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Case study

Study of the shear strength evolution over time of two-component backfilling grout in shield tunnelling

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ABSTRACT

The two-component backfilling system is the most commonly used method to fill the annular void created during the advancement of shield machines. This unavoidable void, strictly linked to the technology of shield machines, must be filled continuously in order to avoid mostly surface displacements and lining movements. Today, this technology is the most frequently used due to operative and technical advantages, which lead to economic savings. However, despite intensive use of this backfilling technology, very little information is currently available concerning the evolution of the material in function of the curing time. Historically, the uniaxial compressive strength has been used as the main parameter for testing the compliance of a certain grout with the site-specific technical requirements, but nowadays shear strength is also starting to be considered by designers even if this topic has never been investigated.

In this work, a laboratory test campaign focused on shear strength and its evolution in function of curing was performed. These tests put alight the fast mechanical growing of the two-component grout from the shear strength point of view and it should be remarked that at the current state of research there are no investigations concerning the shear strength in the context of a drainage approach.

Both short and long curing times were investigated according to the direct shear test, performed under drained conditions. The Mohr-Coulomb failure envelope model was selected for the study and its widening in time highlights the peculiarity of this technology. Starting from a liquid phase at t_0, values of cohesion (c') and friction angle (φ') grow in function of curing, reaching 126 kPa and 22° at 3 h and exceeding 270 kPa and 40° at 28 days.

1. INTRODUCTION

The filling of the void created during the advancement of shield TBMs is fundamental in the mechanized excavation process [1,2]. The gap, which is unavoidable due to the difference in diameter between the lining extrados and the head of the machine, must be continuously filled in order to avoid surface subsidence or lining movements [3]. Different technologies have been used over the years for this purpose, and the incredible results in the minimization of surface settlements are the key aspect that launched the two-component technology on the market since its first documented use in 1982 [4]. Effectively, two-component grout technology,

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when correctly applied, allows a homogeneous, uniform, and immediate contact between ground and lining (avoiding punctual loads on linings) and locks the rings into the designed position, avoiding movements due to both the segment's self-weight and thrust forces generated by the TBM advancement. Furthermore, if the backfilling is carried out completely and homogenously in all parts of the gap, it plays an indisputable role in the waterproofing of the system, helping the action of the gaskets [5–8]. To properly achieve all the above-mentioned goals, the injected material should start to harden instantaneously after exit from the grout nozzles [9]. This achievement is guaranteed only by a proper design of both the backfilling equipment and the grout [10].

In detail, two-component grout is made up of two liquids, referred to as components A and B. Component A is a cement mortar that is expressly designed to be chemically and physically stable and characterized by long workability, commonly up to 72 h [11]. It is typically made up of cement, water, bentonite, and retarding/fluidifying agent, although new studies have recently highlighted that ingredients coming from the concrete industry (such as blast furnace slag) are also starting to be successfully used in the preparation of component A [12]. Component B is an accelerator admixture that is added to the flow of component A just a few centimetres before the grout nozzle [13]. It is typically a sodium silicate solution [14]. The turbulent mixing of components makes it possible to obtain a unique fluid which gels in some seconds, depending on the volume percentages of components. Differently from other double component technologies (as for example for nanosilica applications, where the gel time decreases in function of the accelerator increasing [15]), higher is the accelerator percentage, higher is the gel time [11]. After jellification, the grout starts to increase its mechanical strength instantaneously [16].

Nowadays, two-component grout is the main technology used for backfilling [17–20] and the uniaxial compressive strength (UCS) is the key mechanical parameter used due to two aspects which are strictly linked. First, it is the key parameter imposed by designers in tunnelling projects to characterize two-component grout at both short (some hours after the injection) and long (commonly 28 days after the injection) curing times. Second, the UCS is the only parameter used to certify the compliance of a produced grout with the site-specific technical requirements [21]. Nevertheless, new parameters have recently started to be used together with the UCS for this purpose, such as the elastic modulus or the shrinkage, and on some construction sites, the indication of these parameters was successfully integrated in the technical specification [22]. Differently from the above-mentioned parameters, the shear strength is not well-established in common use, even if recently, acceptance criteria of construction sites include also to verify if a certain grout satisfy a minimum value of shear strength with reference to a certain curing time. On the other hand, considering the design phase of a project, the shear strength is assuming always higher importance in numerical models that consider the shear strength of the backfilling as stabilizing action for the lining stability during the excavation phase.

This research is focused on the study of the shear strength of two-component grout in function of the curing time. A new approach based on the direct shear test is proposed and its main strengths and weaknesses are pointed out. The choice of the direct shear test instead of the triaxial one is related to the more agile equipment needed, the simpler interpretation of results, and the shorter testing time required. Different curing times have been tested, and the evolution hardening trend described in terms of cohesion (c') and the friction angle (φ') has been obtained as the outcome. The obtained failure criteria envelopes, drawn according to the Mohr-Coulomb model and contextualized with the curing times, can be considered as a powerful instrument for designers in the project phase and for project management company engineers in the testing phase.

