A preliminary study of the parameters influencing the perfomance of two-component backfill grout

Studio preliminare dei fattori che influenzano le performance delle malte bicomponente da backfilling

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Abstract

In the mechanized tunnelling with Tunnel Boring Machines (TBM), the filling process of the tail void that is created simultaneously to the advancement of the TBM between the excavation profile and the extrados of the precast concrete segments of the final lining takes on particular importance. The effectiveness of this operation depends on the injection methods and the mechanical characteristics of the injected material, which is crucial for the success of the excavation, the correct positioning of the lining elements and the reduction of the effects induced on the surface (settlements). This note presents the preliminary results of a study on the two-component backfill grout commonly used during mechanized tunnelling to fill the annular gap between the excavated soil and the lining. The research, carried out by GEEG srl, startup of Sapienza University of Rome at the geotechnical laboratory of Dept. of Structural and Geotechnical Engineering and the chemical laboratory of Dept. of Chemical Engineering, Materials, Environment, is still ongoing and aims to a better comprehension of the chemical and physical factors that influence the performance of these mixtures and to the standardization of the test procedures to be applied in order to measure them. In particular, the data here presented explore the influence of the composition and the methods of preparation of the specimens on the mechanical properties of the grout obtained with alkaline and alkali-free accelerator.

Sommario

Nello scavo meccanizzato di gallerie con Tunnel Boring Machines (TBM) assume particolare rilievo il riempimento del gap anulare che si viene a creare contestualmente all'avanzamento dello scavo tra il profilo di scavo della TBM e l'estradosso del rivestimento delle gallerie in conci di calcestruzzo prefabbricato. Dalle modalità di iniezione e dalle caratteristiche meccaniche del materiale iniettato dipende l'efficacia di questa operazione determinante per la buona riuscita dello scavo, il corretto posizionamento del rivestimento, la corretta distribuzione degli sforzi sui conci di rivestimento e la riduzione degli effetti indotti in superficie. Questo contributo presenta i risultati preliminari di uno studio sulle malte bicomponente comunemente iniettate attraverso lo scudo delle TBM nello lo spazio anulare a tergo conci. La ricerca, portata avanti dalla startup di Sapienza GEEG srl presso i laboratori di geotecnica del Dipartimento di Ingegneria Strutturale e Geotecnica e il laboratorio di chimica del Dipartimento di Chimica Materiali Ambiente, è tutt'ora in corso e ha lo scopo di contribuire alla comprensione dei fattori chimici e fisici che influenzano le prestazioni di queste miscele e alla standardizzazione delle procedure di prova con cui misurarle. In particolare, i dati qui presentati riguardano l'influenza della composizione e delle modalità di preparazione dei provini sulle caratteristiche meccaniche delle malte ottenute con accelerante alcalino e alcali-free.

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1. Introduction

A very important task for the successful excavation of a tunnel with *TBM* technology is the immediate filling of the void between the lining and the excavated soil; an operation, known as backfilling, which generally consists in the injection of cement mixtures



at the end of the *TBM* shield. These mixtures are entrusted with various functions, such as providing an uniform contact between the lining and the surrounding soil in order to avoid settlements at the ground surface, as ensuring the homogeneous transmission of stress between the soil/rock mass and the lining, thus avoiding the generation of concentrated loads, as supporting the rings in

the correct position avoiding misalignments, as bearing part of the loads transmitted by the *TBM* during the thrust and, eventually, improving the impermeabilization. Therefore, it seems evident that these grouts must achieve certain requirements in terms of workability, setting time and mechanical properties. In this regard, the best choice appears to be the two-component grout, because it combines an almost immediate development of the strength with the pumpability necessary for conveying the fluid from the mixing site (usually outside the tunnel) to the excavation front where the injection takes place. This grout consist of two fluids: a component A (cement, bentonite, water and a retarding agent which inhibits the setting during transport) and a component B (accelerating additive), which produce a gel within seconds from the moment they are joined, i.e. the injection.

As often happens in the world of civil engineering, the use of two-component grouts spread widely before the complete comprehension of the chemical-physical phenomena ruling it, therefore the mix design and its characterization before and after setting were entrusted to engineering and construction practice before that relevant scientific studies were published. In the last decade, several authors and research groups [2,8,10,11] have developed research activities on two-component grouts with the aim of defining standards that can allow the comparison of data from different laboratories and construction sites, as well as the optimization of the mix design, the verification of the design requirements and the support to Contractors and Designers in defining the most suitable solutions for specific projects.

