Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds)
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Single and two-component grout as high-performance backfilling materials

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ABSTRACT: Segmental lining is not usually applied in hydraulic pressure tunnels but may become a viable alternative if it can withstand internal pressure variations and it is possible to fill the tunnel annular gap with high-performance backfilling material, as single-component grout or pea gravel. The research here presented is aimed at studying a mix design for the backfill to be used in a pressure tunnel subjected to severe hydraulic conditions, considering both single and two-component grout. The requirements (high strength and stiffness, cyclic load resistance and durability) are quite common when considering a traditional grout but become challenging for a two-component one. The experimentation consisted in a preliminary phase to find mix designs that conjugated pumpability of the fresh mixture and mechanical properties of the hardened grout, followed by a testing phase on the best recipes, under static and cyclic loads. This paper presents a comparison between the two solutions.

1 INTRODUCTION

The present research is developed in the context of studying a new lining concept for the construction of the Inclined Pressure Shaft (IPS) of the Snowy 2.0 pumped hydro-electric project (Australia), with an internal diameter of 9.9 m and a length of 1.6 km. The IPS lining solution, currently under study, is a single pass tensile resistant segmental lining including steel couplers, named as Force-Activated Coupling System (Valiante et al., 2023).

The tunnel lining is subject to extreme hydraulic loads, with a steady state pressure ranging 690-780 m and the internal pressure variations due to the water hammer reaching +29 bar for the positive variations with respect to the steady state and –27 bar for the negative variations.

Since the lining is drained by means of the hydraulic connectors, it is almost unloaded during water filling of the scheme and only transient loads act on the lining due to water hammer events. During positive transients the lining displacement is restrained by the equivalent radial bedding stiffness of the coupled surrounding rock mass and backfill between the segmental lining and the excavated rock surface. The backfill grout represents a deformable layer due to its elastic modulus, which is lower than the rock mass bedding stiffness, thus its influence on the overall bedding stiffness is not negligible.

The properties of the backfill grout have been recently investigated by several authors, among which Antunes (2012), Thewes (2013), Youn and Breitenbücher (2014), Mähner and Hausmann (2017) and Todaro et al. (2022). In the specific framework of this work, the crucial role played by the annular backfill grout is to provide homogeneous and sufficiently stiff confinement to the lining, particularly in the long term, considering the operational conditions of the project in terms of cyclic loads and hydraulic conditions.

DOI: 10.1201/9781003348030-147

In high pressure hydraulic tunnels, the common practice is to adopt single-component backfill grout, mainly for the high strength and stiffness requirements. However, two-component backfill grout provide advantages in terms of quick setting and early support of the lining, stability under water flow and good pumpability and workability (ITAtech 2014, Thewes & Budach, 2009).

The aim of this research was to develop single-component and two-component backfill-grout materials capable to achieve very high performance in terms of strength and stiffness and, at the same time, providing good performance also in terms of durability under cyclic loads.

2 PROJECT REQUIREMENTS

To limit the lining deformability under positive transient load, the project requirements were particularly high in terms of mechanical strength to be achieved, as well as high durability performances. In addition, the material had to be tested under cyclic loading, considering it would experience millions of internal pressure oscillations over the 150 years lifetime of the plant, making the fatigue verification one of the most important aspects.

Table 1 reports the specifications initially set for the backfill grout. The range of variability for the parameters considers the different hydraulic loads along the IPS, with the bottom of IPS requiring higher performances for the grouts.

Compression strength higher than 20 MPa was particularly demanding for a bi-component grout, as this material has generally UCS values in the range of 2-5 MPa (Peila et al. 2015), however, higher values have been recently achieved in previous studies (De Carli et al. 2022).

Regarding the Young modulus, a value of 5 GPa was also uncommon for a two-component backfill material. On the contrary, both values of UCS and Young modulus are easily achievable adopting a single-component backfill mix.

