

High performance TBM Backfill grout

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ABSTRACT: In mechanized tunnelling, the filling of the void between the segmental lining and the TBM excavation profile represents a very important activity, required to minimize surface settlements and to ensure a proper confinement to the underground structure. During the design phase of a tunnelling project, the studies are usually oriented to the definition of the characteristics and rheological properties of the mix in fresh and early-stage conditions, while the properties of the hardened material (e.g. strength and stiffness) are investigated often for comparative purposes and are not directly related to particular design requirements.

This paper presents the results of a Research activity performed by Webuild, Lombardi and GEEG, to deeply analyse the evolution of the mechanical properties of the backfill grout over the curing time, analysing the effects of cyclic loads and different curing conditions in the durability of the material and, finally, proposing solutions for high performances two-component back-filling materials.

The laboratory program was conducted on fresh and hardened material, in confined and unconfined conditions and with a focus on cyclic loads and durability behaviour under demanding and unusual load conditions.

The results provided detailed information on the behaviour of the backfilling grout materials on short and long term, on the relation between mix design and mechanical strength, on the effect of several parameters (i.e. pH, temperature, dissolved salts, ...) on the durability of the material and useful insights on the possibility to significantly increase the capacity of this material through an accurate selection of materials and mix design.

KEYWORDS: Tunnelling, Underground space, Environmental sustainability, Instrumentation, Site investigation

1. INTRODUCTION

In mechanized tunnelling an important role in guaranteeing the correct execution of the excavation phases and the stability of the tunnel in the short and long term is played by the filling of the void between the segmental lining and the excavation profile. This must be adequately realized to provide an uniform contact between the lining and the surrounding soil/rock material (Oreste et al., 2021), to create a connecting layer between the lining segments and to ensure the homogeneous transmission of stress between the soil/rock mass and the lining, to contribute in minimizing misalignments of the lining segments and to provide impermeabilization (Di Giulio et al., 2020), to avoid surface subsidence on short- and long-term (e.g. Talmon and Bezuijen, 2005).

The effect of the material properties, considering the stiffness and strength values, has not yet been thoroughly investigated in an exhaustive manner.

Evidences are available on a series of purely practical aspects, such as the injection methods and the curing conditions able to significantly influence the development of stiffness and strength over time, even if organic data or sufficiently understanding are not yet achieved.

Finally, due to the rapid development of new materials and to the difficulty in developing specific experiments, there is an almost total absence of detailed information on the durability of these materials, with specific reference to particularly critical environments or curing conditions.

In the most common use of back-filling, it is essential to ensure that all the void volume created between the excavation profile and the extrados of the lining is adequately filled by the grout.

In this sense, the short-term characteristics and the evolution in the first seconds / hours of the mechanical strength of the material are much more important than the maximum strength or stiffness developed by the material over months.

Furthermore, referring to the two-component grouts, there are several practical reasons to require a not excessively viscous and dense A component and that it does not have a tendency to harden too soon, risking damage to the plant in the event of an unexpected TBM stop while, after the contact with the B component, quickly developing a sufficient strength.

The filling represents then a completion element for which are required:

- pumpability;
- neglectable bleeding;
- quick hardening;
- long term strength (commonly about 2.0 MPa at 28 days).

For these purposes mono-component or two-components grouts are generally used and dedicated laboratory tests are performed for specific projects to verify the capability of a selected mix design, or to select the proper mix design, to meet the aforementioned requirements.

Only recently, significant efforts have been made to simulate in the laboratory, as faithfully as possible, the real injection method of two-component backfill grout for TBM applications (Di Giulio et al., 2020).

The great variability of the mix designs used, of the characteristics of the raw materials used (cement, bentonite, accelerator, retarder, ...), and the very different methodologies for measuring physical and mechanical characteristics used, makes it extremely complex to express correlations of general validity.

Nowadays the destination of the tunnel to be realized can be different from the traditional use, as for hydraulic/hydroelectric contexts, where the internal loads applied to the lining generally reaches extremely high and periodically changing values. All these elements necessarily lead to new perspectives and to new and more demanding needs in terms of mechanical characteristics and durability guarantees in the material that fills the annular gap: differently from before, the stability of the entire system is also affected by its behaviour.

Durability, loading/unloading conditions, fatigue, stability over the time and high strength become then new elements to be added to the already requested pumpability, bleeding and fast hardening characteristics.

In this contribution are included some results of an extensive study developed by Webuild, Lombardi and GEEG having as its primary purpose the analysis of the potential of two-component backfill-grout materials in achieving high performance in terms of strength and stiffness and, at the same time, providing good performance also in terms of durability in particularly aggressive environments.

The second aim of the study was to test and understand how the real injection conditions in the excavation phase of these materials could modify the development of their mechanical characteristics over time.

The third element, to which the study gave particular importance, was the analysis of the potential correlations between the curing conditions and the long-term properties of the materials.

