Tunnelling for a Better Life – Yan, Celestino, Thewes & Eberhardt (Eds)

Durability of two-component backfill grout: An experimental study

Marta Di Felice & Anita Di Giulio*
GEEG, Geotechnical and Environmental Engineering Group, Rome, Italy

Nicola Valiante
Webuild S.p.A., Rozzano, Italy

ABSTRACT: Two-component grout is widely used in mechanized tunnelling to fill the annular gap behind the segmental lining. Besides the numerous advantages of this technology, it is well known that this type of mortar is subject to rapid degradation processes when exposed to air, even for short periods of time. This is not a concern under normal operating conditions, i.e. underground and often below the water table, but it may be detrimental to the quality of the backfilling in case part of the grout is temporarily exposed to air during the construction phases. In lack of dedicated standards, the purpose of this work is to share a laboratory experience on a topic that has not been fully addressed in the literature. The research activity presented in this paper was specifically designed to evaluate the effect of exposure to air and dry soil on a high-performance two-component mortar. The experimental study entailed the execution of visual inspections, UCS tests and mineralogical analyses on small and full-scale specimens subjected to specific exposure environments for an observation period of six months. The results show that, depending on the imposed conditions, there is a certain degree of decay of the mechanical properties but that they remain above those required by technical specifications.

Keywords: Tunnelling, TBM, Backfilling, Two-component grout, Laboratory test, Durability

1 INTRODUCTION

In TBM tunnelling, the use of two-component grout as backfilling material for the annular gap behind the segmental lining is experiencing a great diffusion, encouraging further technical and scientifical research on this topic. Several studies, among which Thewes and Budach (2009), Pelizza et al. (2010), Antunes (2012), Youn and Breitenbücher (2014), Mähner and Hausmann (2017) and Todaro et al. (2022), dealt with the mechanical characterization and the standardization of testing procedure for this material. On the other hand, there is little published knowledge on the long-term behaviour of two-component grout under site conditions as well as in the laboratory. Only recently a comprehensive work by Peila et al. (2015) provided some case histories and laboratory experience. Furthermore, on-site quality checks are generally not made public.

The long-term behaviour of the backfill as a component of the support system of the tunnel together with the lining is important not only in terms of safety and costs, but also to improve sustainability. Hence, its durability should be considered since the design phase.

Laboratory testing of two-component grout usually refers to standards made for concrete and single component mortars (for example UNI EN 11417-1:2012, UNI EN 13057, UNI EN 13295), which cannot be fully applied when the material is exposed to aggressive environments. The exposure conditions of the backfilling in fact are not comparable to those of the structural concrete and also several of those tests entail oven drying, which has proven to be detrimental for the integrity of the two-component grout.

For the backfilling grout, usually working in confined environments and below the water table, the exposure to aggressive environments during the tunnel life may be related to the characteristics of the groundwater (i.e. acid, rich of chlorides, sulphates) or to particular construction phases, during which the grout can be subjected to drying or low temperatures. In this context, it seems appropriate to define the experimental activity according to the conditions and needs of the specific project.

With the goal of sharing a laboratory experience focused of the long-term behaviour of the backfill, this work presents the study of the durability of the backfill grout carried out for the Inclined Pressure Shaft of Snowy 2.0 Project, carefully approached

---

*Corresponding author: anita.digiulio@geeg.it

DOI: 10.1201/9781003495505-138

starting from the design phase due to the special features of the backfilling required for this very challenging project (De Carli et. al (2022) and Di Giulio et al. (2023)).

The performance requirements were:

- unit weight>20 kN/m^3 or porosity<50%
- Unconfined Compressive Strength UCS≥15–20 MPa
- Young modulus E≥3.0–5.0 GPa
- Decay of UCS&E<20% after 10^6 loading/unloading cycles

The selection of a mix design able to meet these targets and its mechanical characterization was followed by a further experimental activity aimed at assessing the grout durability under specific site conditions; in fact, the project schedule involves a construction phase during which the drainages that cross both the lining and the backfill will be operational. These drainages will be necessary to discharge the external hydraulic load acting on the lining in a phase in which the tunnel will be dry but will probably put the backfill in contact with air for a few months. The object of the study was to verify if the two-component grout could withstand, without damage, this temporary phase.