Finally, it is worth to mention that a grout stiffness of 5 GPa had the effect to reduce between 6% and 25% the rock bedding stiffness along the IPS, due to the presence of the backfill grout. Thus, it is a crucial parameter to be achieved to limit the tunnel lining deformability.

Table 1. Project specifications for the backfill grout.

Parameter	Test	Acceptance Values
Uniaxial compressive strength	Uniaxial compressive strength test	≥ 15–20 MPa
Young modulus	Uniaxial compressive strength test with strain measurements	≥ 3.0–5.0 GPa
Decay of properties after cyclic tests	Cyclic compression test	< 20% after 10^6 cycles
Segregation	Bleeding test	< 5% after 3h
Fluidity/Viscosity	Marsh cone	35-45 sec
Gelling time	Hardening time	10-18 sec

3 TESTING CAMPAIGN

3.1 *Materials*

Two-component backfill grout consists of two fluids: a component A (binder, bentonite, water and a retarding agent which inhibits the setting) and a component B (accelerating additive, usually sodium silicate), which produce a gel within seconds from the moment they are mixed, i.e. the injection. In this study a superplasticizer agent, to improve the component A’s workability, and a filler, to increase the mechanical performance, were also included. Single-component grout consists in a mixture of binder, bentonite, water and sand; in this case chemical admixtures (retarder and superplasticizer) were added to improve the fresh state’s properties.

The binder used is a mix of general-purpose cement and ground granulated blast furnace slag, in about even proportions. Usually, in the production of grouts bentonite is used to avoid bleeding/segregation, while the retarder is added to delay the setting time and therefore maintain for a longer time the workability of the component A. The accelerant, used only for two-component grouts, reduces the setting time ensuring a rapid gelling of the mortar and increasing the rate of development of mechanical resistances. Based on the properties required of the mortar, other admixtures may be necessary: in this research a superplasticizer or high range water reducer was added to both two-component and single-component recipes, to decrease the water/binder ratio that can be reached maintaining the desired fluidity of the mixture.

The filler, added to the two-component grout to increase the stiffness and strength of the grout, is a silica flour with D90 of 50 μm. The sand, used for single-component mixes, was a well graded quarry sand with maximum size 4mm. This choice was dictated by both intents to use a standard material, and therefore to be able to carry out reproducible tests in the laboratory, and to allow greater adhesion of the cement paste on the surface of the rough grains, thus improving mechanical strength.

3.2 *Experimental program*

The experimental program consisted of a preliminary phase which identified two mix designs (a two-component and a single-component grout) based on evaluations of the properties of the fresh grout and on UCS tests after a few days of curing, followed by a complete study, which included static and dynamic mechanical tests carried out on the two selected mix designs.

3.2.1 *Preliminary phase*

The adequacy of a backfilling material is not fully defined by the mechanical performance exhibited by the hardened material but depends on the properties that ensure a successful injection, as stability, pumpability and setting time, evaluated on the fresh material. The experimental program envisaged a series of trials for both mortars tested, to define optimal mix designs that would meet the technical specifications. The consistencies of two-component and single-component grout are quite different in their fresh state, so that, depending on the material, different types of tests were carried out to evaluate workability and pumpability.

To meet the requirements on strength/stiffness, it was necessary to reduce the values of water/cement ratio far below those commonly used for this kind of applications (about 2.5 in the Authors' experience, in line with the data reported by Todaro et al., 2022). The introduction of a superplasticizer allowed to reach w/c around 0.80 for two-component grout and 0.60 for the single-component, which represent a good compromise between increasing solid structure and maintaining segregation and fluidity in the ranges stated by design specifications (Table 1). In addition to the familiar water/cement ratio, other indicators have been reported to have more insights on the behavior of each mix: the water/binder ratio, defined by European standard EN 206-1 and useful when supplementary cementitious materials are present in the mix; and the Rheological Index (IR), which corresponds to the volumetric ratio between all the solid particles, including filler and sand, and water (Linger et al., 2008). Table 2 report the results of this screening phase and the selected mix designs.