The ongoing study carried out at the geotechnical laboratory of DISG and the laboratories of DICMA, both of the Sapienza University of Rome, of which some preliminary results are here presented, aims to identify the factors that most influence the performance of the two-component grout, through the adoption of procedures for sample preparation that replicate as much as possible the real ones and repeatable test conditions. The mixtures were prepared using both a classic alkaline accelerator, sodium silicate, and an alkali-free accelerator.

2. Chemical and physical parameters influencing the gel formation: effects of pH and temperature

Two-component grouts can develop a moderate mechanical strength thanks to their ability to modify their texture into gel [10]. The gelification takes place when a component A (cement, bentonite, water and retarder) come at contact with a component B, the accelerator, which promotes the reaction. Different formulations of the accelerating component are available.

The classic formulation exploits the presence of an alkaline activator [3], mainly consisting of SiO₂ and Al₂O₃ in an amorphous form, [10] which acts as a promoter for the cement hydration reaction. In particular, the silicate is made available in the form of Na₂SiO₃·9H₂O [6] since the silicate sodium salt is compatible with all types of cement and its solutions maintain their properties unaltered with changes in temperature, humidity, and can endure the action of oxidizing or reducing agents. However, an excessive dosage of silicates leads to a detrimental effects such

as the reduction of resistance over the 28 days of ageing with the formation of fractures depending on the curing conditions [1], and the triggering of alkali-silica reactions (*ASR*) responsible for chemical degradation and loss of cohesion of the grout over time [7].

To overcome this kind of problems, formulations of accelerator with an alkaline content lower than 1% [9], commonly defined *alkali-free*, were produced. According to literature studies, so-dium silicate is partially replaced by aluminium sulphate for its coagulating capacity [13] and for its capability to enhance the formation of primary ettringite, which acts substantially as a setting regulator [9].

An element that radically distinguishes alkaline and alkali-free products is represented by the pH value. The first have very high pHvalues (in the range 11-13) while additives with low alkali content are characterized by acidic pH conditions (2-3).

Due to the different pH conditions, the triggering of the gelification in alkaline mixtures and in alkali-free formulations takes place in different ways.

The favourable conditions for the gel formation were studied through laboratory tests conducted using both types of accelerators.

It has been observed that the formation of gel with the use of mixtures based on sodium silicate is favoured by a reduction in the high initial pH values. In fact, through the addition of acetic acid to a commercial mixture, it is possible to observe a quick transition from liquid to gel state which develops in about 2 minutes when an optimal pH of 8 is reached. Away from this value toward more alkaline as well as more acidic values, this transition occurs in gradually increasing time. These studies, conducted at different temperatures, have shown that the gelification process is faster at temperatures above 25°C.

To understand the effect on the gel time of the retarder alone, acidification tests were carried out on mixtures of retarder and sodium silicate. The result was an evident slowing down of the process (from 2 minutes without retarder to 90 minutes when the retarder is added for a volume equal to 1% vol. with respect to the silicate solution). This phenomenon can be attributed both to the acidic nature of the retarder (pH = 5), which has a key role as previously reported, and to its organic nature (total organic carbon - TOC = 167.51 mg / I) which can cause a delay in gelification [14] and, finally, to the dispersant/fluidifying effect of the species responsible for the formation of the gel.

The tests conducted on alkali-free accelerators have highlighted the need to use a source of hydroxyl ions (OH⁻) to have the gel formation and in particular, reaching a concentration of sodium hydroxide (NaOH) equal to 1.5 M, it was possible to obtain a solid gel starting from 100 ml of commercial product. The retarder, as for the the alkaline formulation, allows to obtain a gel in longer times. A significant slowdown in gel formation was observed when the accelerator and retarder were mixed together in a volumetric ratio of 9: 1.

By conducting the same tests at different temperatures with alkaline formulations, it was possible to observe a faster gelification for values above 40°C. This phenomenon is probably due to the enhancement of Brownian motion of the particles which accele-



rates the aggregation kinetics. The addition of salts also reduces the gel time because they act as catalysts. Using the alkali-free formulations, the temperature did not show any significant effect on the gel formation, although it may have a more relevant role during the ageing phase of the materials [4].

3. Factors influencing the backfill grout performance

The requirements for two-component grouts mainly concern the component A and usually consist in limitations on the density, on the Marsh funnel viscosity and on the bleeding which are applied also to conventional mixtures, or they can be measured on the mortar after the addition of the accelerator, such as the gel time and the compressive strength at different ages.