2 MATERIALS AND METHODS

Two-component backfill grout consists of two fluids: a component A (binder, bentonite, water and a retarding agent) and a component B (accelerating additive, usually sodium silicate), which produce a gel within seconds from the moment they are mixed. The materials used and the mixing process significantly affect the behaviour of the grout, therefore, in the laboratory, particular attention was paid to the supply of the actual materials from the jobsite and to the mixing system, that was designed to simulate as closely as possible the injection system of the TBM. The durability of the grout was considered at an early design stage, with constrains on the binder and the filler to be used and on the porosity to be achieved.

The mix design reported in Table 1 (Di Giulio et al. 2023) was obtained after a trial phase aimed at finding a proper balance between the characteristics of the fresh and hardened grout, i.e. achieving high-performances while maintaining the component A fluid and stable enough to be pumped. The special features of this mix design with respect to common practice (Thewes and Budach 2009) are the use of a composite slag/cement binder, the low water/binder ratio (0.85), the reduced amount of bentonite, and, most importantly, the introduction of a superplasticizer to improve the workability and of a filler (silica flour) to impart structure. The component B was sodium silicate, which dosage is about 11% of the total weight of 1m^3 of grout.

Table 1. Mix design.

Binder (kg/m^3)	608
Filler (kg/m^3)	339
Water (kg/m^3)	518
Bentonite (kg/m^3)	2.8
Retarder (kg/m^3)	11.3
Superplasticizer (kg/m^3)	3.6
Accelerator (kg/m^3)	176

A series of laboratory tests was performed to measure the properties of the component A (viscosity at the Marsh' cone, density, gel time) and to verity the performance requirements on the hardened grout (unit weight, porosity, Unconfined Compressive Strength and elastic moduli). The unit weight and porosity were 16.5 kN/m^3 and 35%, respectively; the average UCS of the mortar was 36 MPa after 28 days and the average value of the Young's modulus was 10 GPa.

2.1 *Experimental program*

As already pointed out, the experimentation could not follow the existing standards for durability testing due to the peculiar features of two-component grout, so the study was carried out with a site-specific approach, dealing with expected conditions that could be detrimental for the grout integrity and performance on the long-term.

The experimentation lasted six months and consisted in the execution of UCS tests on samples cured in different environments, and in the preparation of a full-scale sample simulating the grout around a drainage hole, subjected to visual inspections, UCS tests and mineralogical analyses.

2.1.1 *Curing at controlled humidity*

The effect of a prolonged exposure to air was investigated on prismatic specimens, cured in water at constant temperature for about four months before the beginning of the tests. The samples were sealed in paraffin leaving free one of the bases, as shown in Figure 1, and then were kept at 25 °C in containers with relative humidity equal to 50%, 90% and 98%.

Temperature and humidity were monitored by a thermometer and a hygrometer for the entire test duration. After a first inspection, executed after two months of exposure, it was decided to continue the observation up to six months, exposing other samples (now six months old) to the worst conditions, i.e. 50% relative humidity. At the end of the fixed period of exposure the samples were subjected to visual inspection and UCS tests.

2.1.2 *Full-scale set-up: Simulation of the drainage hole*

A specific test set-up, illustrated in Figure 2, was developed with the aim of studying in the laboratory the potential degradation of the portion of grout surrounding the drains.

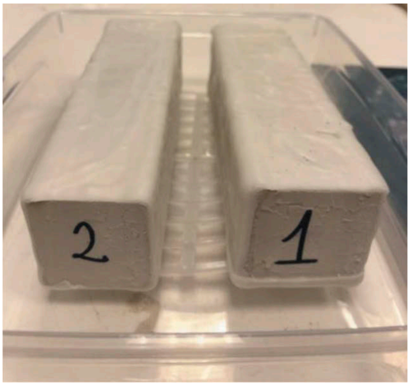

Figure 1. Prismatic specimen sealed in wax.

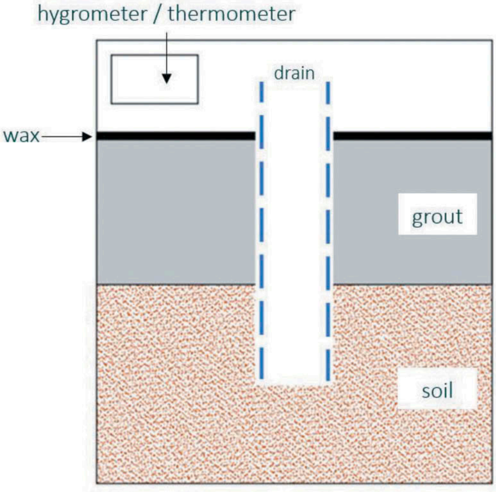

Figure 2. Scheme of the set-up for the simulation of the drainage.