Finally, the last extremely innovative element of the research project was certainly the desire to investigate the behaviour of materials under cyclic stress. This aspect, never tested before for the two-component backfill grouts, has certainly provided elements of considerable interest regarding the behaviour and properties of these materials.

2. EXPERIMENTAL PROGRAM

2.1 Aims

This research activity aims to verify the ability of two-components backfill-grout to fulfill the requirements commonly considered (Table 1) and the requirements specifically defined (Table 2). The activity was organized to select several combinations of materials and dosages to meet the aforementioned performances.

Table 1 - Backfilling common qualitative required performance.

| |
|--|
| A component |
| Be pumpable |
| Do not settle |
| A+B components |
| Quick evolution of the mechanical strength |
| Durability (no degradation) |
| Resist to flushing (presence of water during the installation) |
| Complete and uniform void filling |

The research activity, developed in the GEEG laboratories of La Sapienza University of Rome, has been focused on the design of two different mix designs with the required properties as per table below.

Table 2 - Backfilling specific required performance.

| Properties | Type 1+ | Type2 |
|--------------------------------------|----------|----------|
| Long-term compressive strength | >4 MPa | >10 MPa |
| Cyclic load resistance | required | required |
| Resistance to aggressive environment | required | required |

2.2 Materials and mix designs

Since, as well known, the characteristics of the materials directly and significantly influence the behaviour of the backfilling, the study took into account an extensive experimental investigation of:

- cement;
- bentonite;
- accelerator;
- retarder;
- addition of filler (silica powder).

To select the cement type and composition (cement/slag ratio) several preliminary tests were performed using a standard mix design with two different cement suppliers and two different cement/slag ratios.

The experimental program included tests on different combinations of the selected cement/slag with materials (accelerator, retarder, bentonite) from different suppliers, named hereinafter P1, P2 and P3, and filler (silica powder).

The mix design of each tested combination is listed in tables 3 and 4.

Table 3 - Backfilling component combination tested for mix Type 2.

| Materials | Tested Mix combination for Type 2 | | | | | |
|-----------|-----------------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| | P1 | | P2 | | P3 | |
| | mix 1 | mix 2 | mix 1 | mix 2 | mix 1 | mix 2 |
| | (kg/m ³) | (kg/m ³) | (kg/m ³) | (kg/m ³) | (kg/m ³) | (kg/m ³) |

| | | | | | | |
|-------------|-------|-------|-------|-------|-------|-------|
| Binder | 446.0 | 440.3 | 380.0 | 354.2 | 510.6 | 500.8 |
| Filler | 0.0 | 43.9 | 516.3 | 613.3 | 0.0 | 50.1 |
| Water | 758.0 | 745.4 | 593.9 | 571.6 | 726.7 | 712.7 |
| Bentonite | 27.9 | 27.4 | 0.0 | 0.0 | 20.3 | 19.9 |
| Retarder | 4.6 | 4.6 | 8.9 | 9.1 | 0.0 | 0.0 |
| Accelerator | 91.8 | 89.8 | 91.9 | 83.3 | 100.9 | 98.9 |

Table 4 - Backfilling combination tested for mix Type 1+.

| Materials | Tested Mix combination for type 1+ | | |
|-------------|------------------------------------|----------------------|----------------------|
| | P1 | P2 | P3 |
| | (kg/m ³) | (kg/m ³) | (kg/m ³) |
| Binder | 294 | 294.0 | 266 |
| Water | 817.5 | 814.9 | 824.5 |
| Bentonite | 18.5 | 35.0 | 24.7 |
| Retarder | 3.7 | 4.9 | 3.0 |
| Accelerator | 89.4 | 90.0 | 74.1 |

2.3 Mixing processes for two-components backfill-grout

The process by which the two components A and B are brought into contact and mixed in the short time before the grout hardens is an important element able to significantly affect the development over the time of the mechanical properties of the grout (Di Giulio et al., 2020). The laboratory activity includes three different Injection and mixing processes, namely Static Mixer Injection System, SM (M1), Scaled TBM Injection System, SIS (M2) and manual (M3).

2.3.1 The “Static Mixer Injection System” (SM)

A static mixer is an engineered device for the continuous mixing of fluid materials; this leads to a very effective mixing process and a complete and homogeneous mixing of the two components in a single grout flow.

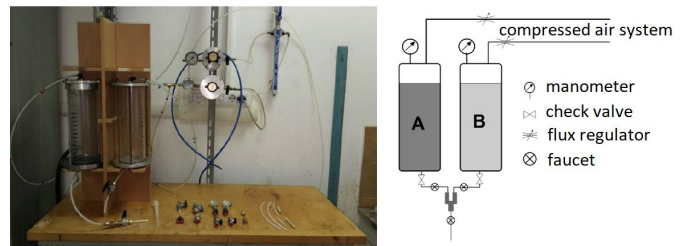


Figure 1 - Laboratory mixing system for two-components backfill grouts tests (modified after Di Giulio et al., 2020).