In this study, the tests on component A were carried out by varying the type of bentonite and its hydration time in water before adding the cement and the retarder: the results obtained show a moderate connection between the hydration time and the bleeding of the mixture and a more significant correlation with the viscosity. More in detail, mixtures with identical proportions between the components were prepared changing only the mixing time of the bentonite in water - from 10 minutes to 24 hours – and their time of passage through the Marsh funnel was measured obtaining from 4 to 120 seconds of difference according to the type of bentonite used. In general, as already known in literature, it has been found that a longer hydration time slightly reduces the bleeding but significantly increases the viscosity of component A, in a way that can even prevent the mixture to meet the design requirements.

As for the verification of the requirements after the addition of the accelerator, the difficulty of univocally define these parameters appears clearly to those who try to measure them for the first time, as the questions: how to determine when did the mixture become a gel? How to perform an unconfined compressive strength test one hour after mixing, on a specimen which is sometimes too soft to be extracted from the mold?

The method commonly applied nowadays to measure the gel time in the laboratory involves the use of two containers: in one the accelerator is added to component A, then the mixture is passed to the other measuring the time until the hardening consistency of the mixture no longer allows this flow between containers [12]. The strong subjectivity of this test results clearly from this description, being it dependent on the operator, on the container used and on the mixing mode of the two components, which in this case can be done only manually, giving up trying to replicate what happens in a real injection.

Similar complications are encountered in the evaluation of the strength at very short age: in some cases it is impossible to perform UCS tests on the specimens after one hour from mixing and although it is instead possible to measure the shear strength of the samples with other types of tests (usually applied to soils) there are no such standards for mortars.

Finally, during this study we experienced considerable difficulties, using exactly the same mix design, in reproducing with different

mixing methods a mixture with constant characteristics: this is an evident sign of the key role played by the mixing method and of the need to agree on a standard when the evaluation of the design requirements is involved.

In an attempt to isolate the factors that most influence the assessment in the laboratory of the mechanical properties of two-component mortars, the tests here presented explore the adoption of different dosages of both alkaline and alkali-free accelerator, two different types of bentonite and two different mixing methods.

3.1. Samples preparation

The mortars prepared with the alkaline accelerator (sodium silicate) were mixed using average dosages found in literature as commonly adopted for backfilling, from which the values shown in Table 1 in correspondence of the column "Mix 1" were extrapolated; the dosages for Mix 2 and Mix 3 were obtained varying the percentage of accelerator around the average value, equal to 8% by weight, in order to appreciate the effect of the silicate. The other components of the mix were slightly modified to obtain a constant ratio between the liquid and the solid phases of the mix, equal to 2.5, and particularly between the liquid and the cement content.

The selection of the dosages for the preparation of the mixtures with alkali-free accelerator was instead the result of experimentation. In this case the mix design applied for the classic silicate (Mix 1 of Table 1) did not work, so we added cement to the mixture until we observed the formation of the gel, thus reaching the liquid/solid ratio necessary for the reaction to occur. At this point the six mixes shown in Table 2 were produced maintaining this ratio fixed while changing the percentage of accelerator in a wide range, not knowing which mix designs are commonly used. It can be interesting to note that the grout prepared with alkali-free needs much more cement (liquid/solid ratio equal to 1.5) than the alkaline one, probably due to the different chemical reaction that, as discussed in paragraph 2, requires the hydroxyl ions provided by the cement.

All the mixes were prepared with the same cement, CEM IV / A 32.5 R-SR, but other types will also be analysed in the future, as the content of clinker and blast furnace slag is a very important factor for the chemical reaction that they produce with the accelerator [10]. The mixes in Table 1, with alkaline accelerator, were made using two types of bentonite. Chemical additives (accelerator and retarder) from different manufacturers were tested.

All the specimens prepared according to the mix designs reported in Table 1 were made in two ways: with manual mixing and with a system developed in order to simulate a more realistic injection system. The manual method entailed mixing component A with a Hobart mixer, starting from the suspension of water and bentonite (sometimes kept in hydration for the previous 24 hours, as discussed in paragraph 3) then adding the retarder before the cement. After ten minutes of stirring, the measurements with the Marsh funnel were carried out and the component B was finally added up. The mortar was then poured into molds of dimensions 4x4x16 cm. The mixing system developed by the startup, shown in Figures



	Table	1. Dosages ad	opted for th	e preparation	of the samples	s with the	alkaline accelerator
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Mix design (% in weight)	Mix 1	Mix 2	Mix 3	
Cement	25.7	25.8	25.8	
Bentonite	2.5	2.5	2.5	
Water	63.2	67.2	59.1	
Retarder	0.4	0.4	0.4	
Accelerator	8.1	4.1	12.2	
Liquid/solid ratio	2.5	2.5	2.5	

Table 2. Dosages adopted for the preparation of the samples with the alkali-free accelerator.