A 40x40x18 cm block of grout was prepared leaving a PVC pipe (80 mm external diameter) in the centre. The grout was poured directly on a layer of sand, simulating the contact between backfill and rock mass, while the impermeable lining was simulated by a top layer made of wax. The casting of this full-scale sample (Figure 3) was the most challenging task of the experimentation, requiring the laboratory team to build a new system able to pour about 40 L of mixture in a continuous flow under 1 bar of pressure, which was much more complex than the system previously used and already discussed in De Carli et. al (2022).

After 40 days of curing in sealed conditions, the PVC pipe was extracted and replaced with a smaller slotted pipe, leaving a gap of about 2 mm between the hole wall and the external surface of the drain. The system thus made was then kept at a temperature of 25 °C and relative humidity, *hr*, of 70% for six months, during which visual inspection and UCS tests were performed at regular intervals.

Figure 3. Pictures of the full-scale set-up.

The value of relative humidity equal 70% was selected as the minimum among the available environmental measurements taken in another tunnel of the jobsite.

3 RESULTS

3.1 *Prismatic samples in unconfined environment*

As illustrated in Figure 4, which shows longitudinal sections of sawn prisms, the samples presented a dry/discolored external layer, while the inside appeared fresh.

Figure 4. Pictures of sections of samples sawn after exposure to air at different values of relative humidity, from the left: 50%, 90% and 98%.

The extent of the discolouration, localized at the exposed faces, is greater in the specimens exposed to lower humidity values (hr=50%), as could be expected. Beside the external discoloring, the exposure at hr=50% produced the formation of cracks propagating from the free base inwards.

The results of the UCS tests carried out on cubic samples sawn from the prisms are presented in Table 2 and Figure 5. It can be observed that the UCS of the control sample (cured in water for the same period) is about 36 MPa, congruent with the average UCS at 28 days of this mix, and that after two months of exposure all samples provided results comparable or above this value, in the range 34-45 MPa.

The thickness of the altered layer after two months was about 2 mm, but this did not translate in a deterioration of the performance, even for the samples kept at the lowest humidity.

Table 2. Results of UCS tests after exposure to air at hr=50%.

Curing conditions	Time of exposure (months)	Total age of samples (months)	UCS (MPa)
Standard	0	6	35.7
hr=50%	2	6	39.3*
hr=50%	2	6	45.2
hr=90%	2	6	33.8
hr=90%	2	6	40.6
hr=98%	2	6	43.6
hr=50%	6	12	51.6
hr=50%	6	12	29.7*
hr=50%	6	12	44.3
hr=50%	6	12	27.7*
hr=50%	6	12	42.5

*Sample including the exposed surface

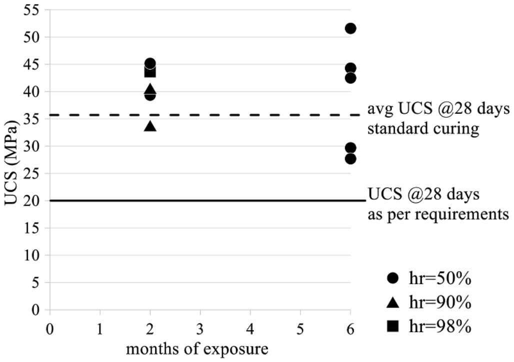

Figure 5. Results of UCS tests after two and six months of exposure to air at relative humidity = 50%.

As anticipated, once seen the cracks proceeding from the exposed face of the samples cured at hr=50%, it was decided to extend the observation period up to six months. The extent of the altered layer grew, producing measurable damages to the strength of the cubic samples containing the exposed surface; in fact, as it can be noted from Table 2 and Figure 5, the UCS values measured on the external portion of the prisms (28 and 30 MPa) are lower than the UCS measured on the internal portion of the same specimens (42-52 MPa).

A picture taken after the UCS test of a cubic sample containing the exposed face is shown in Figure 6. It's worth noting that the test was conducted putting the altered surface parallel to the vertical axis in order to have regular surfaces on which apply the load. Of course, this could have an influence on the results.

3.2 *Full-scale sample with drainage crossing*

The block of grout was inspected after one, three and six months of exposure to air at 25 °C and humidity 70%.

Figure 6. Broken sample with an exposed surface.

Figure 7 shows the microscopic enlargements of the portion of grout immediately around the drainage hole, taken at the first and last visual inspections.