2.3.2 The “TBM Scaled Injection System” (SIS)

The scaled TBM injection systems was specifically developed for this Research activity and could be considered as a reproduction in scale of the TBM injection plant realized to test more accurately the differences that necessarily exist between the laboratory conditions and what will occur on site.

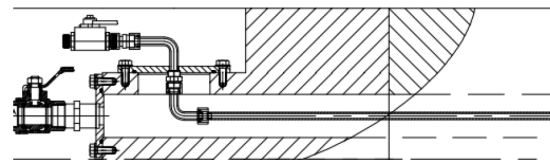


Figure 2 - TBM two-component backfill grout injection plant scheme.

2.3.3 The “manual” mixing process

This is the common method used for mixing and testing the bi-component backfill. The two components are mixed manually in the containers.

The method results in a lower possibility of controlling the mixing of components A and B and, consequently, it is commonly associated to a lower homogeneity of the properties of the hardened grout.

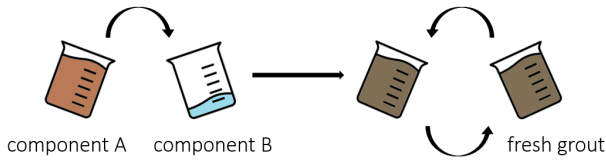


Figure 3 - "Manual" two-component backfill grout mixing process scheme.

2.4 Curing conditions / durability assessments

The procedure proposed in this work consists of the exposure of backfill grout specimens to chemically aggressive environments in order to evaluate their effects on mechanical properties through UCS tests.

The different curing environments tested can be listed in the following Table 5 and Figure 4.

Table 5 - Threshold values for chemical attack exposure class XA3 (UNI EN 206-1:2006).

| Code | Curing |
|------|--------------------------------------|
| C1 | 100% of relative humidity at 25°C |
| C2 | sealed (no water, no air) |
| C3 | 100% of relative humidity at 45° C |
| C4 | 100% of relative humidity at 15°C |
| C5 | pH = 4 water |
| C6 | sulfate rich water (6000 mg/L) |
| C7 | chloride rich water (1000 mg/L) |
| C8 | ultrapure water (for leaching tests) |

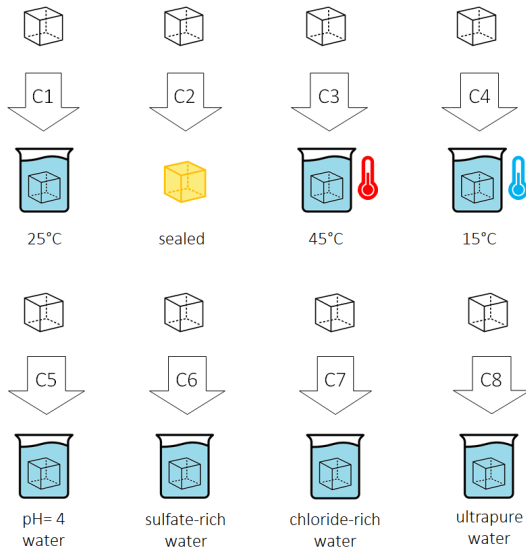


Figure 4 - Schematic representation of durability tests.

The results obtained through the unconfined compression test carried out on the specimens cured in these environments have been compared with those correspondents to the specimens cured in water according to UNI EN 196-1 after 28 and 90 days of curing time

2.5 Laboratory tests

The experimental activity developed can be divided into 4 distinct areas: 1) tests on the fresh component A; 2) tests on the evolution of the mechanical characteristics (strength and stiffness) over time under "standard" conditions; 3) resistance test to cyclic stress; 4) durability tests in different curing conditions and aggressive environments.

2.5.1 Tests on fresh A component

- Bleeding test was conducted according to the UNI 7122 and the bleeding required lower than 5% after 3 hours.

- The Marsh funnel viscosity test has been conducted according to the UNI 11152-13. The test results must fall within the range of 30 to 45 seconds.
- To determine the density of component A, a known volume of mortar (100 mL) was weighed. The test for the determination of the density was carried out on all the mixtures tested in this study.

2.5.2 Tests on hardened grout

- Gelling time, which consists in transferring the mixture (components A and B) from one container to the other until the mortar solidifies, it is possible to determine after how many seconds from the contact between the two components the formation of the gel occurs. The test was conducted according to standards adopted in international literature; the gelling time has to fall within the range of 10 to 18 seconds.
- The unconfined compressive strength, UCS, test has been carried out according to UNI EN 12390-3. The specimens subjected to the unconfined compression test were cubes of 40x40x40 mm³ (type A). The test velocity was equal to 0.5 and 1 mm/min. The UCS test was performed at 1 hour and at 1, 7, 28 and 90 days of curing time.
- The triaxial test was carried out according to ASTM D2664-04. on cylinders with diameter of 38 mm and height of 76 mm. The press speed was equal to 0.5 mm/min and the cell pressures were fixed at 0.5 MPa. The triaxial test was performed at 28 and 90 days of curing time.
- The indirect tensile test (Brazilian test) was carried out according to UNI EN 12390-6. The specimens subjected to the indirect tensile test were cylinders with diameter of 38 mm and height of 76 mm. The press speed was equal to 0.5 mm/min. The indirect tensile test was performed at 28 days of curing time.
- The P-wave and S-wave velocity test is a non-destructive test that can be carried out in both field and laboratory conditions, used to determine indirectly geotechnical properties as the elastic modulus E and the shear modulus G under the hypothesis of elastic material. The test was carried out according to ISMR 1978. The test has been performed at 1, 7, 28 and 90 days of curing time.