2. STATE OF THE ART

The first reference concerning the shear strength of two-component grout can be found in [23]. In that work, the crucial importance of assessing the properties of the two-component grout in the short term is highlighted, as this early juncture is characterized firstly by the lining transportation (commonly in the first 3 h) and secondly by the back-up passage. Antunes [23] classified the shear strength as

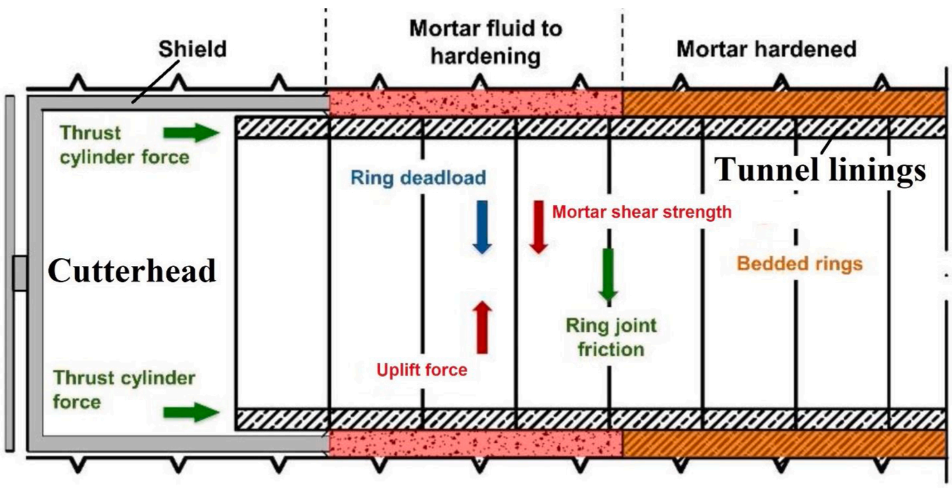

Fig. 1. Scheme of forces acting on rings and areas of different "ages" of the backfilling grout (modified from Mähner and Hausmann [26]).

a valid parameter for the two-component acceptance criterion, perfectly able to replace or be integrated with the UCS and the penetrometer in testing the grout compliance with the site-specific technical requirements.

Thewes [24] recognized that the undrained shear strength was the most important parameter involved in the immediate support of rings. In that work, as a simple reference value for preliminary and expedite calculations, an undrained cohesion value of 3–5 kPa is suggested. That research was the first to also provide a method for determination of the undrained shear strength, namely the cone-penetrometer.

Youn and Breitenbücher [6], reporting the typical parameters for cementitious grout applied to the annulus gap, listed a shear strength higher than 2 kPa related to 30 min of curing (after the activation of the two-component grout), commonly ranging between 5 and 10 kPa, 24 h after casting. This value was considered by the authors to be the minimal shear strength able to ensure the avoidance of critical deformations caused by the buoyancy forces. That paper was focused on the influence of the dewatering phenomenon on the shear strength of mono-component grout (in function of different percentages of binder elements and aggregates); however, very interesting information pertaining to the procedure for testing were provided. The DIN [25] was used as the technical standard and a shear vane was pre-installed in the testing sample at a depth of about 90 mm. Tests were carried out at programmed times, ranging between 5 and 480 min after the casting phase.

Mähner and Hausmann [26] provided a scheme of forces involved in the lining stability (Fig. 1). Three areas can be recognized in function of the backfilling curing: the machine (where the new ring is assembled and the backfilling is not yet present), the mortar fluid hardening area (short term), and the mortar hardened area (long term). In the second one, the flotation forces should be balanced by the ring dead load and the friction due to the cylinder thrust forces. Additionally, a sufficient shear strength of the mortar could completely eliminate the flotation.

These authors introduced a calculation algorithm that could provide the required minimal shear strength value able to avoid any stress on the ring joints starting from the geometrical tunnel dimensions, mortar parameters, and the machine advancement rate. In the specific analysed case, related to a tunnel diameter of 10 m and a mono-component mortar used as backfilling technology, a shear strength of 2 kPa was required. Additionally, a laboratory test campaign is also described, performed according to DIN [25], by using a shear vane and testing samples cured for times ranging between 10 and 420 min. It was underlined that a value of 2 kPa was reached after 6–7 h of curing.

Schulte-Schrepping and Breitenbücher [27] designed and developed a special device able to simulate the annular gap grouting on a semi-technical scale. After the grouting phase had been performed by using a common two-component mix design, the shear strength was tested with a shear vane according to DIN [25]. The outcomes showed shear strengths of 23 kPa after 40–50 min and 52 kPa after 90 min.

All the above-mentioned references are based on the undrained shear strength, measured until some hours after the jellification. This choice can successfully reflect the real behaviour of the grout only in the very short term. During the lining assembly, indeed, the staked parts for the new ring are located very close to previously injected ones (mortar fluid to hardening, in Fig. 1): the load applied on the grout is not instantaneous, and consequently the water present in the mortar is able to flow away. Also, in the long term, that is, during the back-up advancement, the weight applied to the backfilling grout is not instantaneous. In conclusion, a drainage approach should be considered.

2.1. DIRECT SHEAR TESTS ON TWO - COMPONENT GROUT

The direct shear test performed on a material different from the ground required some preliminary reflections and considerations.

The direct shear test was developed for soils that should be tested under drained condition, although the Casagrande shear box is

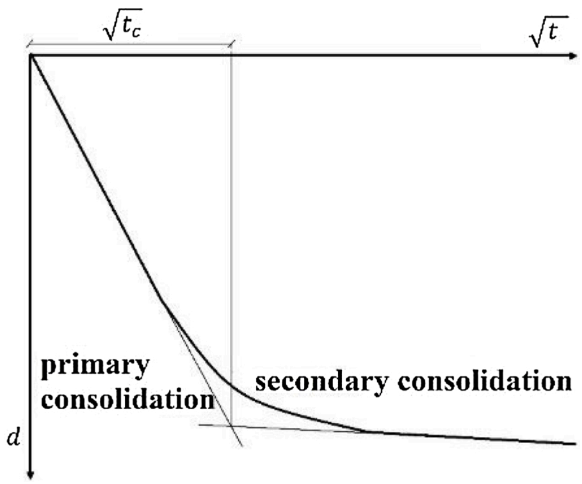

Fig. 2. Example of a time-settlement curve to determine the time for primary consolidation.

not equipped with a pressure gage. Although for soils it is simple to overcome this impediment by choosing a shear rate that is able to ensure that the drained condition is compatible with the hydraulic conductivity of the tested material [28], for the two-component grout the identification of a suitable shear rate is more complex. First, the hydraulic conductivity of this material was completely unknown, and second, the potential effect of the curing on the conductivity has never been studied before. Anyway, considering results reported in Shah et al. [16], it is possible to predict a consolidation phase (mandatory before shearing) with a duration compatible with the fast hardening reaction of the material and, after that, preliminary laboratory tests provided time-settlement curves characterized by primary and secondly consolidation phases typical of the soils during drainage. Hence, the direct shear test under drained condition has been deemed suitable for research purposes, and therefore tests were scheduled on samples cured for 1, 3, and 24 h and 28 days, respectively.

