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Two component backfilling in shield tunneling: laboratory procedure and results of a test campaign

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ABSTRACT: The two-component backfilling system is becoming the most frequently used method to fill the annular gap created during shield machine advancement. It is based on the mixing of two fluids (mortar and accelerator) that flow through separated pipelines from the batching station to the machine tail and are mixed few centimeters before the output nozzles. The induced turbulence allows a good mixing and the obtained new material gels in few seconds. The mortar is easy to be pumped, stable and preserves its workability for long time. The mixing process allows an easy management of the gelling time and the hardening speed of the final product. The check of the material properties is important and should be carried out before starting tunneling to assess both which mechanical properties can be obtained and how to manage the final resistance and the gelling time. Since no standardized laboratory schemes are available, laboratory procedures for both mortar manufacturing and testing the obtained samples are presented. The results of tests on hardened two-component grout produced with different mix design are also presented and discussed.

1 INTRODUCTION

When tunnels are excavated with a full face shielded machine an annular void is created by the advancement of the shield between the soil and the segmental lining. The filling of the gap with a material of specified mechanical properties is an operational of paramount importance for the excavation process and for the final tunnel quality (ITATech, 2014). The size of this annular gap (herein called annulus) is function of the head overcut, the thickness of the shield and the size of the tail brushes (Thewes & Budach, 2009). The creation of this annulus is part of the tunnel construction process and the consequent annulus filling process must be conducted in a continuous way.

A perfect filling operation minimizes surface settlements (Peila et al., 2011; Pelizza et al., 2010), blocks segments in the designed position, bears the back-up load, ensures the uniform contact between ground and linings (avoiding punctual load on concrete) and increases the waterproofing of the tunnel segmental lining.

The backfilling grouting mixes consist in materials that should be easily transportable and should be stable from chemical and physical point of view. Different materials and technologies have been applied for this purpose, also in function of the geotechnical properties of the medium that embeds the tunnel (Thewes & Budach, 2009; Mähner & Hausmann, 2017).

In the last years, the use of two component grout is spreading in many job sites (Antunes, 2012) due to the technical advantages that this technology can provide: immediate hardening, easy transportation and pumpability, stability during time of the mixes when stand on the machine before injection. For this type of mix it is important to highlight that a suitable mix design must be chosen

and tested before the start of the works in order to get a mortar and an hardened two component grout that can satisfy the following features:

-the gelling time must have an order of magnitude of seconds;
-the hardened material must become stiff and hard in a very short time;
-the mortar should be fluid and homogeneous in all the pumping phases;
-the hardened material must be homogenous in every point of the annulus;
-the fluid grout must not be washed out by water flow.

To get all the above-mentioned properties, tunnel engineers must pay attention to the mortar design because only with a careful additives metering it is possible to satisfy all those technical requirements and in the design technical documents a clear assessment of the fresh mortar and hardened grout properties must be highlighted. Furthermore the chosen material must be able to guarantee the quality of the mix and to completely fill the voids and the possible irregular shape. Moreover, the mix should not choke the injection lines.

Thanks to these advantages the use of two component mix is becoming more and more popular but, despite the large number of applications, a limited amount of researches have been carried out in these field are there are no fixed and standard requirements on the laboratory testing of mortar and hardened grout properties. Each designer prescribes different requirements in function of their personal technical document, ideas or calculations. Therefore, there is the clear need to define fixed and univocal test procedures that can allow the comparison of outcomes among different job sites.

In the following a laboratory test procedure for producing and testing both the mortar and the hardened grout is presented to provide a basis for discussion.

2 TWO COMPONENT MIXES GENERAL ASPECTS

The two-component mix is typically a super fluid grout, stabilized in order to guarantee its workability for a long time (from batching, to transport and injection), to which an accelerator admixture is added at the injection point into the void annulus around the segment lining (ITAtech, 2014). The two fluids (identified in the following as component A and component B), are made up of:

- component A: cement, bentonite and a retarding/fluidifying agent;
- component B: accelerator admixture, mainly composed from sodium silicate diluted in water.

The mix gels a few seconds after the addition of the accelerator, (normally 10-25 seconds, during which the TBM advances approximately 2-15 mm), exhibits a thixotropic consistency and starts developing mechanical strength almost instantaneously.

This system usually injects the components under pressure throughout the shield in the void annulus and the obtained mix is able to penetrate into any voids present in this area and into the surrounding ground also, depending on its permeability thus allowing a perfect backfilling of the whole system.

Furthermore, the retarding agent added to the grout has a plasticizing effect and is able to inhibit the mix from setting thereby guaranteeing its workability for very long time (up to 72 hours when necessary) after batching: this facilitates stockpiling grout in the mixer-containers that are bigger than the theoretical volume of material to be injected for every ring (Dal Negro et al., 2017). This is useful in avoiding one of the most common mistakes coming out on the job sites, that is, batching and stockpiling only the theoretical amount and not more. Therefor not being prepared for any possible uncertainty if, eventually, a bigger void is found that needs to be filled in, you would leave the crown unsupported for too long time leading to potentially consequences for the ground stability.

The bentonite content inside the mix (generally not less than 25 kg/m^3, depending on the bentonite quality) increases significantly the homogeneity and the impermeability of the hardened mix. Furthermore, it minimizes the bleeding and helps in achieving the thixotropic consistency when the flow stops because the void annulus is full and so helps in the gelling process, conferring higher impermeability to the system (less than 10-8 m/s) and allow to keep the internal humidity inside the mix itself after its hardening in a confined environment.