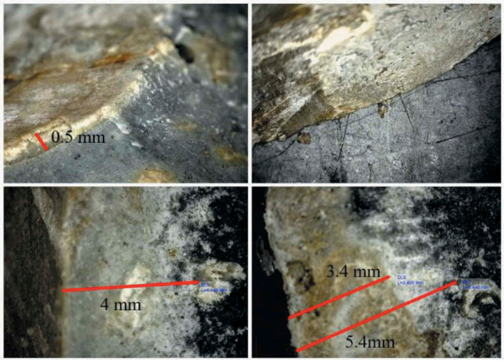

Figure 7. Enlargements of the layer of grout exposed to air within the drainage, after 1 month (above) and 6 months (below).

The boundary between altered and "fresh" grout can be easily spotted by colour, so it was possible to measure its progress over the time. After one month, the thickness of the altered layer was less than 1 mm, about 0.2 – 0.5 mm, after 3 months it was about 3-4 mm, after six months it was between 4 and 6 mm.

During the first and last inspection, portion of the block near the drainage hole were sawn to obtain cubic samples for UCS tests. The results are reported in Table 4 and Figure 8.

Table 3. UCS tests on samples retrieved from the block.

Time of exposure (months)	Density (Mg/m3)	UCS (MPa)
1	1.66	36.7
1	1.70	29.5
1	1.64	28.1
6	1.68	29.9
6	1.68	22.3
6	1.59	26.2
6	1.70	28.6

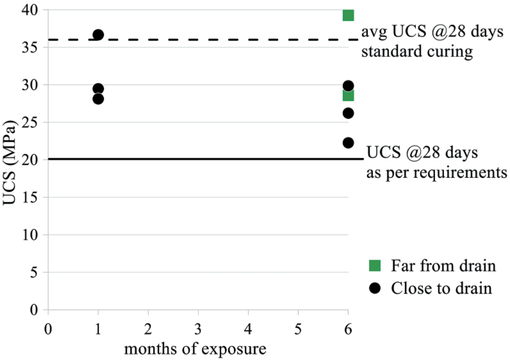

Figure 8. UCS values after 1 and 6 months of exposure.

The measured UCS values, even if always higher than the threshold of 20 MPa set by performance requirements, are generally below the average UCS expected for this mix design at 28 days. This difference may be due to the preparation of the block, which entailed the injection of a huge volume of grout in a single step and a dry, even if sealed, curing. These conditions made the formation of joints and small defects in the block practically unavoidable. Also, the presence of these joints made quite difficult the preparation of cubic samples from the block (from which the modest number of tests that could be executed).

The result show that a reduction of strength due to the exposure to air can be detected comparing the UCS values obtained at different inspections. In fact, after six months of exposure, the samples closer to the hole had an average UCS of 26 MPa, about 17% lower than that of the samples taken close to the hole after one month (31 MPa). Also, visual inspection allowed to observe that the failure of these samples occurred along pre-existing surfaces, while samples retrieved beyond a layer of about 10 cm from the drainage hole provided higher UCS values and appeared fresh after the tests, as shown in Figure 9.

Figure 9. Pictures of samples retrieved from the full-scale block. On the left a sample taken far from the drainage hole, on the right one taken close to it.

3.3 *Mineralogical analyses*

Portions of the block were subjected to mineralogical (DRX - X-ray diffraction) and petrographic analyses to understand the process of alteration that the grout experiences when exposed to air.

Table 4 synthetizes the results of DRX analyses carried out at three and six months on altered and fresh portions of grout.

Table 4. Results of mineralogical analyses.

	3 months		6 months	
Phases	Fresh	Altered	Fresh	Altered
Quartz	27	27	27	26
Calcite	8	9	10	10
Gypsum	1	1	1	1
Vatherite	-	24	-	23
Aragonite	-	4	-	2
Ettringite	3	-	3	-
Smectite	-	-	-	-
Alite/belite	0	-	2	-
Portlandite	-	-	-	-
Amorphous	60	35-40	57	38

It can be noted that the recognized phases are practically the same, with a significant part of the samples composed by not-crystalline phases and quartz (the filler), compounds contained by the clinker as gypsum, calcium silicates (alite/belite) and other hydration products. The altered layer contains more vaterite, a meta-stable form of calcite, at the expenses of the amorphous phase.

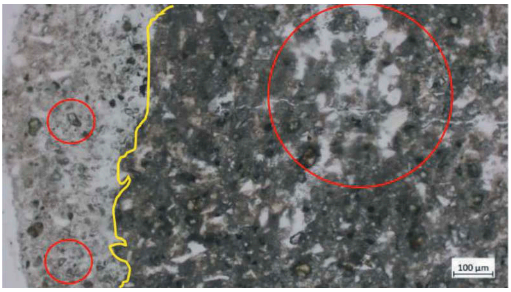

Figure 10. Detail of the passage between altered and fresh grout (yellow line). The porosity is shown in the red circles.