As previously said, different types of tests were carried out to evaluate the properties of the fresh two-component and single-component grout. The fluidity of two-component grout component A was evaluated by means of the Marsh cone's test (ASTM D6910) at 0 and 72 hours after production, obtaining values higher than the reference of 35-45 s for a typical 2k mix (André et al., 2022), but nonetheless acceptable considering this special application. This was due to the presence of substantial quantities of binder and filler necessary to achieve the desired performances. As for the single-component grout, being the Marsh cone test not feasible, and in lack of dedicated specifications, the fluidity was evaluated comparing mini-slump tests and flow table test (ASTM C1437) at 0 blows instead of 25 (which is the practice for concrete), searching for the maximum that could be measured, i.e. 10 cm for the mini-slump and 30 cm for the flow table).

The bentonite was included to avoid bleeding (evaluated according to ASTM C940) and was found very important to avoid segregation of the sand particles in the single-component grout. For the two-component mortar it was also necessary to evaluate the gel time, which gave values in the optimal range of 10-18 seconds only with an amount

Table 2. Mix designs selected for subsequent tests. Dosages in kg/m^3.

Materials	Single-component	Two-component
Cement	350	243
Slag	233	365
Water	350	518
Bentonite	4.6	2.8
Filler	-	339
Sand	1165	-
Retarder	0.9	11.3
Superplasticizer	6.9	3.6
Accelerant	-	176
w/c	0.60	0.85
w/b	0.71	1.12
I.R.	1.85	0.64

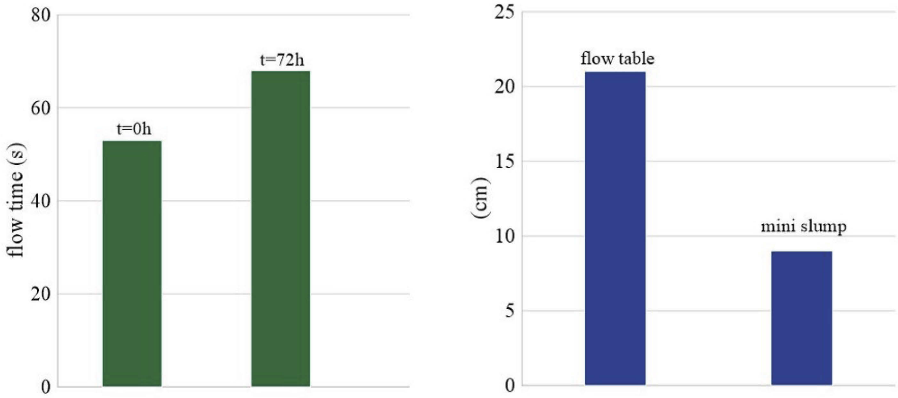

Figure 1. Results of tests conducted on grouts in the fresh state: two-component grout on the left and single-component on the right.

of sodium silicate of about 11% by weight on a cubic meter of grout, much higher than the values of 7-8% typically observed by the Authors and consistent with literature data (Todaro et al., 2022). Lower dosages did not produce an homogeneous gel but the formation of lumps in about 3-5 seconds; this was probably due to the unusually high amount of binder. The setting time for the single-component grout, on the other hand, was approximately 6-8 hours.

The specimen's preparation, which significantly affects the development over time of the mechanical properties of the backfill grout (Di Giulio et al., 2020), was made by mixing components A and B with a specifically developed system, described in [1,2]. The single-component mortar, on the other hand, was casted manually into the molds. Figure 2 show the hardened specimens of both grouts.

