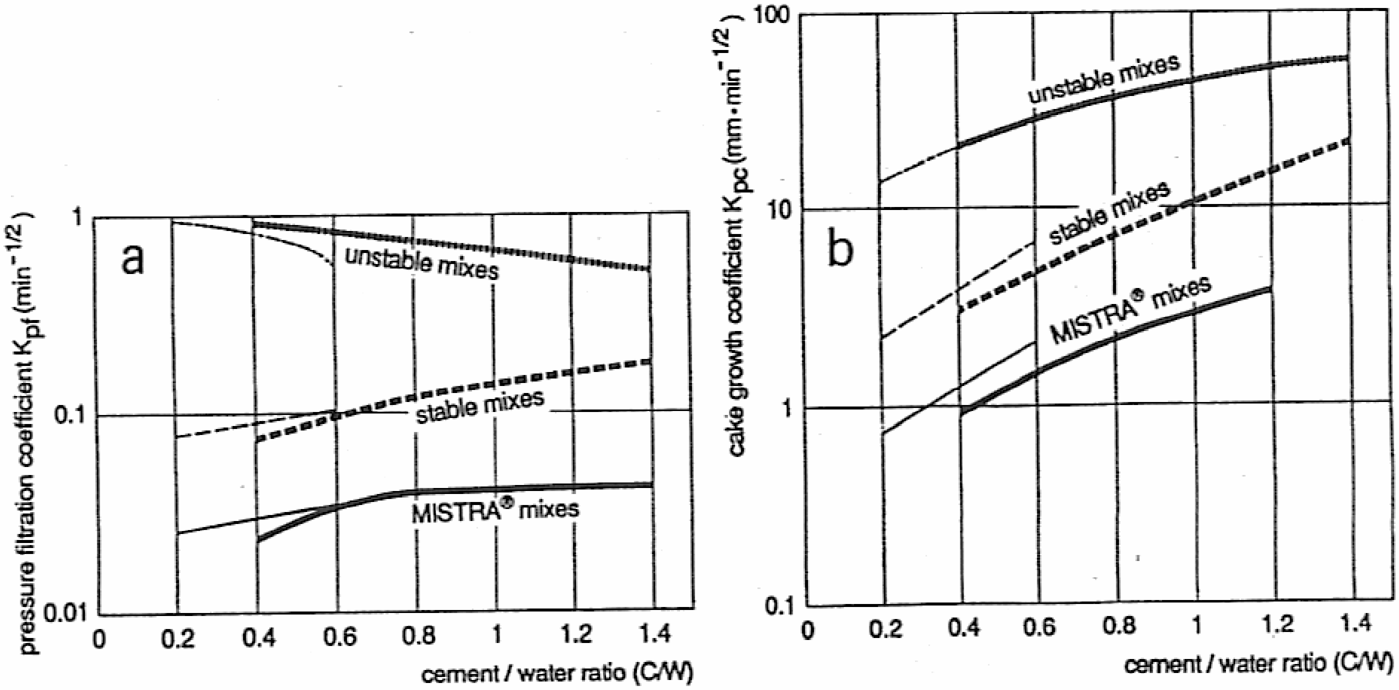


Figure 6. a) Pressure filtration and b) cake growth coefficients of different mixes, related to cement content.

approximately in the ranges 3 to 5 and 3.5 to 11 cP (respectively 29-30 and 29-32 Marsh). These values remained practically constant within 4 hours from preparation. All the mixes presented the behaviour of a substantially Newtonian fluid, being free from cohesion for up to 4 hours.

- <u>Stable mixes</u>: the initial apparent viscosity for both groups increased from 16 to 50 and 19 to 43 cP respectively (40 to 93 and 44 to 55 Marsh). Cohesion changed from 11 to 45 Pa and 13.5 to 35 Pa, respectively. The mixes evolved rapidly with time, tending to exceed the measurement capacity of the Marsh and Rheometer equipment within 4 hours.

- <u>Stable mixes with additives</u>: the apparent viscosity, for both groups, was decidedly lower than that of the ordinary stable mixes, and showed initial values between 9 and 18 cP (37 - 52 Marsh). The cohesion was also much lower than that of the ordinary mixes and was controlled by the additive content. The initially recorded values varied between 2 and 8 Pa. The rheological deterioration of the mixes with time was fairly slow, especially with C/W ratios lower than 0.6.

In all stable mixes, the fineness of the two cements used had an important influence on the rheological properties. In particular, with equal cement and bentonite content, cohesion and viscosity rose sharply with cement fineness. In <u>Figure 5</u> the apparent viscosity values are correlated with those of plastic viscosity. It may be seen that the ordinary stable mixes were farthest from the Newtonian behaviour. Stable mixes with additives, on the contrary, while forming part of the Binghamian bodies, presented a less rigid behaviour, closer to that of Newtonian fluids both initially and 4 hours after preparation.