2.5.3 Resistance tests to cyclic stresses

Due to the possible transient loads and daily manoeuvres in a typical hydroelectric plant, the tunnel lining and consequently the backfilling material is subjected to various cycles per day of load/unload cycles for about 150 years. In order to model this configuration and analyse the resulting behaviour of the materials, the back-filling grout was subjected to the cyclic compression test as in Table 6.

Table 6 - Summary of cyclic compression test parameters.

| cycles number | (-) | 500 | 500 | 1000 | 1000 | 2000 |
|------------------------|-----|--------|--------|-------|-------|-------|
| axial load (MPa) | | 0÷1.5 | 0÷2.5 | 0÷1.5 | 0÷2.5 | 0÷2.5 |
| application period (s) | | 2 | 2 | 2 | 2 | 2 |
| curing time (days) | | 28, 90 | 28, 90 | 90 | 90 | 90 |

2.5.4 Durability tests

The analysis of the materials durability, with specific reference to the curing environments described in detail in Table 5, were developed by analysing the difference in strength and stiffness of the samples subjected to these conditions compared to the same parameters measured on the samples subjected to C1 curing.

3. RESULTS

3.1 Backfill grout Type 1+

The following table shows the results of the tests performed on the fresh component A. Considering the aforementioned limits all results are in line with the requirements except the P2 gel time.

Table 7 - Summary of the results of the tests on fresh A component.

| | viscosity t=0 h | viscosity t=72 h | bleeding | density | gel time |
|-----------|--------------------|---------------------|----------|---------|-------------|
| | (s) | (s) | (%) | (g/mL) | (s) |
| P1 | 34 | 33 | 4.0 | 1.17 | 16 |
| P2 | 36 | 37 | 3.0 | 1.21 | 36 |
| P3 | 34 | 33 | 4.0 | 1.17 | 16 |

Considering the mixing process M1 (SM) and M2 (SIS) and the curing C1 (100% of humidity at 25°C), in the following tables are presented the average values of the UCS over the time for the backfill grout type 1+.

Table 8 - UCS test results.

| | P1M1C1 | P1M2C1 | P2M1C1 | P2M2C1 | P3M1C1 | P3M2C1 |
|--------|--------|--------|--------|--------|--------|--------|
| (days) | (MPa) | (MPa) | (MPa) | (MPa) | (MPa) | (MPa) |
| 0 | 0.03 | 0.03 | 0.07 | 0.05 | 0.07 | 0.04 |
| 1 | 0.92 | 1.47 | 1.57 | 1.02 | 0.94 | 1.33 |
| 7 | 3.64 | 5.33 | 4.96 | 4.46 | 4.12 | 4.03 |
| 28 | 6.29 | 8.45 | 7.32 | 6.62 | 6.65 | 5.19 |
| 90 | 6.39 | 7.07 | 6.43 | 6.82 | 7.06 | 7.16 |

The same results are proposed in the comparative graph of figure 5.

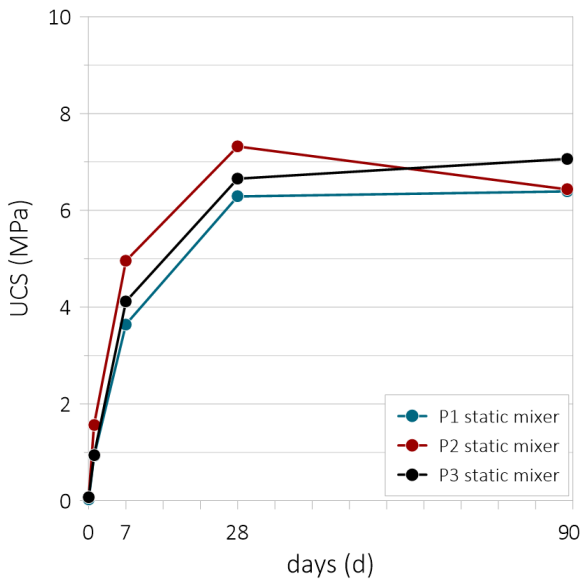


Figure 5 - UCS test results for mix type 1+ 4MPa.

The graphic relative to the UCS value under different environmental condition are below shown.