2.2. SUMMARY OF THE STANDARD

Shear tests were carried out according to CEN ISO [29]. As described in this technical regulation, the shear test is composed of two distinct phases: consolidation and shearing. The aim of the first phase is to forecast the maximum rate of shear displacement able to ensure shearing carried out under drainage condition, while the second is the breaking of the sample under a pre-determined shear plan. The consolidation phase outcomes consist of a chart where the vertical settlements (d) in function of the square root of time ($\sqrt{t}$) are graphed (Fig. 2). This function is commonly called the time-settlement curve [29] and in the case of a successful drainage process, two different lines should be observed on the chart, corresponding to the primary and secondary consolidation phases.

By extending both lines linearly and reporting the obtained intersection point on the time axis, the square root of the compaction time ($\sqrt{t_c}$) can be obtained. Once t_c has been computed, the maximum rate of the shear displacement (v_{max}) can be computed using Equations (1) and (2):

$$t_f = 13 * t_c \tag{1}$$

$$v_{max} = s_f / t_f \tag{2}$$

where t_f is the failure time and s_f represents the horizontal shear deformation at sample failure. According to the standard, in the case of an absence of experience with the tested material, a value close to 1 mm is suggested for s_f in the case of stiff soil. Also, ETC5-ISSMGE [30] was consulted and for marly clay an s_f value of 1 mm is suggested. Therefore, considering that this material is more similar to the two-component grout, the value of 1 mm was chosen for the present work. As the last step, v_{max} is estimated.

Once the shear rate (lower than v_{max}) has been chosen, the shearing starts and the shear force applied to the sample in function of the horizontal displacement is recorded over time. The τ_{peak} is obtained as:

$$\tau_{peak} = T_{peak} / A \tag{3}$$

where T_{peak} is the maximum shear force recorded during the test and A is the integer sample area. After each test, values of τ_{peak} and σ'_v allow the drawing of one point on the failure criteria chart. It should be noticed that in the context of this research, the residual shear strength was not investigated.

2.3. THE TEST PARAMETERS USED

Without any references, the consolidation phases and hence the subsequent shearing ones were performed by applying the same pattern of vertical strengths independently of the considered curing time. To select the pattern of vertical strengths, the short term was considered, and consequently, the values were chosen to be close to the UCS of two-component grout cured for 3 h [21]. The vertical effective strength values (σ'_v) used are reported in Table 1.

The σ'_v values are comprehensive of the equipment weight used for the load application.

Due to the complexity and the peculiarities of tests performed after just 1 h of curing, the related shearing phase was treated separately from other curing times.

2.3.1. PARAMETERS USED TO TEST SAMPLES CURED FOR 3 AND 24 HOURS AND 28 DAYS

In the tests performed on samples cured for 3 and 24 h and 28 days, it was considered appropriate to proceed to shearing by always using the same shear rate. Hence, the curing time of 3 h was considered as limiting, as the younger samples were characterized by a

Table 1
Vertical effective strengths for the direct shear tests.

	σ'_v (kPa)
1	49.96
2	99.92
3	199.85
4	299.77

longer consolidation phase (i.e. longer t_c). A consolidation time of 10 min was verified as the shortest one able to permit the clear observation of $\sqrt{t_c}$ on the chart. Furthermore, the consolidation phase was started 5 min before 3 h of curing was reached. This testing program were applied in order to accomplish shearing within the shortest time possible after 3 h of curing, consistently with the occurrence of the drained condition.

Fig. 3 reports the time-settlement curves related to tests performed on samples cured for 3 h. With graphical constructions drawn according to Fig. 2, the t_c values were computed and ranged between 0.1 and 0.2 min.

After that, according to the procedure described in the previous paragraph and by using Equations 1 and 2, a v_{max} equal to 0.43 mm/min was computed. However, in order to balance potential speed fluctuations of the shear machine, a further safety factor close to 3 was applied, reducing the rate of shear to 0.13 mm/min. The shearing phases had a scheduled duration suitable for covering a horizontal displacement of at least 5 mm.

2.3.2. PARAMETERS USED TO TEST SAMPLES CURED FOR 1 HOUR

The determination of the rate of shear displacement related to 1 h of curing was the more controversial research phase. Two opposite aspects were taken into account. On one hand, it is necessary to accomplish the test in a limited time, as close as possible to 1 h of curing. This constraint is strictly linked to the fast hardening reaction that characterizes the two-component grout for this short curing time. As reported in [21], the hardening reaction of the grout after 1 h of curing is so fast that the variation in strength related to just some minutes of delay (or advance) cannot be neglected. On the other hand, it is necessary to accomplish the consolidation phase successfully and hence to find a shear rate slow enough to ensure the drainage condition. Anyway, preliminary tests highlighted the impossibility of accomplishing the consolidation phase in a useful time (more than 1 h was needed for the consolidation alone). Consequently, the durations of the consolidation and shearing phases were a priori fixed equal to 5 and 10 min, respectively, according to the decision to accomplish each test in at least 1 h and 10 min. The consolidation phase was started 5 min before 1 h of curing, and the shearing rate was set equal to 5 mm/min.

2.4. APPARATUS AND MATERIALS USED

Direct shear tests were carried out using the devices shown in Fig. 4.

The two-component grout was produced according to the mix design reported in Table 2, which is a typical two-component mix design.