As regards <u>stability</u>, bleed development is shown in <u>Figure 4</u> while the behaviour of the grouts under pressure is illustrated in <u>Figure 6</u>, in terms of pressure filtration (K_{pf}) and cake growth (K_{pc}) coefficients. The following conclusions may be drawn:

- <u>Unstable mixes</u>: these rapidly lost (in less than a minute) all free water. This led to very high K_{pf} and K_{pc} values, ranging between 0.97 and 0.5, and 13 and 50 respectively, as a function of cement content. Bleed was always fast and high, ranging between 20 and 90% within 4 hours, depending on cement fineness and C/W ratio.

- Stable mixes: these tended to show an improved water retaining capacity: K_{pf} remained in the 0.7 to 0.18 range and K_{pc} remained limited in the 2 to 20 range. Bleed was always less than 2% within 4 hours.

- Stable mixes with additives: the resistance to pressure filtration was enhanced: K_{pf} was always below the limit value 0.04 while K_{pc} did not exceed 3. There was no bleed.

Strength and permeability characteristics were measured only on stable mixes (both Ordinary and Additivated), leaving out the unstable mixes that are generally characterized by final C/W ratios much greater than the initial ones. The results are shown in Figure 7. In general, higher strengths were obtained, with equal C/W ratio, by the additivated mixes. Permeability values were, however, more interesting: mixes with additives showed, on average, a 10 times lower permeability than ordinary stable mixes and these results were further regulated by the additive content.

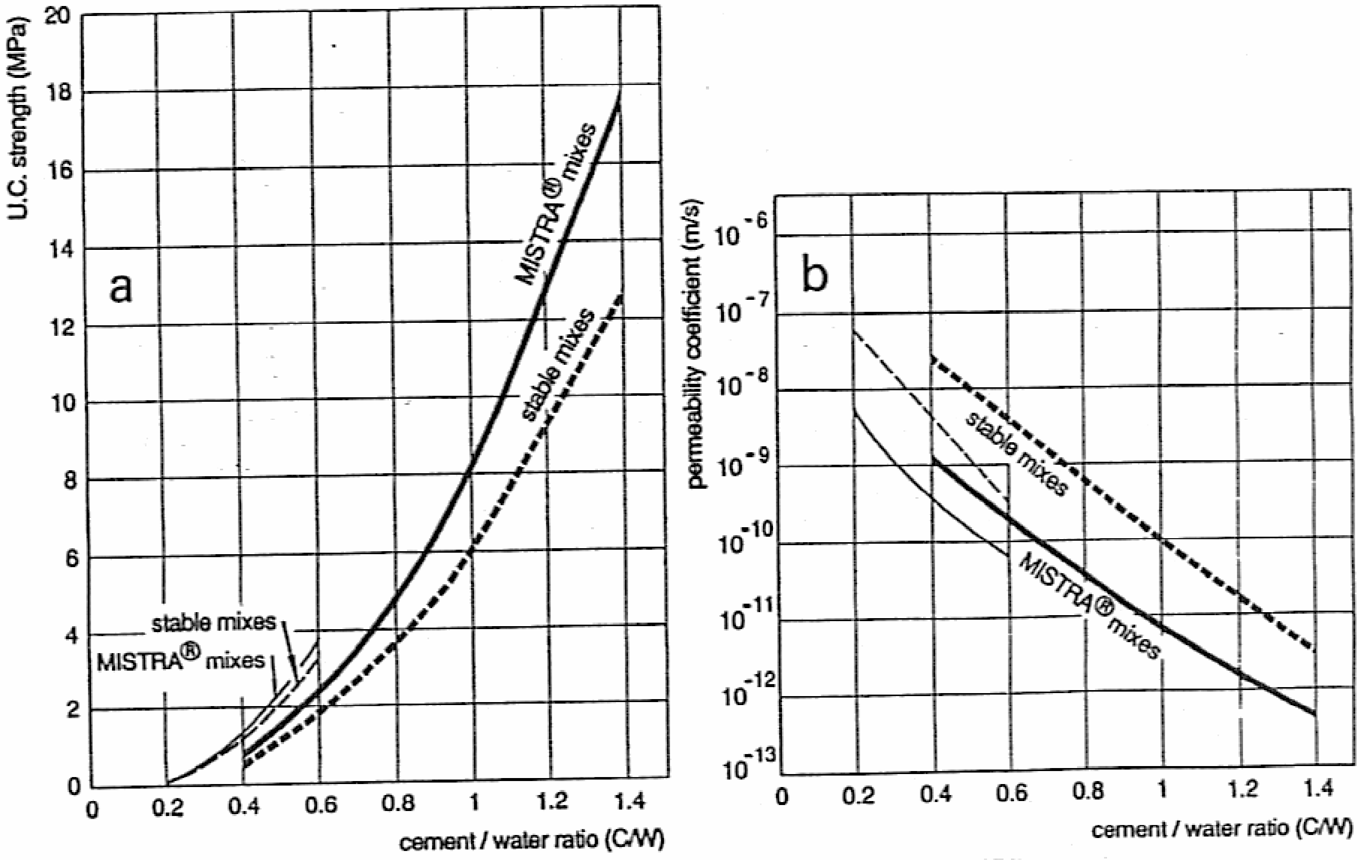


Figure 7. a) Unconfined compressive strength, and b) permeability of stable and MISTRA^{R} mixes (at 28 days)