Mix design (% in weight)	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Cement	36.7	36.7	36.7	36.7	36.7	36.7
Bentonite	3.3	3.3	3.3	3.3	3.3	3.3
Water	56.7	54.1	51.4	48.7	47.4	43.4
Retarder	0.5	0.5	0.5	0.5	0.5	0.5
Accelerator	2.7	5.3	8.0	10.7	12.0	16.0
Liquid/solid ratio	1.5	1.5	1.5	1.5	1.5	1.5

1 and 2, consists of two cylindrical containers connected at the lower end to two pipes that join at the end in a short stretch made by a static mixer, of about 15 cm length. Component A and B are separated in their respective containers and pipes until they meet in the final section before being "injected" directly into the molds. The system is equipped with valves that allow to dose the components and is able to apply an adjustable pressure to the outlet flow. The real *TBM* injection systems, with some variations depending on the *TBM* supplier, consists of two lines that are joined in a final stretch of the pipe, in which the mixing of the components happens without the static mixer just before the injection at the end of the lining segments; the laboratory system is obviously different from the real one in many ways but, compared to the manual mixing, provides a much more realistic method of samples preparation.

The mixtures containing the alkali-free accelerator were prepared exclusively with the manual method due to the high viscosity exhibited by component A which, at the dosages adopted in these tests, would have clogged the static mixer. The curing of the specimens was always in conditions of 100% humidity.

3.2. Laboratory test

A summary of the tests carried out is shown in Table 3. The tests on component A, i.e. the measurement of bleeding and Marsh funnel viscosity according to UNI standards, were not performed on the samples prepared with alkali-free accelerator, while the gel time was not evaluated for the mixtures prepared with the mixing system because the formworks were immediately filled by the fluid jetting out from the pipeline, making the procedure illustrated in paragraph 3 impossible to apply in this case.



Figure 1. Mixing system with the static mixer.



Figure 2. Operating scheme of the mixing system.

The unconfined compressive strength tests at ageing of 1, 7 and 28 days were carried out in accordance with UNI standards, on the two halves of the prismatic samples after sawing (the flexural tests were not performed). For some samples, especially those prepared with the mixing system, it was possible to execute the tests even after an hour of ageing, while some others, those prepared manually, were impossible to extract from the cast until after 24 hours. In this case, the undrained shear strength was instead measured by means of vain tests and fall cone tests, obtaining trends that were quite consistent with the UCS values recorded at 24 hours.

Where possible, the velocities of the elastic longitudinal and shear waves, V_P and V_S were measured.

3.3. Discussion of the results

The tests performed on the fresh component A showed some experimental evidences:

 the characteristics of the bentonite (mineralogical composition) affect the bleeding and the viscosity, also according to the hydration time. The types of bentonite commercially available are very different from each other also regarding this aspect:



Table 3. Summary of the test executed.

Type of grout	Mixing method	Bleeding	Viscosity	Gel time	UCS
Algeling and henterite 1	Manual	Х	Х	Х	Х
Alcaline acc. – Dentonite T	Mixing system	-	Х	-	Х
	Manual	Х	Х	Х	Х
Alcaline acc. – Dentonite Z	Mixing system	-	Х	-	Х
Alkali-free acc. – bentonite 1	Manual	-	-	Х	Х

in identical mix designs of component A, bentonite 1 showed times at the Marsh funnel always less than 45 s with variations of about 5 s in correspondence of hydrations lasted 10 minutes and 24 hours, while bentonite 2 showed 50 s in the first case and more than 3 minutes in the second;

- adopting mix designs consolidated by practice, usually the bleeding is not a constraining requirement;
- component A for the alkaline accelerator has viscosities always much higher than the limits usually imposed in order to assure the pumpability of the mixture.

As already noted in other studies [12] the gel times increase as the percentage of accelerator increases, which in the laboratory allows the preparation of more homogeneous specimens but may be an undesirable eventuality on site, causing to exceed the threshold values required (usually less than 20 seconds). Increasing the percentage of alkaline accelerator (at least up to the tested 12%) produce an increase in the strength of the grout, therefore the dosage of the accelerator must be chosen balancing the opposite effects of these two important performance requirements according to the main function entrusted to the backfill. The gel time further increases when using the alkali-free accelerator.

The results of the unconfined compressive strength tests are shown in the following figures. As anticipated and shown in Figure 3, the UCS values increase with the percentage of accelerator in a way more or less evident depending on the mixing method, but the truly remarkable result is the great influence of the latter on the strength developed both at short and long ageing. In fact, for the same mix design and ageing, the specimens prepared with the more realistic mixing system show UCS values more than doubled when compared to those prepared manually. This phenomenon is most likely due to the greater energy and better homogenization provided by the system with the static mixer that makes the mixing more effective [5].