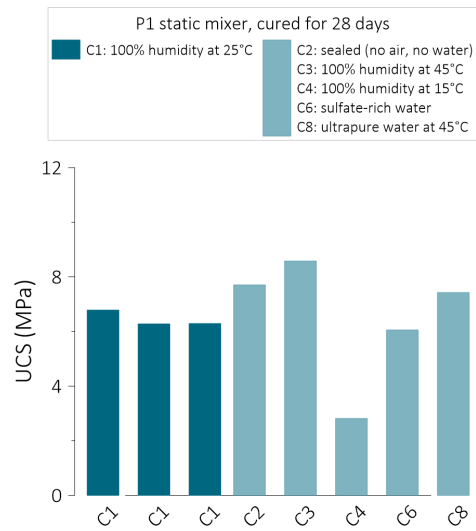


Figure 6 – Durability evaluation (UCS test results) for P1 type 1+ after 28 days of curing in different environments.

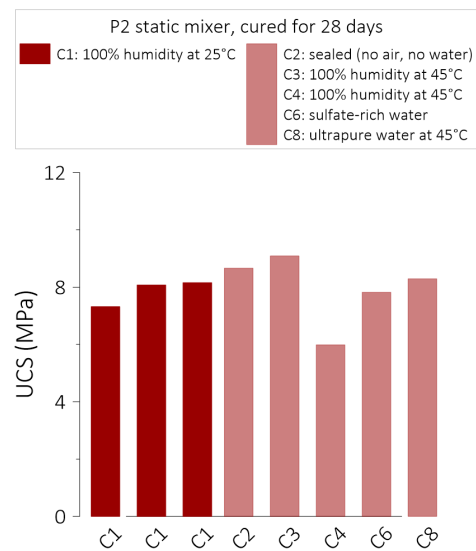


Figure 7 – Durability evaluation (UCS test results) for P2 type 1+ after 28 days of curing in different environments.

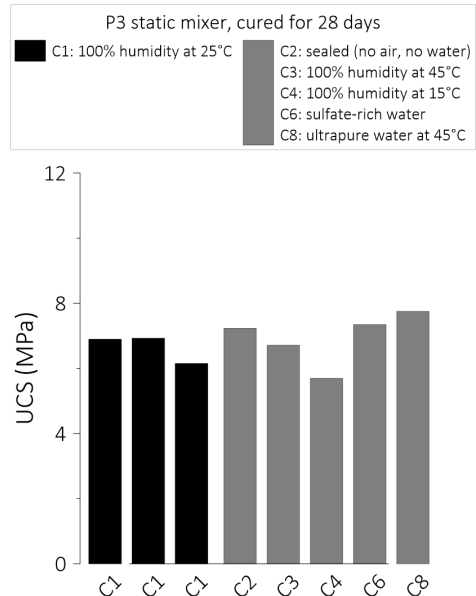


Figure 8 – Durability evaluation (UCS test results) for P3 type 1+ after 28 days of curing in different environments.

In the following figures are shown some elaborations of the cyclic tests for axial load from 0 to 2.5 MPa and 1000 cycles.

In the following tables are presented the average values of the UCS strength measured over the time for the type 2 backfill grout.

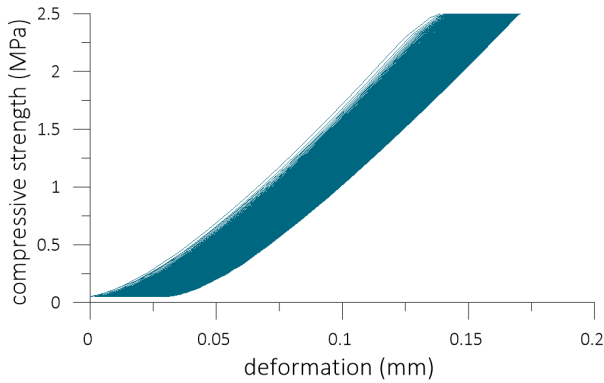


Figure 9 – Cyclic compressive test for P1 type 1+ after 28 days of C1 curing.

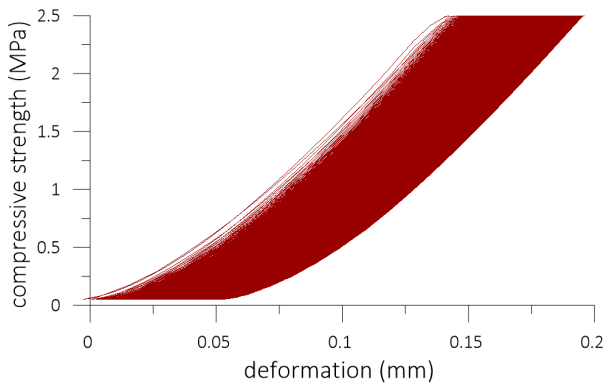


Figure 10 – Cyclic compressive test for P2 type 1+ after 28 days of C1 curing.