4 RESULTS

4.1 *Unit weight and porosity*

The values of unit weight, γ, and porosity, n, of both grout types are reported in Table 3. The first was measured at different curing times and shows, beside a certain experimental dispersion, a slight increase over the time that is due to the formation of hydration products that fill

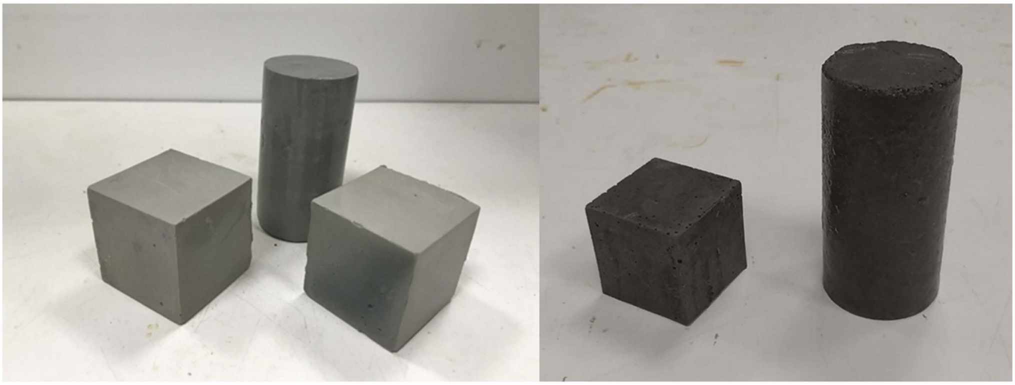

Figure 2. Two-component grout (left) and single-component grout (right) specimens.

the voids; this should be reflected also by a correspondent decrease in porosity over the time, but such measures were performed only at 28 days. According to the available standards, the measurements of void ratio/porosity of hardened grout and concrete are referred to dry values, which for the two-component grout means completely altering the sample structure by oven drying. In order to obtain reliable values, it was decided to dry the samples at 40 °C until the stabilization of the weight was observed, measuring the specific weight of the solid, γ_s, on the dry powder. The porosity was then calculated as $n=1- \gamma_d/\gamma_s$, where γ_d is the unit weight of the dry sample. The temperature of 40 °C was selected to avoid inducing possible thermo-chemical alterations in the sample.

Table 3. Unit weight and porosity measurements at different curing times.

Time (-)	Single-component γ (kN/m^3)	n (%)	Two-component γ (kN/m^3)	n (%)
1h	-	-	15.9	-
1d	20.7	-	16.1	-
7d	20.6	-	16.0	-
28d	20.9	19	16.5	35

In the Authors' experience, consistent with the evidence reported by Todaro et al. (2020), unit weight values for a typical two-component grout are about 12 kN/m^3, so that a value of about 16 kN/m^3 seems quite impressive, and likely a physical limit to be achieved without compromising the pumpability of the fresh mortar.

4.2 *Unconfined compression test and elastic moduli*

The mechanical properties in static conditions were evaluated by means of unconfined compression tests at different curing times. UCS tests were conducted on cubic specimens (40x40x40 mm) after 1 hour and 1, 7 and 28 days of curing in water at 25°C. Figure 3 (left) reports all the results together with the average UCS over the time: as expected, the development of strength shown by the two-component grout is quicker but eventually is fully recovered by the single-component, reaching about 36 and 40 MPa, respectively. The Young's moduli, *E*, were measured only at 28 days, on cylindrical samples with 46 mm of diameter and h/d ratio equal to 2. The strains were recorded by means of strain gauges. Tests were conducted following the standard for concrete UNI EN 12390-13:2013 and the average values of the tangent Young's modulus, calculated as per ASTM E111 at 50% of the UCS, were 10 GPa for the two-component grout and 20 GPa for the single-component.