The component A is produced by mixing for 12 min the proper ingredients, starting by activating the bentonite (7 min of mix) after that the cement (3 min of mix) and the retarding fluidifying agent (2 min of mixing) are added. Detailed information on the laboratory equipment for the mixing process and the production of component A can be found in Todaro [11].

2.5. SAMPLE PREPARATION

For the sample casting, [21] was taken as a reference. Briefly, once the right volume percentages of component A and component B are metered, quantities are put in 2 different tanks. After that, the component A is poured in the component B and quickly the whole grout is again poured in the previous tank. At the end (the mixing has to be accomplished spending a time lap shorter than the gel time), the grout is poured in the mould. The main difference respect the procedure described in [21] consists in the moulds used; in this

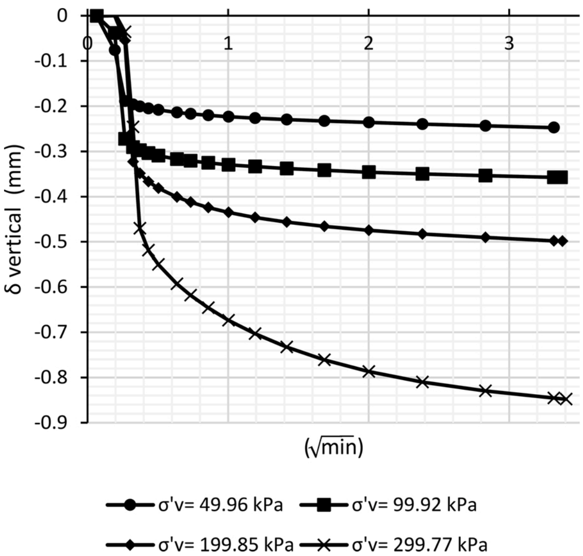

Fig. 3. Time-settlement curves related to samples cured for 3 h.

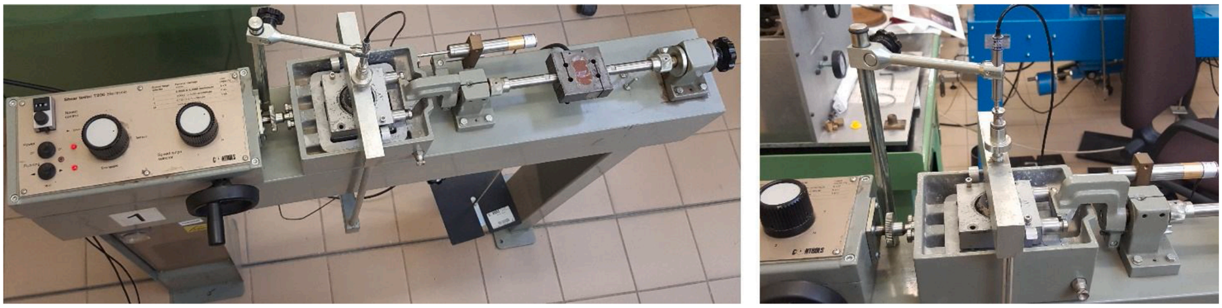

Fig. 4. Shear machine (left) and Casagrande shear box fixed on the shear machine (right).

Table 2
Mix design used. Dosages are referred to 1 m^3.

COMPONENT A	Water (kg)	853
	Bentonite – Clariant Bentonil CV15 (kg)	30
	Cement Buzzi – CEM I 52.5 R (kg)	230
	Retarding/fluidifying agent – Mapei CBS1 (kg)	3.5
COMPONENT B	Accelerator – Mapei CBS3 (kg)	81

research they were cylindrical steel ones with a diameter of 50 mm and height of 30.54 mm. According to the reference, after the casting phase samples held in moulds were hermetically sealed in order to avoid water losses due to evaporation. After that, the curing time started in a controlled environment, with an air temperature of 23 ± 2 °C. For just the samples cured for 28 days, after the first 24 h, the sealing protection was removed and the samples were put in water, constantly under temperature control, until the end of the curing process. Fig. 5 depicts (from left to right) the mould pattern and the two tanks of components A (grey liquid) and B (transparent liquid), the samples covered after the casting, and the same samples after 3 h before the start of the tests. It is evident that it is crucial for samples to be covered during the curing time; in fact, the uncovered material appears completely cracked due to the dehydration process.

Concerning the demoulding, Fig. 6 shows two photos summarizing the operation. The left panel depicts a sample that has not yet been demoulded (1), positioned on the Casagrande shear box (2), while the one on the right shows a picture taken just before pressure was applied by means of a pushing frame (4) and a push cylinder (3) on the sample. By rotating the pushing frame flywheel manually,