The formulation and the metering of single elements of component A is a very important operation in order to ensure the manufacturing of a suitable two-component hardened grout therefore

also in laboratory for sample preparation a great care should be taken into account. Every single component that constitutes component A and the relative percentages of the various components are strongly linked with the behavior that the mortar will have in the fluid and hardened phase: for example the quantities of cement and of bentonite influence the final uniaxial compressive strength of the grout but, since, bentonite helps to keep also in suspension the cement particles, a surplus of bentonite in the mix design could lead to a not pasty mortar i.e. a not pumpable mix.

For what concerns the component B, once the percentage of sodium silicate inside the liquid is fixed, the main design parameter is his amount in the final two-component grout, i.e. the volume percentage of component B on the whole mix, that regulate the hardening mix.

In the scientific literature, there is a limited amount of informations about two component grout and the available ones concern case histories that describe practical experiences from different job sites. Thewes & Budach (2009) presented a good global overview of the most used mixes while Peila et al. (2011) and Boscaro et al. (2015) presented a global description of relevant case histories of applications and the tests of a two component mix. Peila et al. (2011) presented the test carried out in the mix used in the metro C line of the Rome metro. More tests can be found in Novin et al., (2015); Zarrin et al.,(2015); Barnett, (2008); Pellegrini et al., (2009); Ivantchev & Del Rio, (2015); Thewes, (2013); Pelizza et al., (2010); Youn et al. (2016) and Dal Negro et al., (2017).

2.1 *Usually carried out laboratory tests*

The most frequently used laboratory tests on component A are (Peila et al., 2011; Zarrin et al.,2015; Barnett, 2008; Pellegrini et al., 2009; Antunes, 2012) density assessment, viscosity test and bleeding test while on the mix the gelling time assessment is very important. On hardened grout the uniaxial compressive test is usually performed. Also flexural test on the slabs as done for conventional mortar is frequently used.

The goal of the determination of the viscosity and the bleeding is to check if component A maintains his fluid state (i.e. it is pumpable) and if it remains homogeneous (i.e. water and cement do not separate). The assessment of the gel time has the goal to estimate the correct amount of component B be used to obtain a fast gelling while the compressive strength is the main mechanical parameter of the hardened grout that is usually assessed by the various researches.

2.2 *Laboratory preparation of component A*

Since the final quality of the grout is strongly affected by the quality of the component A, a standardized laboratory scale procedure for manufacturing has been developed. The order and the duration of each step of manufacturing has been defined in order to obtain, at laboratory scale, a final product similar to the one obtained on the construction site plant, in terms of specific weight, homogeneity, bleeding, consistency, fluidity and hardening time. On a job site, the component A is produced outside the tunnel (Peila et al., 2011; ITAtech, 2014; Dal Negro et al., 2017) in suitable areas called batching stations, where a high turbulence process allows the production of mortar. Normally job site mixers require few minutes to produce some cubic meter of component A. Although the proposed procedure to produce component A is supported by many previous tests, in order to get a better correlation and validate laboratory outcomes, a successive test campaign should be carried out using mortar coming from the job site batching plant. To ensure a good homogeneity of the final product, the following points should be respected:

- the ratio between the volume of the tank and the volume of the mortar should range between 2 and 3;
- the impeller should be featured with sloping blades able to create large turbulence and should be located in the center of the tank during the mortar preparation. In Figure 1 the chosen impeller is shown;
- the distance between the impeller and the bottom of the tank should be with a minimum that avoids impact during rotation;
- the ratio between the diameter of the tank and that of the impeller should be about 2 to obtain a good turbulence in the tank. The Tunnelling and Underground Space laboratory of Politecnico di Torino impeller has a diameter of 100 mm and the manufacturing procedure is summarized in Table 1.

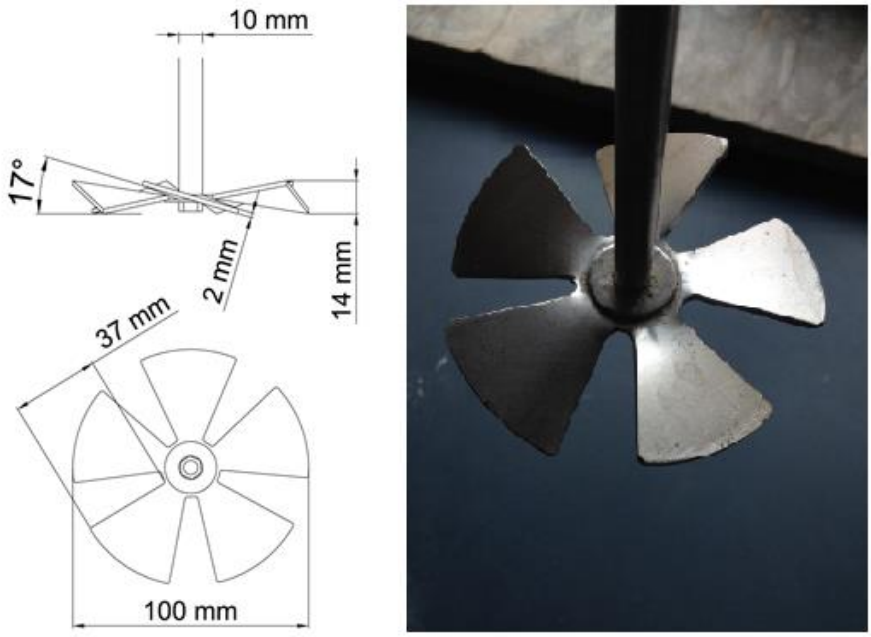

Figure 1. Scheme and photo of the used impeller.

Table 1. Proposed procedure for fresh component A manufacturing.

Operation	Impeller rotation speed (rpm)	duration (min)
fill the tank with water and start the mixer	800	/
add the bentonite increasing the propeller speed at a constant rate	from 800 to 2000	0.5
	2000	6.5
add the cement	2000	3
add the retarding/fluidifying agent	2000	2

3 CARRIED OUT TESTS

3.1 *Tests on component A*

3.1.1 *Specific weight*

The specific weight of the mix can be measured in accordance with the standard EN 1015-6. Three weight measurements are carried out after a time lap of 5 minutes in order to allow the air bubble ascent.