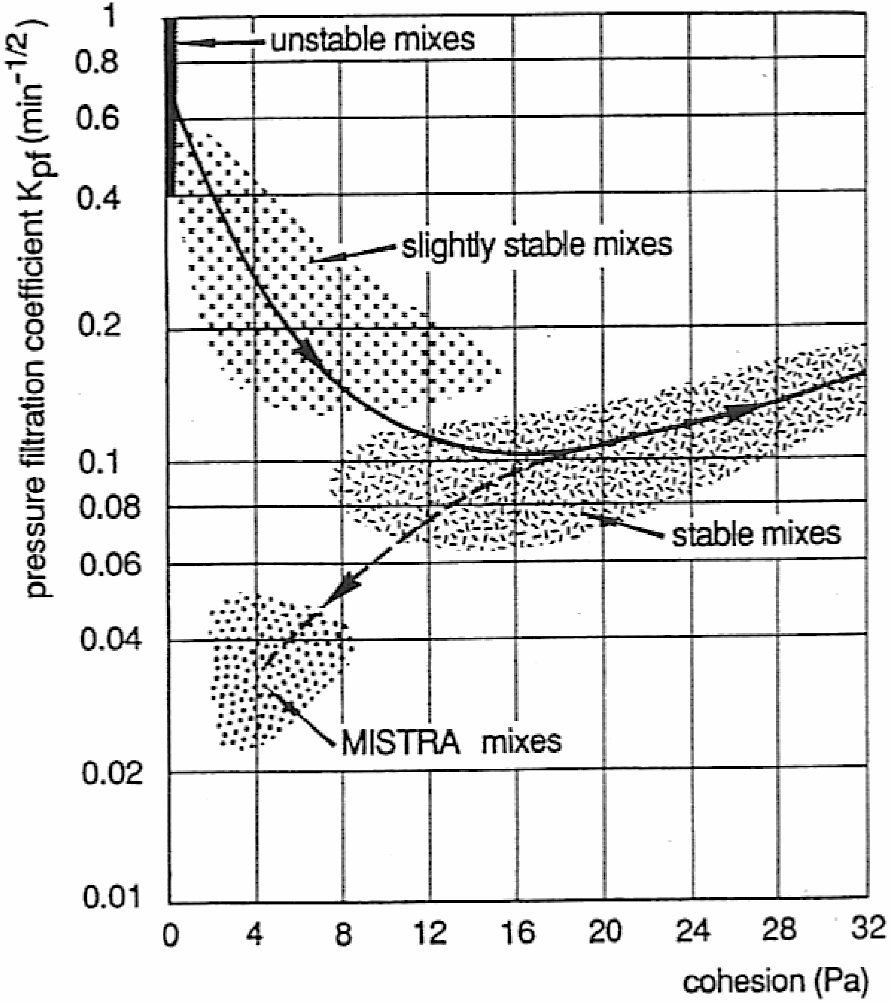


Figure 8. Relationship between stability under pressure and cohesion for the different types of mixes.

Conclusions

The addition of appropriate dispersing agents to the grout permits the use of bentonite for effective stabilization of the mixes, while preventing the associated worsening of the rheological characteristics. Figure 8 shows the pressure filtration coefficient of the various categories of mixes as a function of cohesion: the unstable mixes present practically no cohesion, but this advantage is offset by the high K_{pf} values which means immediate loss of water, development of internal friction, and so grout refusal. On the other hand, the progressive stabilization by means of bentonite causes a reduction of the K_{pf} values but also the simultaneous increase of cohesion. The additivated mixes (MISTRA) simultaneously offer low cohesion (at least 50% of conventional stable mixes), as well as higher stability under pressure (with K_{pf} and K_{pc} reduced on average 5 and 10 times respectively). This way, the additivated stable mixes can increase the radius of influence, even with fairly low pressures.

Furthermore, these MISTRA mixes give a high volumetric yield, with uniformly filled voids, a more efficient waterproofing ability (as a result of the improved penetrability and the lower permeability of the mix), and a higher erosion resistance thanks to improved mechanical strength with equal cement content. Their efficacy in the field has already been proved on a succession of major tunnel and dam grouting projects in Europe and Asia, featuring consolidation and sealing of soils and rock masses.

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