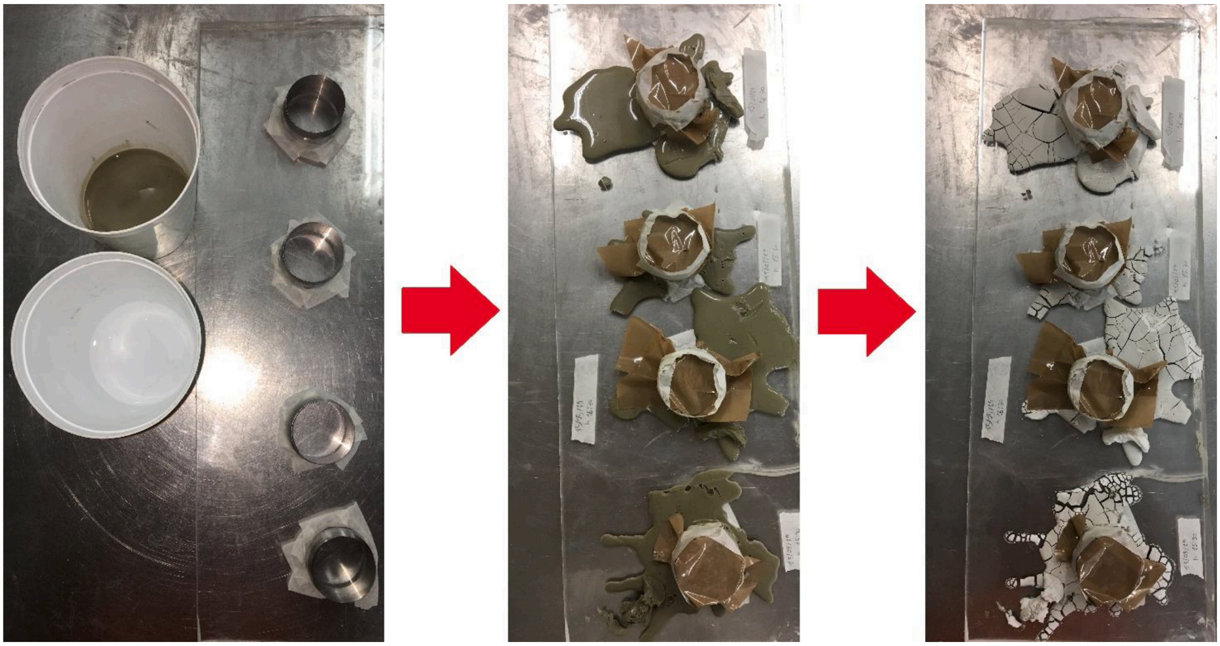

Fig. 5. Casting and curing of cylindrical samples for the direct shear test campaign. From left to right: the mould pattern and the tanks with components A and B, the samples covered after casting, and the same samples after 3 h, just before testing.

the load was applied on the sample slowly and gently until the specimen slipped down in the shear box. The maximal duration of the demoulding phase was previously fixed equal to 30 s to avoid weight loss due to dehydration.

3. RESULTS

In the next paragraphs, the results are presented and discussed. For each curing time, the results are presented in a specific section, in which two charts are reported. The first is related to the shear stress in function of the horizontal displacement while the second represents the Mohr-Coulomb failure envelope. Concerning the latter, values related to the shear peak (τ_{peak}) and the corresponding vertical effective stress (σ'_v) are plotted and interpolated according to the linear regression method, obtaining as the output a function in the form $y = \alpha + \beta x$. In this form, the slope value β and the y-intercept α correspond, respectively, to the friction angle and the cohesion of the studied material [28].

3.1. RESULTS OF SAMPLES CURED FOR 28 DAYS

In the following, diagrams of the shear stress in function of the horizontal displacement and the failure criteria envelope pertaining to the two-component grout material cured for 28 days are reported in Figs. 7 and 8, respectively.

In Fig. 7, the peaks are clearly appreciable. From the diagram reported in Fig. 8, a friction angle of 41° and a cohesion of about 272 kPa can be obtained.

3.2. RESULTS OF SAMPLES CURED FOR 24 HOURS

In the following, diagrams of the shear stress in function of the horizontal displacement and the failure criteria envelope pertaining to the two-component grout material cured for 24 h are reported in Figs. 9 and 10, respectively. Unfortunately, the function related to the vertical effective stress of 99.92 kPa was not recorded due to an acquisition problem. However, the peak value was manually saved and is reported in Fig. 10.

In Fig. 9, the peaks are clearly appreciable. From the diagram reported in Fig. 10, a friction angle of 45° and a cohesion of about 154 kPa can be obtained.

3.3. RESULTS OF SAMPLES CURED FOR 3 HOURS

In the following, diagrams of the shear stress in function of the horizontal displacement and the failure criteria envelope pertaining to the two-component grout material cured for 3 h are reported in Figs. 11 and 12, respectively.

As this test referred to the short curing time, the x-axis threshold was extended beyond the usually adopted 5 mm.

Differently from the previous analysed cases, the peaks are appreciable only for vertical effective stresses of 49.96 and 99.92 kPa.

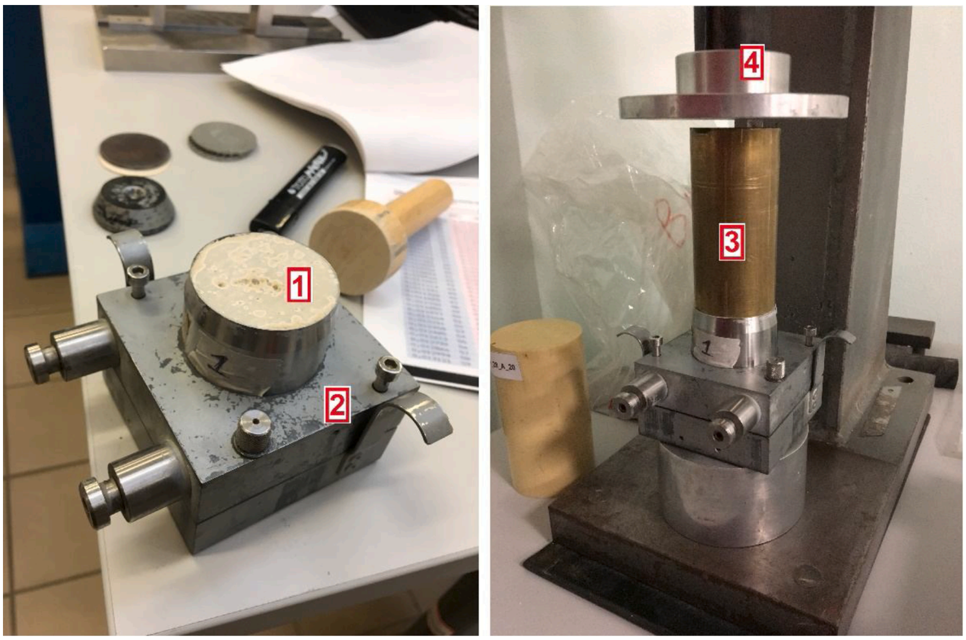

Fig. 6. Specimen of two-component grout before demoulding (left) and insertion phase of the specimen in the shear box (right). Sample held in the mould (1), Casagrande shear box (2), push cylinder (3), and pushing frame (4).