3.1.2 *Flowability*

The flowability is linked with the viscosity of the mix. Instead of performing standard viscosity tests using viscosimeter, the tests are usually carried out using the simple Marsh cone procedure that can be easily used directly on the job site since the test is quite simple. The flowability test consists in the measuring of the time needed to a fix volume of mortar to flow out from the standard nozzle of the Marsh cone (Figure 2). The tests can be carried out in accordance with the standard UNI 11152-13.

The flowability test should be performed at different times to understand how the mix behaves during time and therefore how the increase of viscosity can affect the pumpability of the mix. In this research it was chosen to check each mix design after the preparation (fresh mortar) after 24, 48 and 72 hours of curing without agitation of the mix.

3.1.3 *Bleeding test*

The bleeding value is a percentage index, calculated as the ratio between volumes of loss water and mortar when the mix stand still in a bucket. The loss water is the water expelled from the mortar in a specific time range (Figure 3). The bleeding determination can be performed in accordance with the standard UNI 11152–11. It can be useful to have measurements of the released water after 3 and 24 hours from manufacturing.

3.2 *Tests on gelled grout*

By mixing component A and component B the gelled grout is obtained in just a few seconds. The interval between the mixing of the components and the instant when the obtained material stops to be fluid is defined as gel time. The gel time is the key parameter that leads operators to define the volume ratio between component A and component B. Standard procedures are not available for the measurement of the gel time. In this study a new procedure has been adopted in order to make the operation repeatable. Two tank with volume of 0.4 l were adopted and a fixed amount of 200g of component A was used for all the tests. The proportional amount of component B was determined on the basis of the type of test to be carried out, based on the mix design. Bigger containers and bigger amount of components were used for trial tests of the gelling time but not acceptable results were obtained due to the not homogenous mixing and consequently to not homogeneous hardened material. The proposed procedure is the following: when the two tanks are ready they are quickly mixed by the operator by pouring them in the two tanks. The test time is stopped when the mix is flowing no more from one tank into the other one. It is fundamental to start the test pouring the component A inside the component B in order to have the required turbulence.



Figure 2. Flowability test device installed in laboratory. The filling of the Marsh cone and the measurements of the flow time phase are shown in the center and on the right respectively.

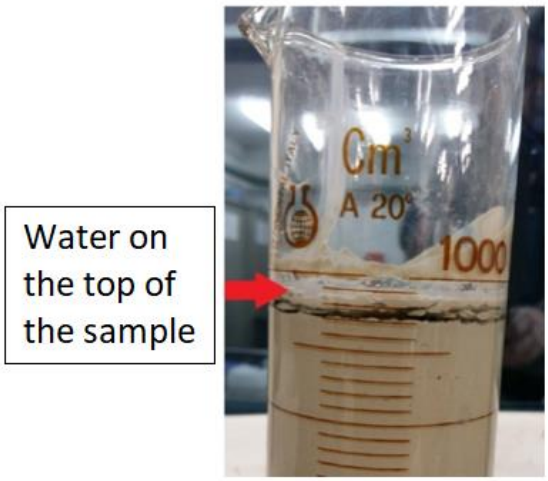

Figure 3. Bleeding test obtained by measuring water layer due to segregation of the mix after a fixed time.

3.3 *Tests on hardened grout: uniaxial compression tests*

Because of a lack of standards for standardized compressive strength test on this type of product (more similar to a hard clay more than a weak concrete) the standard UNI EN 196-1 has been used since it has been proven to be simple to be applied. Although this regulation is not applicable to mortars with very short setting times, it can be adapted to the specific needs of two component grouts. According to this standard the samples to be produced need to have sized of 160x40x40mm.

The sample preparation is not easy with this type of mix since it requires to fill the mould in a very short time (before hardening has started). After filling the mould these are hermetically sealed (in order to avoid water losses due to evaporation) and are cured for 24 hours (with a fix air temperature of 25°). This maturation period is fundamental in order to be able to carry out the demoulding operation without damages the samples. The samples are than cured in clean drinkable water with a fixed temperature of 25°.

Uniaxial compressive tests are then performed on samples with different curing time: 3, 24 hours and 28 days. The compression tests carried out following the UNI EN 196-1 are easy to be applied for samples cured 28 days while for samples with curing time of only 24 hours, it is not easy to split them by flection on three points due to presence of surface weakness: a curing time of 24 hours, indeed, is not enough to provide enough strength to the hardened grout sample. Therefore, forces applied from the three-points flection test cause tools indentation inside the samples, without flexion. For this technical limitation, in order to obtain the two half-samples required from the UNI EN 196-1, a cutting blade was used. For samples with curing time of 3 hours, it is not possible directly to apply the UNI EN 196-1 and also it is not possible to obtain the two half-samples by cutting. Therefore, a special mould was designed with a waterproof plastic layer located on half-length of sample, in order to obtain the halfed samples.

Once obtained the half-samples, the uniaxial compression test campaign has been started by using a unconfined compression testing machine.

Two different types of laboratory devices and setup has been used to perform the test, first one for short term hardening is a press used for testing soils (Wykeham-Ferrance) with a speed of compression between 0.25 mm/min (for 3 hr sample) and 0.5 mm/min (for 24hr sample), 40x40mm plates were used to distribute load on the sample. For 28 days hardened sample the used press is Zwick/Roell with a speed of compression of 3 mm/min, compression device were used to distribute load on the sample.