The effect of the type of bentonite, which was demonstrated important on the fresh mixture, does not play the same role on the mechanical behaviour of the hardened mixture, as can be seen in Figure 4, which shows the UCS values at 7 days as a function of the percentage of alkaline accelerator and mixing method, obtained with two types of bentonite. The most relevant differences are still related more to the method of preparation of the specimens than to the type of bentonite used.

The results of the UCS tests performed on the specimens prepared manually with the alkali-free accelerator, according to the six dosages shown in Table 2, are shown in Figure 5. The figure allows to identify an optimal range in the content of accelerator, which otherwise produces significant strength reductions, particularly if dosed over the 8% in weight. Since the UCS value at 28 days recorded for the mix with 8% seems too high and in disagreement with the trend of the values at 7 days, a greater number of tests is deemed necessary to confirm or deny this result, but it can be confidently affirmed that the optimal dosage of alkali-free accelerator is around 5%, shifted to lower percentages than for the alkaline one. Unfortunately, 24-hour tests couldn't be performed on all mixes, but the undrained strength values at 1 hour were



Figure 3. UCS values as function of the quantity of alkaline accelerator and age of the samples prepared with the manual method (a) or the mixing system (b).





Figure 4. UCS values as function of the quantity of alkaline accelerator and mixing method for two types of bentonite.

measured, showing a maximum of 90 kPa at 5%, thus confirming the existence of an optimal dosage even at short ageing times. Figure 6 reports a comparison between the UCS values at 28 days obtained for the specimens with both accelerators in correspondence the same dosages, which shows how their mechanical properties are comparable at long ageing time (this is not true for short times). However, making this comparison it must be kept in mind that the mixtures with alkali-free accelerator are produced with a higher cement content.

Finally, when both measurements were available, an almost linear correlation was observed between V_P and V_S data and the UCS values of the grout. This eventually allows the indirect estimate of the mechanical properties and the evaluation of the dynamic elastic modules of these materials.

4. Conclusive remarks

The data here presented constitute the preliminary results of an ongoing study, however they lead to draw some conclusion relevant for this stage of the research work. First of all, it should be highlighted the fundamental role that the preparation of the specimens in the laboratory plays in the evaluation of the mechanical properties of the grout to be expected on site, and therefore the need to define a procedure, as close as possible to the real one in terms of pressure and flow of the two components, that can be



Figure 5. UCS values as function of the quantity of alkali-free accelerator and age of the samples.



Figure 6. Comparison between UCS values at 28 days with alkaline and alkali-free accelerator (manual mixing).

replicated in any laboratory; this is always useful but can be crucial if the aim is optimizing the mix design rather than checking the requirements. A further research development in this direction will be trying to reproduce in a more faithful way also the curing conditions, a very important aspect that several researchers in the world are already facing.

Accordingly, the estimate of the gel time, a requirement as important as it is poorly standardized, depends on the mixing methods so it should reflect the real duration of the chemical reaction on site or refer to standard conditions. Based on the observations here exposed, the gel is formed more slowly with manual mixing, with an increase in the amount of accelerator and with the transition from alkaline to alkali-free formulations. Furthermore, the comparison between mixes prepared with alkaline and alkali-free accelerator has highlighted some substantial differences regarding the dosages of cement, the consequent fluidity of the component A and the setting and hardening times, which could lead to modifications of the injection systems and of the acceptability requirements of these mixtures if the adoption of alkali-free additives proves to be convenient from a chemical or environmental point of view.

An effective mixing system made possible, for some mix designs, to obtain specimens having moderate mechanical strength (about 3 MPa) after only 7 days of ageing using a 32.5 cement, which open new paths for laboratory experimentation on grout mixtures able to develop considerably higher compressive strength with different types or classes of cement.

Having understood how some chemical-physical characteristics such as pH and temperature control the development of the gelification reactions and the consequent mechanical properties, further studies on the chemical reaction that regulates the phenomenon could direct the choice of dosages and injection modes in the design as well as in the execution phase.

Finally, it seems useful to recall how further efforts in defining the characteristics of these materials also in terms of stiffness are necessary, being this an extremely relevant parameter in the correct design of the interaction between the tunnel lining and the surrounding soil or rock mass.

In order to prevent the degradation of the mortars, it is necessary to take into account not only the effects of mechanical actions which can be exerted immediately after the injection, but also



environmental actions. Exposure to water (washout) as well as acid attack or attack of sulphides and chlorides are examples of conditions that could compromise the quality of these materials, endangering their durability.

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