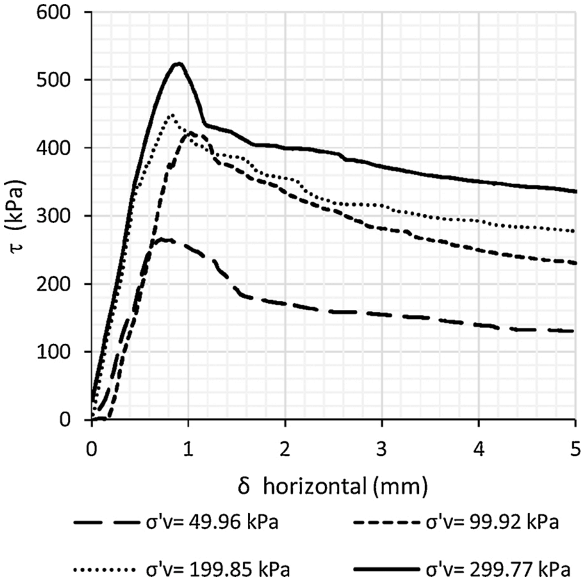

Fig. 7. Shear stress in function of the horizontal displacement. Samples cured for 28 days.

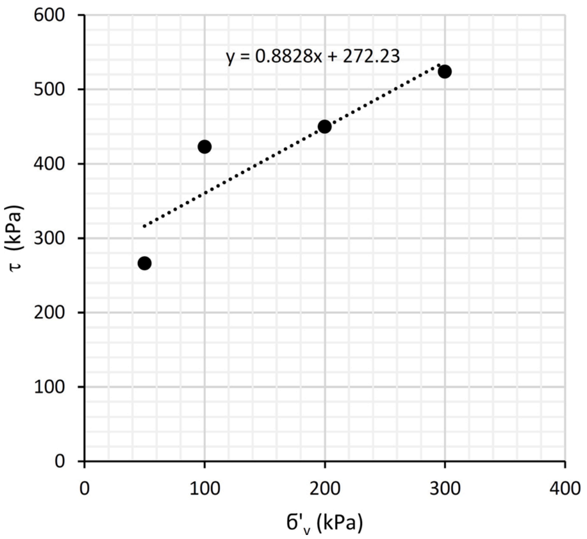

Fig. 8. Mohr-Coulomb failure criteria envelope pertaining to two-component grout samples cured for 28 days.

For the two higher vertical effective stresses, peaks are not observed. In more depth, taking into account the curve related to $\sigma'_v =$ 199.85 kPa, it would seem that it tends to a constant value close to 200 kPa for horizontal displacements ranging between 2 and 4 mm, and for bigger displacements, it increases slightly again. For the selection of the peak, the value of 200 kPa has been deemed more reliable compared to the maximum obtained value of about 219 kPa. Regarding the curve related to σ'_v= 299.77 kPa, it would seem that it tends to a constant value close to 250 kPa for horizontal displacements of about 4 mm. As in the last case, there is a hint of a growing trend for further displacements. Exactly as in the previous case, the value of 250 kPa was recognized as the peak for drawing the failure envelope criteria. The decision to select the "first" constant value as the peak was taken considering the reference curing time of the grout. In fact, considering the fast hardening process that characterize the short curing time [31], the material continued to harden over time, and although the resistance section decreased during the shear, the shear strength could potentially rise slowly. Hence, for those particular cases, it was deemed incorrect to select the maximum value of the chart, as this maximum value potentially depends on the duration of the test.

From the diagram reported in Fig. 12, a friction angle of 22° and a cohesion of about 126 kPa were computed.

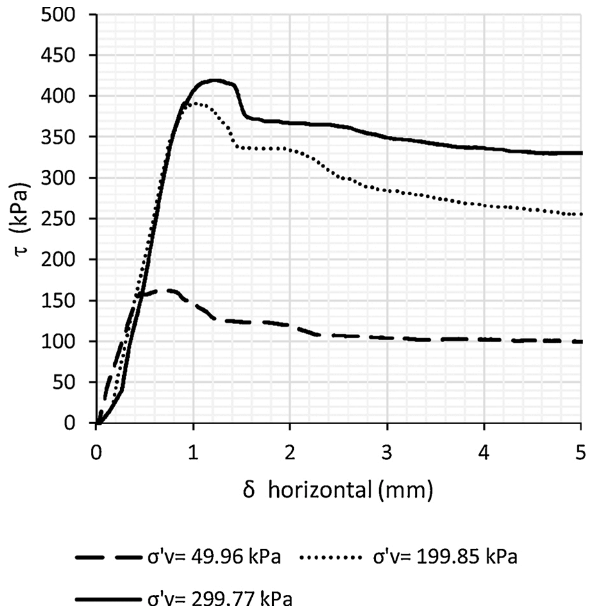

Fig. 9. Shear stress in function of the horizontal displacement. Samples cured for 24 h.

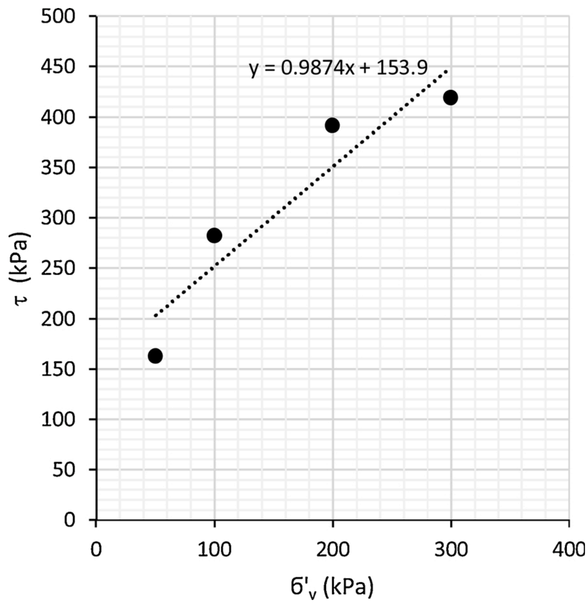

Fig. 10. Mohr-Coulomb failure criteria envelope pertaining to two-component grout samples cured for 24 h.