4 PRELIMINARY LABORATORY TESTS CAMPAIGN

A preliminary laboratory test campaign has been developed on four different mix designs. Mix designs 2, 3 and 4 were manufactured using the same kind of water, high resistance cement (Buzzi CEM I 54.5 R) and sodium bentonite (type 1) changing for each mix design the accelerator/retarding agent supplier. Mix design 1 is the same of mix design 2 but using a type of bentonite provided from a different supplier (type 2). All the used mix designs are summarized in Table 2.

Table 2. Used mix designs for the preliminary test campaign.

MIX DESIGN	1	2	3	4
Cement (kg)	230	230	230	260
Bentonite (kg)	30 (type 2)	30 (type 1)	28 (type 1)	28 (type 1)
Water (kg)	853	853	819	819
Retarding agent (kg)	3.5	3.5	5	2.5
Accelerator (kg)	81	81	90	80

The tests have shown that the density of Component A is relatively constant for all the mix design and is mainly influenced by the amount of cement in the mix and by the water/cement ratio. In Table 3 a summary of the results are shown reporting the average values of a wide set of tests.

Table 3. Average values of the measured density of the 4 different mix designs.

mix design	density (kg/l)
1	1.15
2	1.17
3	1.19
4	1.22

Regarding bleeding (Table 4), while the values on the short term (3 hours) are almost the same for all the mixes, even though with slightly higher values for mix designs 2 and 4, on the long term (24 hours) mix design 4 shows a much higher bleeding value than all the other.

This depends on the lower water-cement ratio. The worst behaviour of mix design 4 is confirmed by the viscosity value data (Table 5): mix design 4 has very higher flowing times than the other 3 mix that at 24 hours show a very similar behaviour. Furthermore, at 72 hours was not possible to carry out any more the test due to the density of the mix.

The uniaxial compressive tests show that all the mixes reach a compressive strength of about 1 MPa in 24 hours as summarized in Figure 5 while figures from 6 to 13 report in the detail obtained stress-deformation diagram for all mixes at different ages (3hr, 24hr and 28 days).

Table 4. Average values of the measured bleeding of the 4 different mix designs.

mix design	bleeding (%) t = 3 h	bleeding (%) t = 24 h
1	0.52	2.80
2	1.04	2.09
3	0.70	2.40
4	1.21	8.50

Table 5. Average values of the measured flowing time of the 4 different mix designs.

		flow time (s)		
mix design	fresh mortar	24 h	48 h	72 h
1	32	36	39	43.8
2	34.5	41	43	51.2
3	38	40	40	42
4	36	60	82	Not possible to executed

The gel time has been evaluated both for the mix design value of accelerator (Table 6) and for different values, in order to study the influence of the accelerator percentage on the variation of gel time. This information if very important for the job site management, where setting the correct gel time is of key importance for the correct balance between avoiding pipes stocking and to get a quick grout setting. It is possible to see that increasing the amount of accelerator there is an important increase of the gel time and that this behaviour is more or less similar for all the mix designs (Figure 8). It is interesting to observe that the effect of the accelerator is less effective on the mix design 4 that was also the one with more cement and less water.

Table 6. Average values of the measured gel time of the 4 different mix designs.

mix design	gel time (s)
1	11
2	8
3	10
4	7

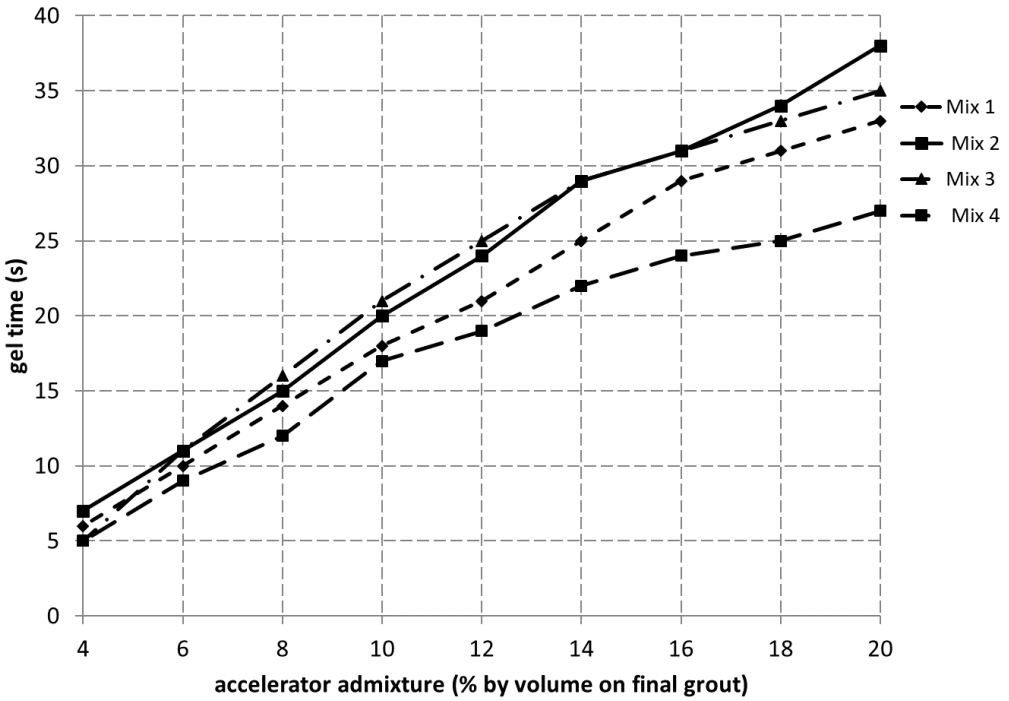

Figure 4. Accelerator admixture vs gel time.