The petrographic study highlights the separation between the white and dark layers already observed at a macroscopic level, sometimes gradual and sometimes neat, the latter associated with a higher porosity. The porosity consists mainly of spherical voids presumably due to air entrapped during mixing, but also from narrow cracks probably due to shrinkage (Figure 10).

The altered portion is characterized by a predominantly micritic matrix typical of carbonation due to reaction with the CO_2 in the air.

4 CONCLUSIONS

The study here presented was carried out to investigate the long-term behaviour of the backfilling grout of the IPS of the Snowy 2.0 project, following a site-specific approach. The experimentation was aimed at evaluating the effects of the exposure to air and low humidity on two-component grout. The experimental activity was developed to simulate specific and severe environmental conditions, in lack of dedicated standards, and involved prismatic samples as well as a full-scale set-up, simulating a portion of grout around a drainage hole.

At the end of an observation period of six months, the following conclusions can be drawn:

- the alteration that the two-component grout undergoes when exposed to air at low humidity is caused by carbonation phenomena and, in this high-performance mix, proceeds from the external surface inwards at an average rate less than 1 mm/month measured on the full scale sample;
- cubic samples obtained from sealed prisms with one free face in contact with air, at relative humidity equal to 50%, provided UCS values in the range 42-52 MPa measured far from the exposed surface, and lower values (28 and 30 MPa) when containing the altered layer;
- in the full-scale sample, the alteration proceeding from the exposed surface (4-6 mm) and the formation of cracks due to the casting procedure, volume of the block and dry curing, produced a reduction of the strength in the layer of grout immediately surrounding the hole. This reduction was observed comparing average UCS values obtained after one and six months of exposure, which are about 31 and 26 MPa, respectively;
- in the full-scale sample, the grout resulted substantially unaffected, in terms of strength and aspect, beyond a layer of about 10 cm from the exposed surface.

ACKNOWLEDGMENTS

The authors would like to thank Snowy Hydro Ltd and Future Generation Joint Venture for promoting and supporting the development of these studies.

The authors would like to thank the laboratory ANALITICA S.a.s. for the mineralogical analyses and the valuable knowledge made available to interpret them.

REFERENCES

Antunes, P., 2012. Testing procedures for two-component annulus grouts. North American Tunnelling proceedings, 14–22.

De Carli, G., Valiante, N., Mancinelli, L. Sebastiani, D., 2022. High performance TBM Backfill grout. Proceedings of the ITA-AITES World Tunnel Congress 2022, Copenhagen (Denmark).

Di Giulio, A., Di Felice, M., Valiante, N., De Carli, G., 2023. Single and two-component grout as high-performance backfilling materials. Proceedings of the ITA-AITES World Tunnel Congress 2023, Athens (Greece).

Mähner, D., Hausmann, M. 2017. New Development of an Annular Gap Mortar for Mechanized Tunnelling. In AFTES International Congress 2017, Paris (FR), 13-16 November 2017.

Peila D., Chieregato A., Martinelli D., Salazar Onate C., Shah R., Boscaro A., Dal Negro E., Picchio A. (2015). Long term behavior of two component back-fill grout mix used in full face mechanized tunneling. GEAM. GEOINGEGNERIA AMBIENTALE E MINERARIA, vol. 144 n. 1, pp. 57–63. - ISSN 1121-9041.

Pelizza, S., Peila, D., Borio, L., Dal Negro E., Schulkins, R., Boscaro A. 2010. Analysis of the performance of two-component back-filling grout in tunnel boring machines. Proceedings of the ITA World Tunnel Congress 2010, Vancouver (CA), May 14–20.

Thewes, M., Budach, C. 2009. Grouting of the annular gap in shield tunneling – an important factor for minimization of settlements and production performance. Proceedings of the ITA-AITES WTC.

Todaro, C., Martinelli, D., Boscaro, A., Carigi, A., Saltarin, S., Peila, D., 2022. Characteristics and testing of two-component grout in tunnelling applications. Geomechanics and Tunnelling, 15: 121–131. https://doi.org/10.1002/geot.202100019

Youn, B. Y., Breitenbücher, R., 2014. Influencing parameters of the grout mix on the properties of annular gap grouts in mechanized tunneling. Tunnelling and underground space technology, 43, 290–299. https://doi.org/10.1016/j.tust.2014.05.021