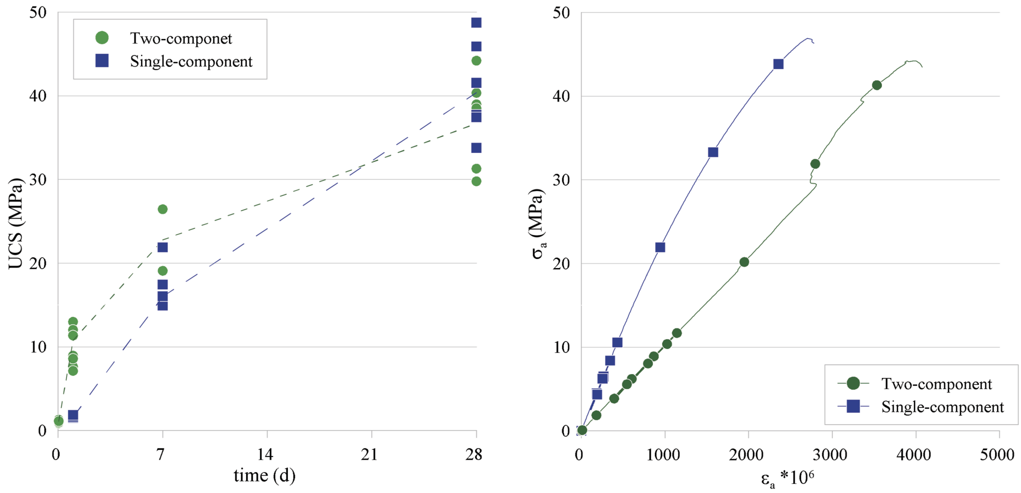

Figure 3. On the left, two and single-component grout's evolution over time of unconfined compression strength. On the right, examples of stress-strain curves for both materials.

4.3 *Cyclic compression tests*

The backfilling material of the hydraulic tunnel will be repeatedly subjected to almost instantaneous variations of pressure related to the operation of the power plant, so that the investigation of the resistance against fatigue of the material assumes great importance to ensure the proper functionality of the structure. In order to study this issue, the selected grout mixes were subjected to cyclic compression test of various duration, applying loading/unloading cycles with a 2 s period (0.5 Hz of frequency) ranging between different load intervals. The loading conditions to be simulated during the cyclic test were defined considering the operational profile of the Snowy 2.0 hydropower plant. After the cycles, the samples were subjected to UCS tests with measurement of the strains (UNI EN 12390-13:2013), which allowed to calculate the tangent modulus at 50% of UCS (ASTM E111).

Details of the cyclic testing and relevant results are listed in Table 4 . The specimens were prisms with dimensions of 160x40x40 mm, maintained in water at 20°C until the beginning of the tests. Cyclic loading was performed in a room at controlled temperature and humidity, 25° C and 98% respectively, which for the two-component samples was a fundamental caution to avoid damages due to drying. In fact, the execution of the complete series of cycles took about 25 days, a long period of exposure to air during which was very important to preserve the integrity of the samples.

Table 4. Results of UCS tests after loading/unloading cycles (0.5 Hz frequency).

N° cycles (-)	Load range (MPa)	Single-component UCS (MPa)	E(GPa)	Two-component UCS (MPa)	E(GPa)
0	-	51.8	-	-	-
0	-	54.1	-	-	-
0	-	66.8	28.5	-	-
0	-	56.2	28.8	38.2	10.8
400	0.0 – 2.0	56.8	31.4	43.8	10.7
400	0.0 – 2.0	53.5	29.6	35.7	10.3
50k	0.0 – 1.0	58.0	27.6	36.1	11.7
50k	0.0 – 1.0	62.5	28.7	36.6	10.4
10^6	0.0 – 0.5	66.8	28.5	36.8	10.6
10^6	0.0 – 0.5	66.4	28.2	46.8	11.7
all the above	all the above	62.6	30.1	42.9	12.0
all the above	all the above	54.7	30.4	38.6	10.8

Figure 4 shows the results in terms of UCS after the cycles, superimposed with the corresponding values, at about the same curing time, obtained on samples not subjected to cycles: it can be noted that for both materials no significant degradation due to fatigue occurred. Furthermore, considering that this part of the study was executed on prismatic samples, the fact that after more than a million cycles the strength of such slender samples can be compared to that obtained on cubic samples (black squares up to 28 days) seems particularly promising. Further evaluations should be made based on a larger number of tests, which was impossible to execute due logistical reasons related to equipment availability and the tight time schedule of this activity.