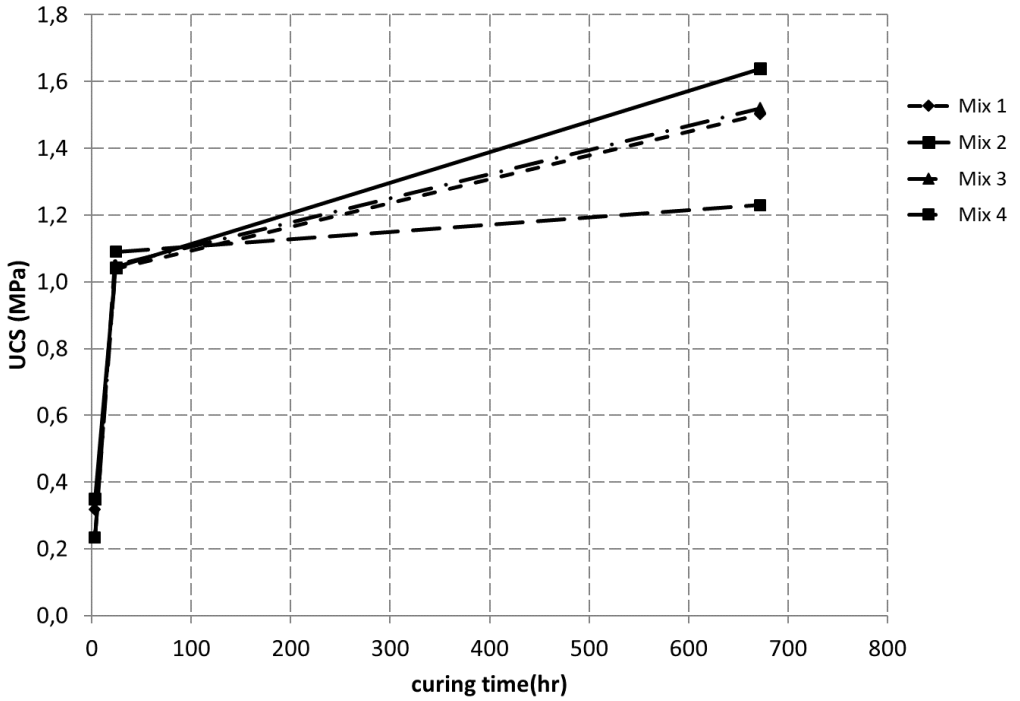

Figure 5. Average measured values of the uniaxial compressive strength for the various mix designs.

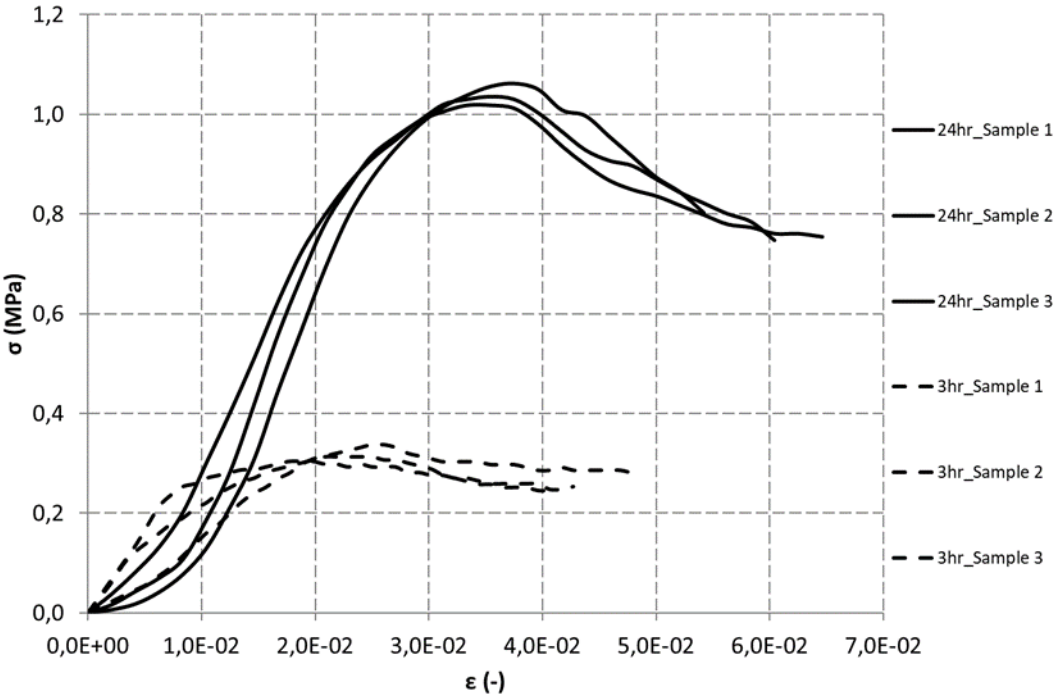

Figure 6. Mix 1, 3hr and 24hr stress-deformation diagram.