3.4. RESULTS OF SAMPLES CURED FOR 1 HOUR

After the accomplishment of tests performed with the vertical effective strength values reported in Table 1, because of an unclear distribution of results on the chart of τ_{peak} versus σ'_v, other values were taken into account and used for testing the two-component grout material cured for 1 h. Table 3 reports all the values of σ'_v used.

In the following, diagrams of the shear stress in function of the horizontal displacement and the shear peak values in function of the corresponding vertical effective strengths are reported in Figs. 13 and Fig. 14, respectively.

Taking into account Fig. 13, the first aspect that should be highlighted pertains to the chaotic nature of the disposition of the experimental curves. The highest values of the shear strength, for example, were reached in the test with a vertical strength of 249.81 kPa, which was not the highest value of σ'_v. Furthermore, the second highest shear strength value concerns the test carried out with a vertical strength of 99.92 kPa, which was the second smallest one. Undoubtedly, for this short curing time, the consolidation phase

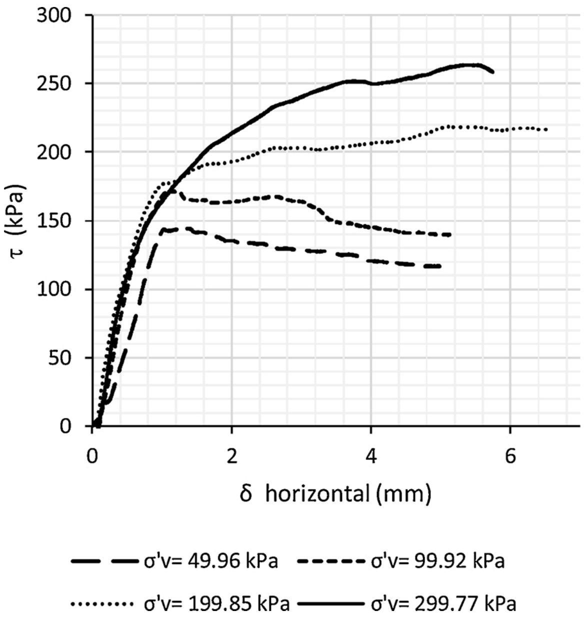

Fig. 11. Shear stress in function of the horizontal displacement. Samples cured for 3 h.

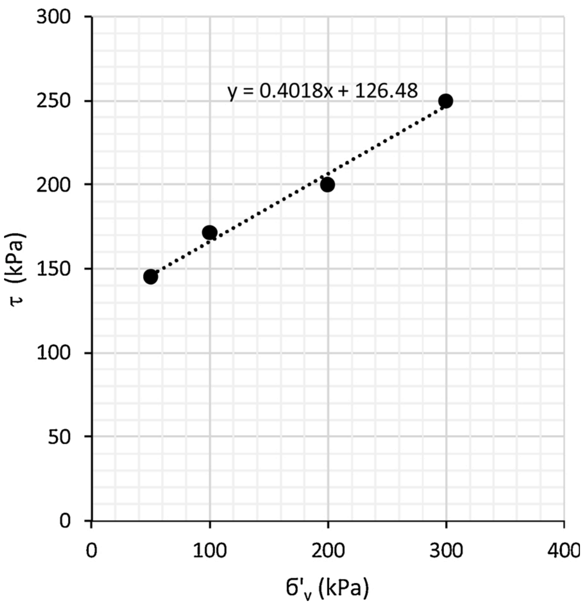

Fig. 12. Mohr-Coulomb failure criteria envelope pertaining to two-component grout samples cured for 3 h.

Table 3
Vertical effective strengths for direct shear tests on two-component grout cured for 1 h.

	σ'_v (kPa)
1	49.96
2	74.96
3	99.92
4	149.88
5	199.84
6	249.81
7	299.77

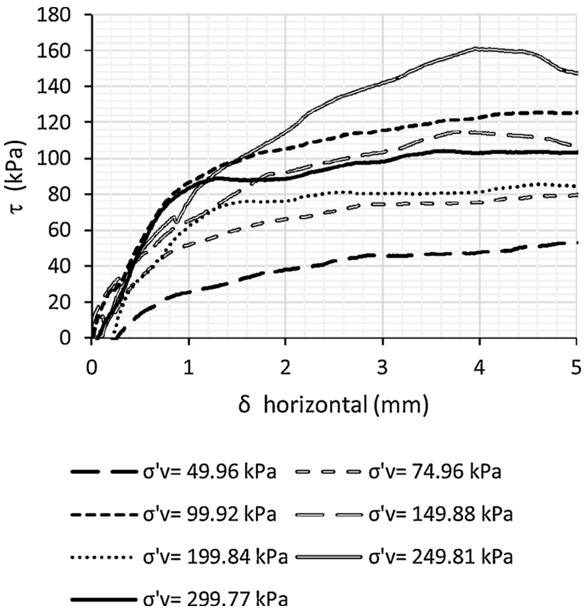

Fig. 13. Shear stress in function of the horizontal displacement. Samples cured for 1 h.