Another interesting outcome is that while the behavior of the single-component follows a trend that can be described by time-strength relations existing in literature, the development of strength and stiffness shown by the two-component grout seems to reach a plateau after about one month of ageing; this topic will be deepened in future studies, because the development of reliable prediction models for the evolution of the performance of two-component grouts over the time allows for a more accurate description of the reaction of the system lining + backfill (Oreste et al. 2021).

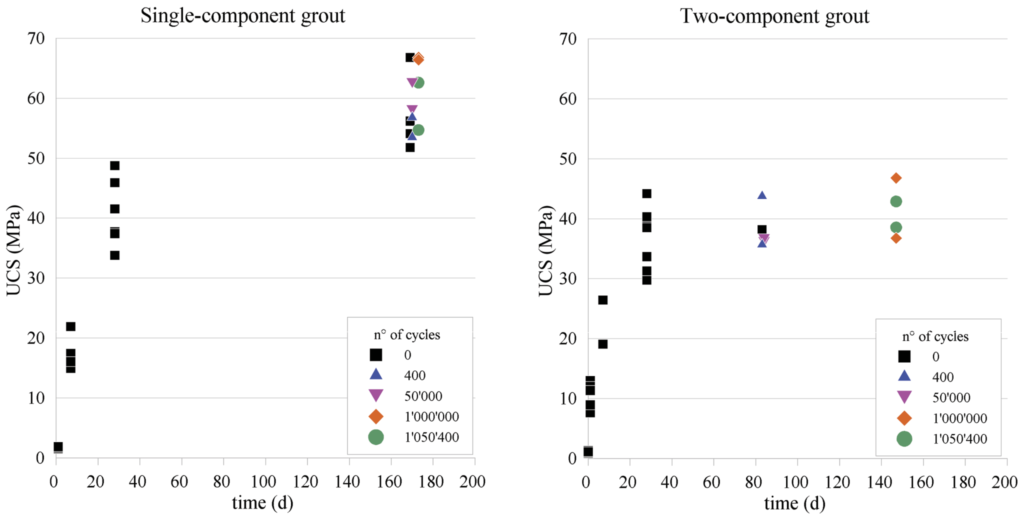

Figure 4. UCS values measured after the loading/unloading cycles together with the corresponding values measured on “virgin” samples (black squares).

5 CONCLUSION

This paper presents the outcomes of a research finalized to identify single-component and two-component grout mixes suitable as backfilling material, in hydraulic pressure tunnels subject to high static and dynamic loads and requiring fatigue resistance.

The study included an extensive trial phase, which was focused on the properties of the fresh mixture, fundamental for a successful filling of the tunnel annular gap, and an assessment of the mechanical performance of the hardened grout under both static and cyclic conditions. The results obtained were compliant with the design requirements, promoting both materials as suitable backfill. However, if the strength and stiffness observed for the single-component mortar were not particularly surprising, it is worth to underline that similar performances have never been reached by a two-component mix, by the author’s knowledge. This was possible using a binder composed by cement and slag with a water/binder ratio far lower than that of typical mixes, introducing a superplasticizer and adjusting accordingly the amount of sodium silicate.

The results obtained, that may be enriched in the future with more tests, especially under cyclic conditions, confirm the possibility to use two-component mixes for this kind of projects where the lining is subject to tension loads, whit the backfill grout playing a crucial mechanical role in the structural verification and requiring a resistance against fatigue.

The testing campaign here presented is still ongoing and is now focused on evaluating the erodibility of the material under expected waterflow with maximum local velocities in the order of 10-12 m/s, as well as to assess the long-term behaviour of the material subjects to different exposure conditions.

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