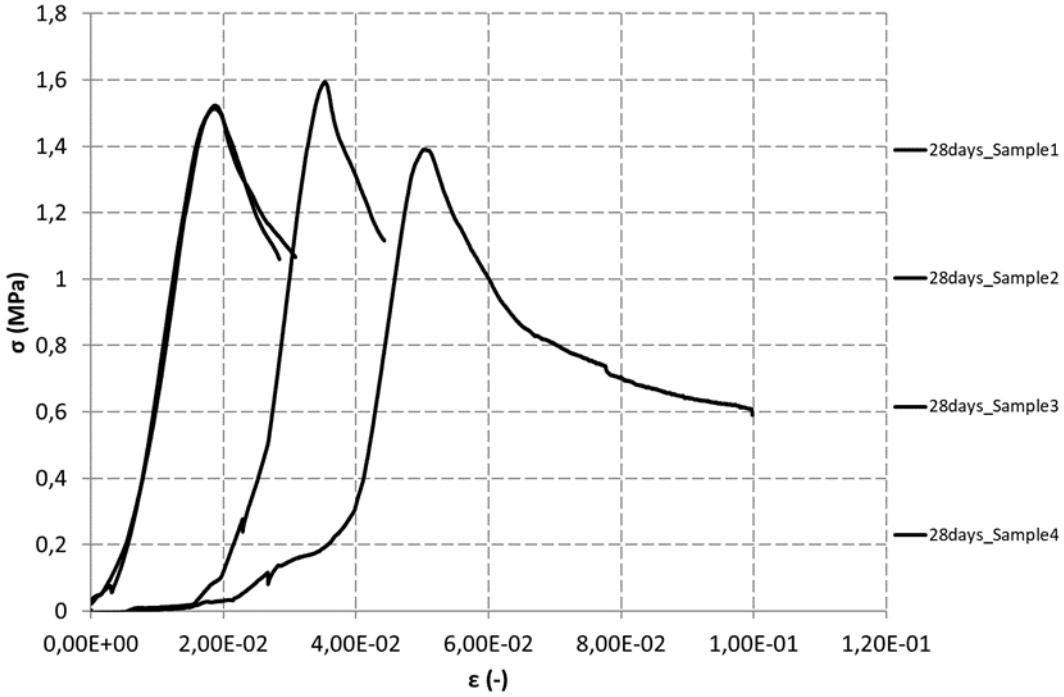

Figure 7. Mix 1, 28days stress-deformation diagram.

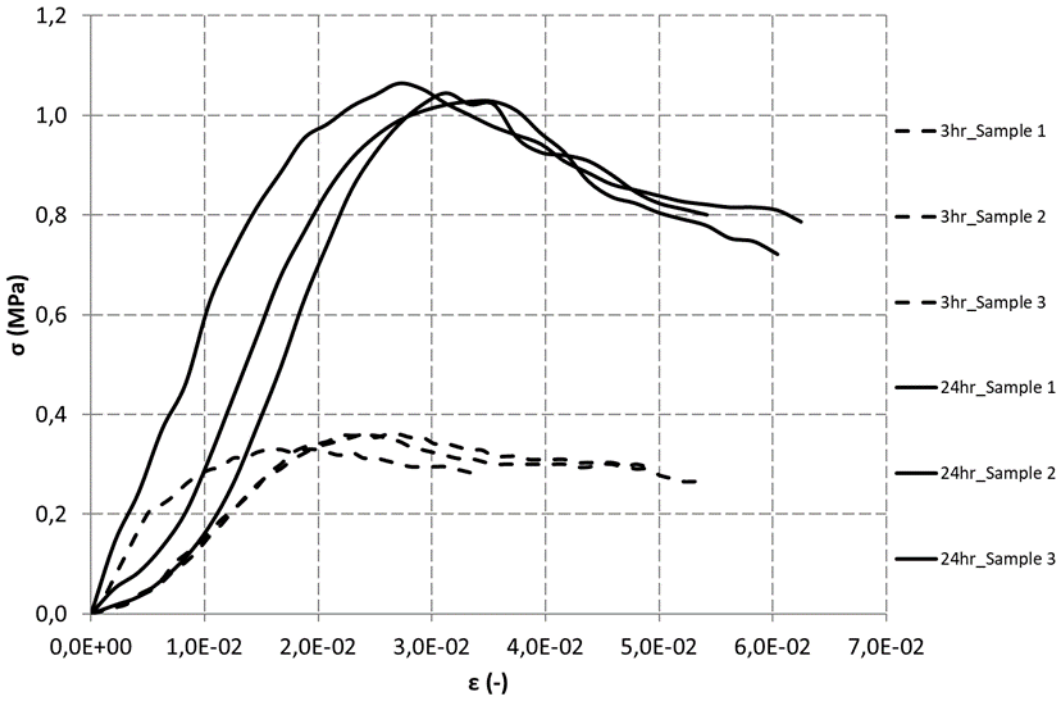

Figure 8. Mix 2, 3hr and 24hr stress-deformation diagram.

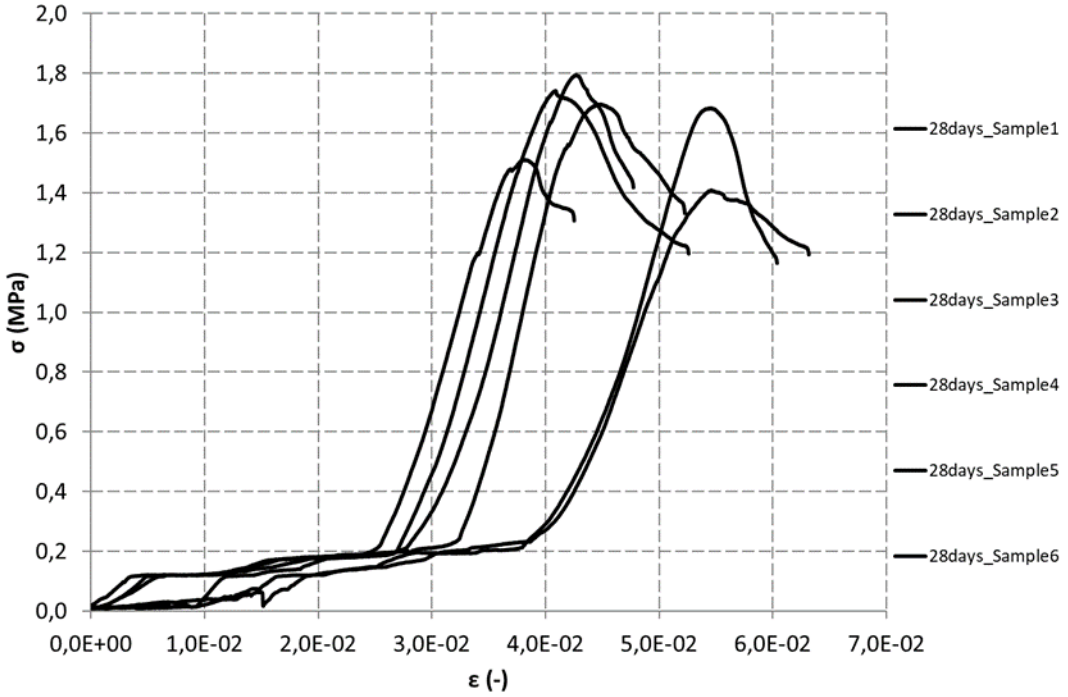

Figure 9. Mix 2, 28days stress-deformation diagram.