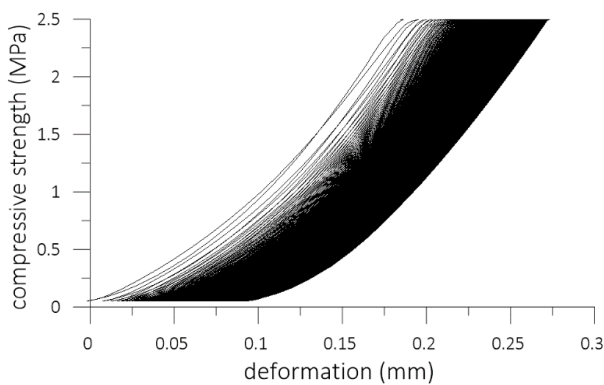


Figure 11 – Cyclic compressive test for P3 type 1+ after 28 days of C1 curing.

Table 10 – UCS test results.

| (days) | P1 mix 1 M1C1 (MPa) | P1 mix 1 M2C1 (MPa) | P1 mix 2 M1C1 (MPa) |
|--------|---------------------------|---------------------------|---------------------------|
| 0 | 0.55 | 0.67 | 0.99 |
| 1 | 3.40 | 3.15 | 1.49 |
| 7 | 10.8 | 9.24 | 13.26 |
| 28 | 14.44 | 14.73 | 15.09 |
| 90 | 16.01 | 16.22 | 15.58 |

| (days) | P2 mix 1 M1C1 (MPa) | P2 mix 1 M2C1 (MPa) | P2 mix 2 M1C1 (MPa) |
|--------|---------------------------|---------------------------|---------------------------|
| 0 | 0.33 | 0.28 | 0.52 |
| 1 | 2.63 | 2.77 | 7.14 |
| 7 | 14.70 | 11.64 | 18.50 |
| 28 | 19.42 | 16.91 | 23.70 |
| 90 | 24.00 | 22.35 | 24.27 |

| (days) | P3 mix 1 M1C1 (MPa) | P3 mix 1 M2C1 (MPa) | P3 mix 2 M1C1 (MPa) |
|--------|---------------------------|---------------------------|---------------------------|
| 0 | 0.23 | 0.15 | 0.07 |
| 1 | 3.10 | 3.12 | n.a. |
| 7 | 13.92 | 8.42 | 13.60 |
| 28 | 20.45 | 9.82 | 17.30 |
| 90 | 23.34 | 11.74 | 19.11 |

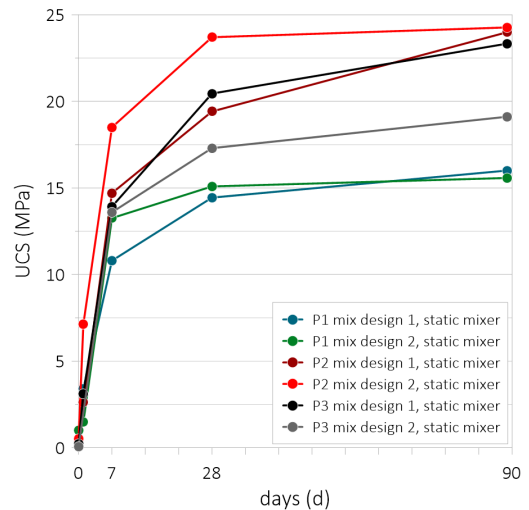


Figure 12 - UCS value for the mix type 2 10 MPa.

The graphic relative to the UCS value under different environmental conditions are below shown.

3.2 Backfill grout Type 2

The following table shows the results of the tests performed on the fresh a component; all results are in line with the requirements except the P2 viscosity at 72h and P2M1 bleeding and gel time.

Table 9 – Summary of the results of the tests on fresh component A.

| | viscosity t=0 h (s) | viscosity t=72 h (s) | bleeding (%) | density (g/mL) | gel time (s) |
|----------|---------------------------|----------------------------|-----------------|-------------------|--------------------|
| P1 mix 1 | 38 | 40 | 5.0 | 1.31 | 7 |
| P1 mix 2 | 38 | 38 | 3.0 | 1.34 | 14 |
| P2 mix 1 | 36 | 57 | 22.2 | 1.57 | 28 |
| P2 mix 2 | 42 | 91 | 4.5 | 1.62 | 16 |
| P3 mix 1 | 38 | 39 | 0.0 | 1.36 | 13 |
| P3 mix 2 | 43 | 40 | 1.0 | 1.40 | 18 |

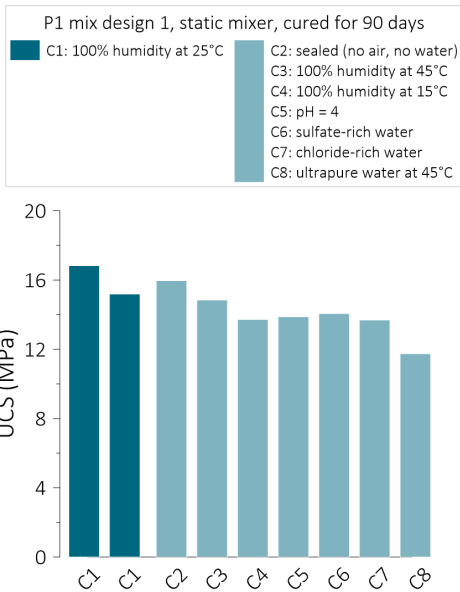


Figure 13 - Durability evaluation (UCS test results) for P1 type 2 after 90 days of curing in different environments.