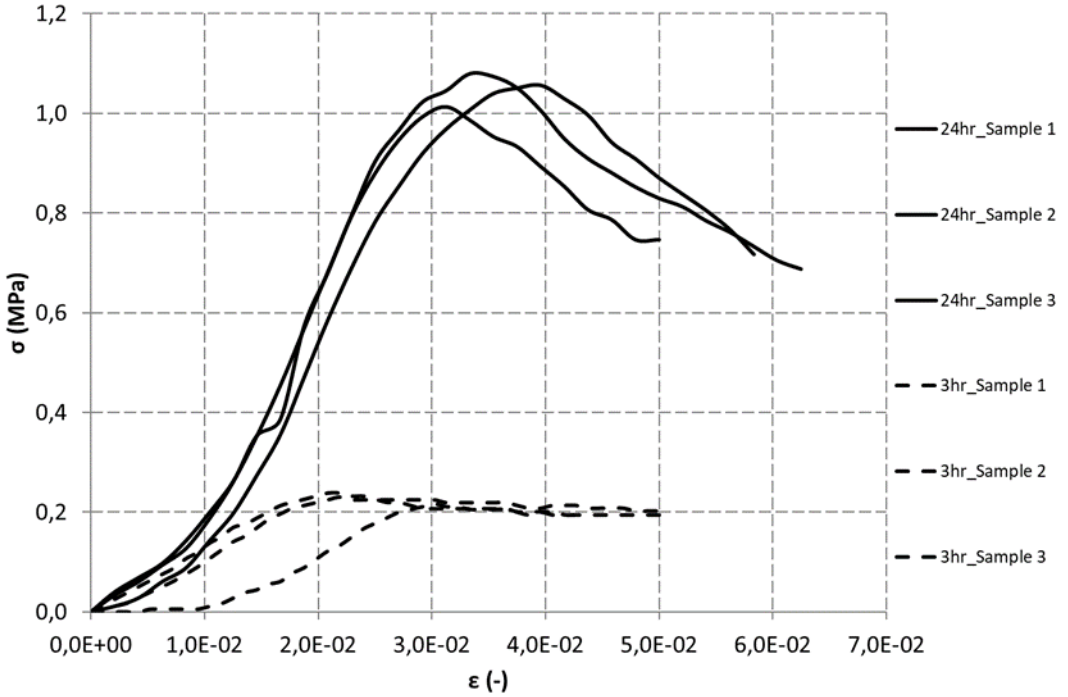

Figure 10. Mix 3, 3hr and 24hr stress-deformation diagram.

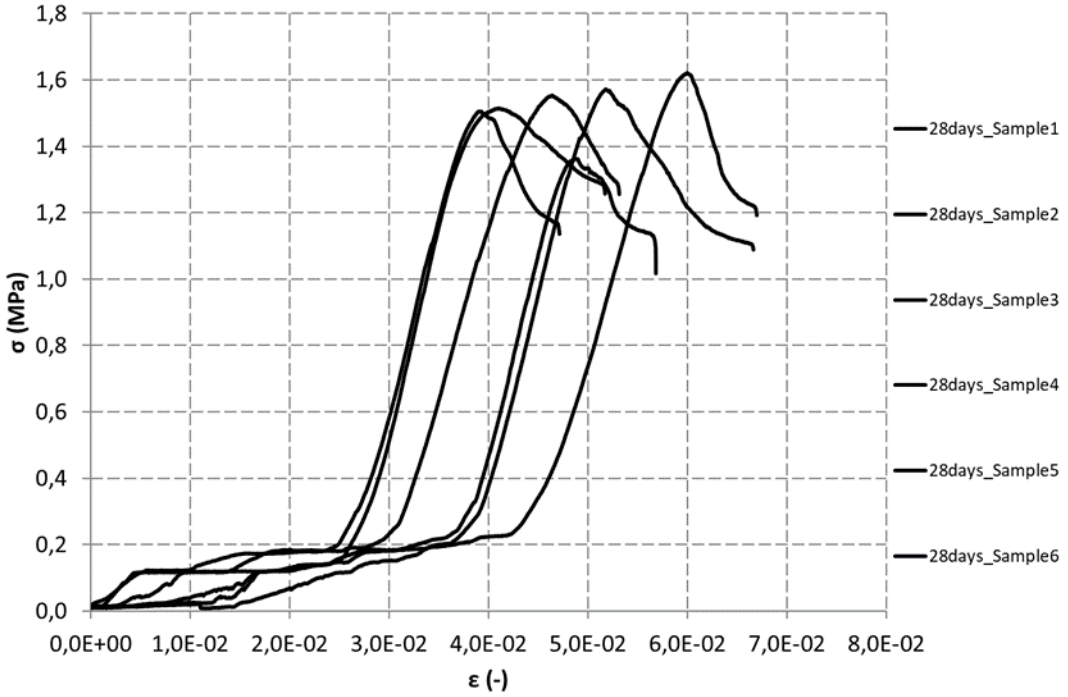

Figure 11. Mix 3, 28days stress-deformation diagram.

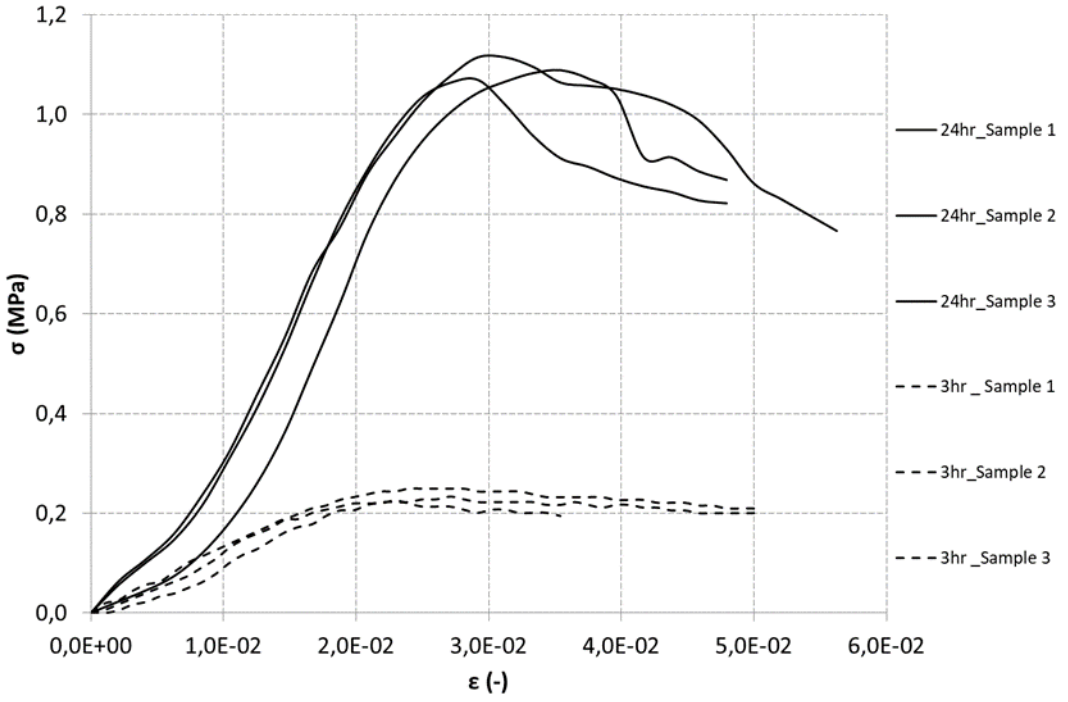

Figure 12. Mix 4, 3hr and 24hr stress-deformation diagram.

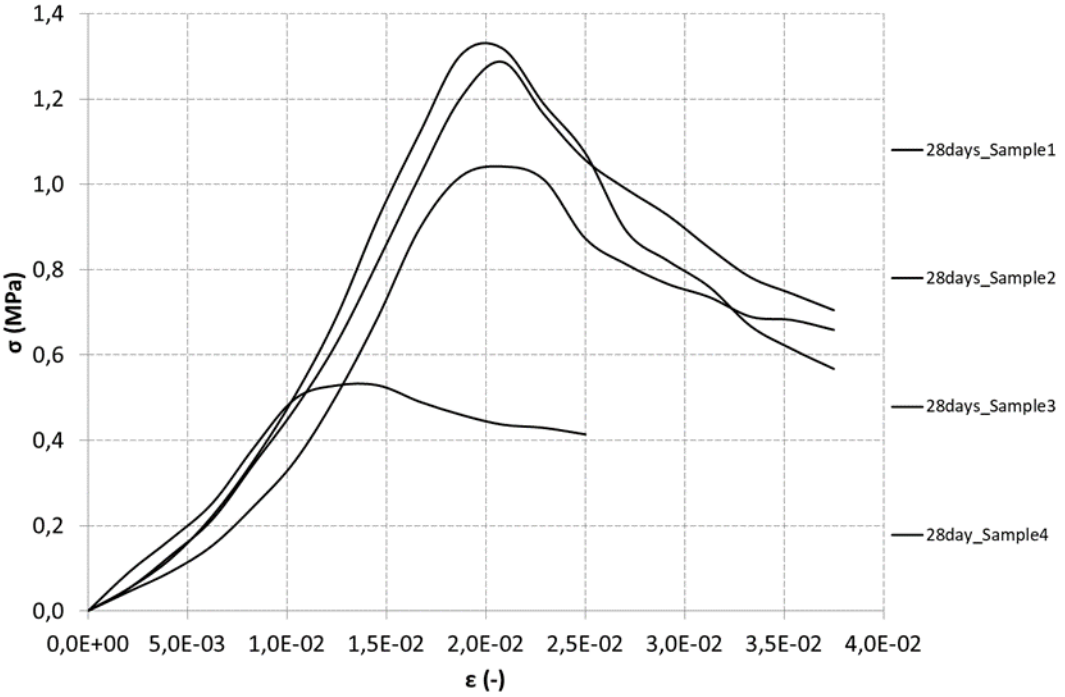

Figure 13. Mix 4, 28days stress-deformation diagram.

5 CONCLUSIONS

The two-component backfilling system is becoming the most frequently used method to fill the annular gap created during shield machine advancement.

Since it is based on the mixing of two fluids (mortar and accelerator) that flow through separated pipelines from the batching station to the machine tail and are mixed few centimetres before the output nozzles, this technology permits to obtain in a simple way a material suitable for the backfilling operation.

In a tunnel project, a preliminary laboratory test phase is necessary in order to set-up the mix design for the two-component backfilling.

The procedure used in the Tunnelling and Underground Space Laboratory of Politecnico di Torino and the results of some standard tests on four different mixes are therefore presented to provide a standardized laboratory schemes and a contribution to the understanding of the behaviour of the mixes in function of their composition.

6 ACKNOWLEDGMENTS

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