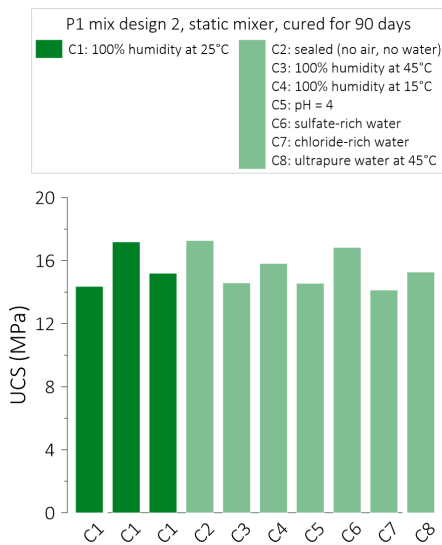


Figure 14 - Durability evaluation (UCS test results) for P1 type 2 after 90 days of curing in different environments.

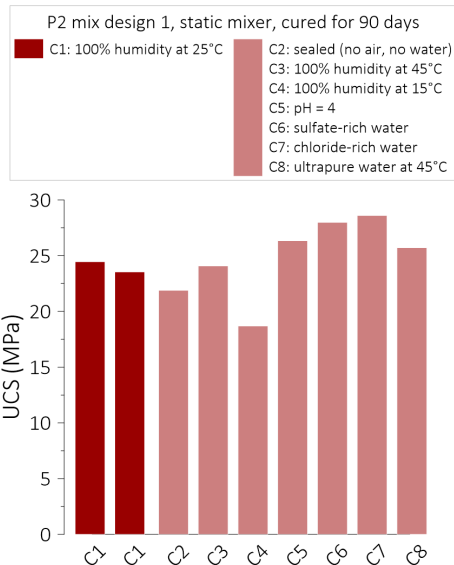


Figure 15 - Durability evaluation (UCS test results) for P1 type 2 after 90 days of curing in different environments.

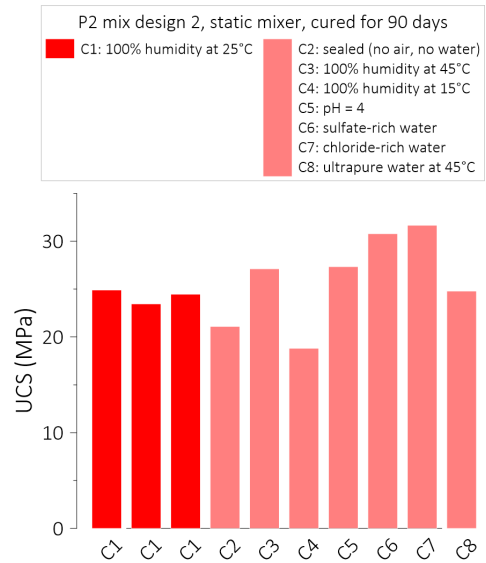


Figure 16 - Durability evaluation (UCS test results) for P1 type 2 after 90 days of curing in different environments.

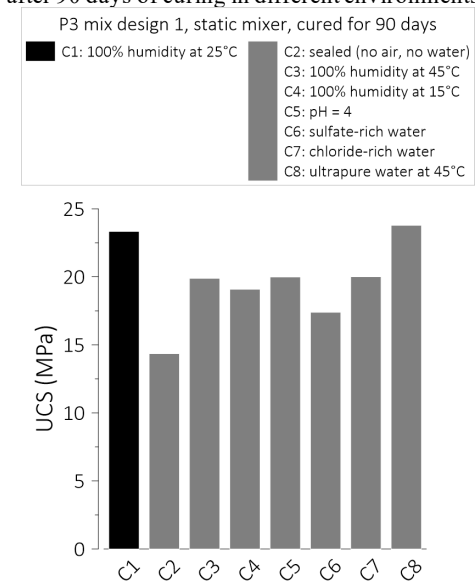


Figure 17 - Durability evaluation (UCS test results) for P1 type 2 after 90 days of curing in different environments.

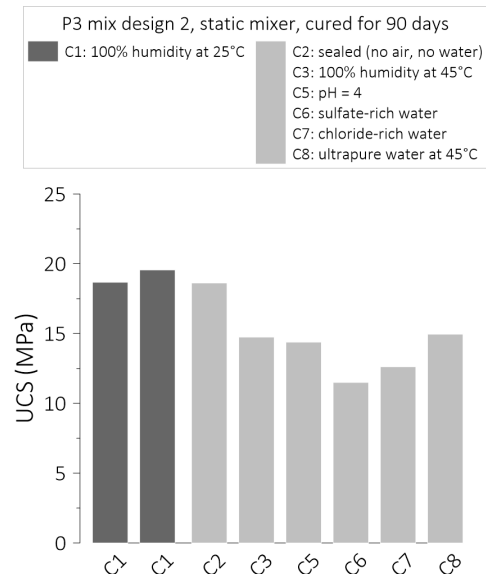


Figure 18 - Durability evaluation (UCS test results) for P1 type 2 after 90 days of curing in different environments.

In the following figures are shown some elaborations of the cyclical tests for axial load from 0 to 2.5 MPa and 1000 cycles.

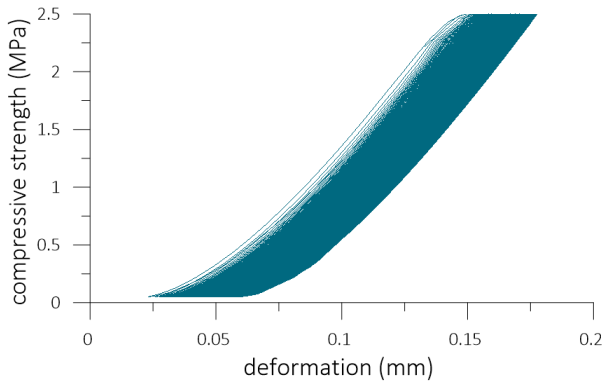


Figure 19 – Cyclic compressive test for P1 mix 1 type 2 after 90 days of C1 curing.

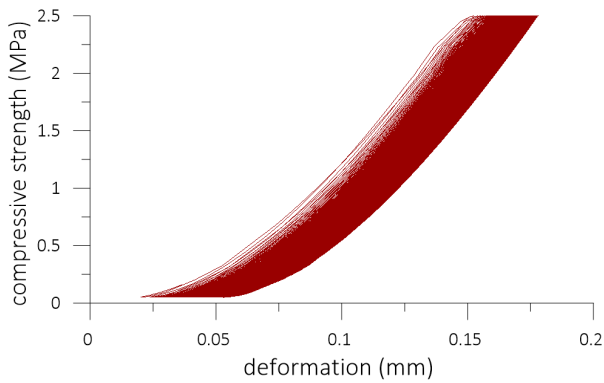


Figure 20 – Cyclic compressive test for P2 mix 1 type 2 after 28 days of C1 curing.

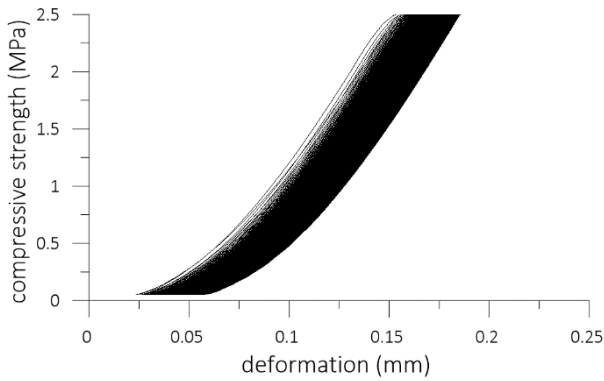


Figure 21 – Cyclic compressive test for P3 mix 1 type 2 after 90 days of C1 curing.

4. DISCUSSION AND CONCLUSIONS

The study presented has highlighted how annulus grouting, if properly designed, is able to play an important role in certain excavation conditions and should not be limited to the sole purpose of backfilling as is currently done.

The study also showed that the use of the right mixes and products, in a favourable cost-benefit ratio, and the use of filler for the mix type 2 allows to reach relevant compressive strength values.

From the values shown it is clearly seen how the evolution of the UCS results over time follows typically increasing trends for all the mix design for backfill grout type 1+ and 2. Moreover, most of the tested mix designs lead to strength values higher than the required ones already after 7 days.

It can also be seen that for 1+ type the UCS results appear very similar and, among the different mix designs tested, P2 leads to slightly higher strength values than P1 and P3.

For type 2, on the opposite, the results are largely satisfactory and decidedly different from each other having maximum values around 15 MPa for P1, values just under 25 MPa for P2 and intermediate values for P3.

About the durability evaluations from the different curing methods, in general, none of the curing environments produced dramatic reductions in strength and that, also considering the variability of the experimental data, it can be concluded that in most cases, the conditions of curing to which the specimens were subjected had no significant effects.

The C4 curing environment, characterized by a temperature equal to 15° C, often determined a reduction or slowdown in the development of strength over time.

It is also interesting to note that the sealed samples did not show any kind of degradation, a sign that the samples during their maturation do not need, in theory, any additional water in respect to that available in the mix design. Finally, no significant degradation was recorded in samples cured in water with chlorides, sulphates and acid pH water.

All the specimens following the cyclical test were in intact conditions without presenting lesions or damages of any kind and that all the samples are characterized by a progressive increase in the deformation of the specimens over the cycles without however a relevant degradation of the strength or stiffness.

4. REFERENCES

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