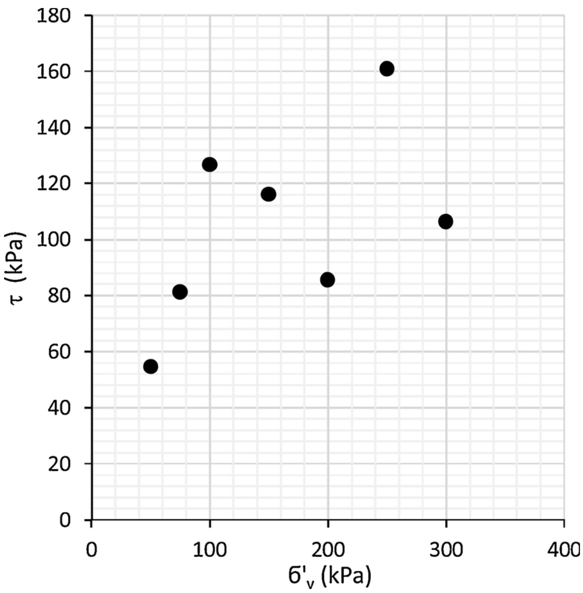

Fig. 14. Shear peaks in function of the corresponding vertical effective stresses pertaining to two-component grout samples cured for 1 h.

interacted with the hardening process in a non-negligible way. As reported in [21], for exactly the same two-component grout (the same mix design), after a curing time of 1 h the UCS was close to 80 kPa. The consolidation phase is indisputably a different mechanism since the tested material constrained the lateral expansion; however, according to the state of the art, the influence of a vertical strength bigger than the UCS applied to a two-component material cured for only 1 h is not known but is undoubtedly not a priori negligible.

Considering Fig. 14, the outcomes are hardly interpretable. Although, on one hand, it can be stated that the tests were not performed under drained condition because the shear rate was too much higher than the suitable value, on the other hand, it is also wrong to consider tests performed under undrained condition. In this last case, the shear strength value (specifically the undrained cohesion, c_u) is usually about half of the UCS, while for the studied case the average of τ_{peak} is about 100 kPa, a very high value compared to half of the UCS, that is, 40 kPa. In Fig. 15, these concepts are graphically summarized, with the integration of the undrained shear strength (c_u) obtained by a vane test campaign [32]. The Mohr circle refers to the UCS value while the two horizontal lines refer to the undrained cohesion value and the average of the τ_{peak} (cohesion in partial drained condition, c_{pd}), respectively.

Finally, strictly speaking, the chart reported in Fig. 15 is incorrect from a geotechnical point of view because the average value of τ_{peak} is not a total stress and it depends by number of tests and normal stresses applied. Hence, it should not be represented on the same chart as the UCS and c_u. Anyway, the purpose of the chart is only to underline the strong discrepancy between the two shear strengths and the effect of the partial drainage condition, intended as the distance between these two horizontal functions.

No meaningful failure criteria can be computed based on the obtained results.

The reduction of the shear rate was not considered useful for the purpose because it led to longer durations of testing compared to the target curing time of 1 h.

In conclusion, for 1 h of curing, the testing time is too much longer than the fast hardening reaction typical of the two-component grout at this curing stage.

3.5. ANALYSIS OF RESULTS

In Fig. 16, comprehensive outcomes of the shear test campaign are reported: three different Mohr-Coulomb failure envelopes are drawn.

Taking into account the failure envelope criteria obtained for samples cured for 3 h, it should be pointed out that the peaks occurred at a time exceeding the exact curing time by about 5%. Considering that the hardening speed of the material after 3 h of curing is lower compared to the first hours and in view of the purpose of the research, this delay may be neglected. However, for tunnelling designers who would like to use this chart for preliminary projects, strictly speaking these tests should be referred to a curing time of 3.15 h.

Anyway, Fig. 16 appears to show failure criteria envelopes related to three completely different materials. This graphical representation easily summarizes the fast evolution of this peculiar material, providing a clear idea of the particularity of this kind of backfilling grout.

Considering the undrained parameters, Table 4 reports an overview of the computed values rounded to the nearest integer.

Taking into account the cohesion, the trend in function of the curing time is not linear. Starting from the value related to 3 h of curing, an increase of 22% is recorded at 24 h, while from this last curing time to 28 days, a further growth of 77% can be highlighted.

With regard to the friction angle, it can be stated that the material can be considered ripe after 24 h of curing; nevertheless a slightly decreasing trend can be observed for samples cured for 28 days. However, the variation of 4° can be neglected bearing in mind that some slight differences between the casted samples are unavoidable, despite all the precautions taken during the casting phase.

4. CONCLUSIONS

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

The shear strength, in addition to the UCS, plays an important role in the stability of the linings, as highlighted in the literature review. This work is absolutely the first attempt to characterize the shear strength of the two-component grout according to a drainage approach. Failure envelope criteria were successfully drawn for the curing times of 3 and 24 h and 28 days and subsequently the drained cohesion (c') and the friction angle (φ') were computed. The specific obtained values are a function of the mix design but the

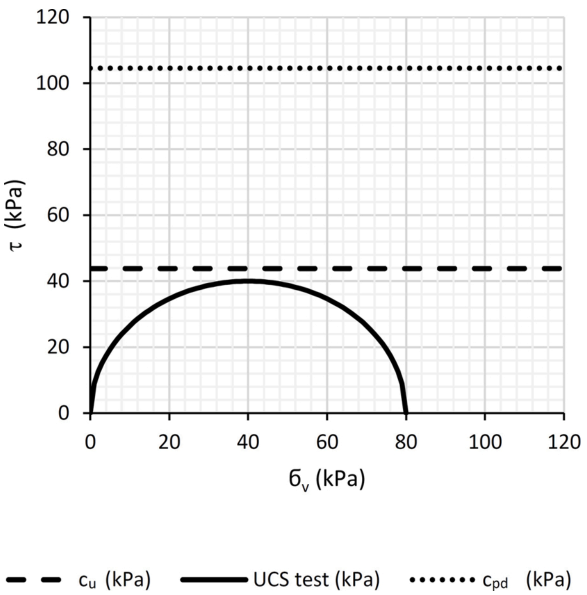

Fig. 15. UCS Mohr circle representation, c_u, and average of τ_{peak} (c_{pd})for the two-component grout cured for 1 hour.

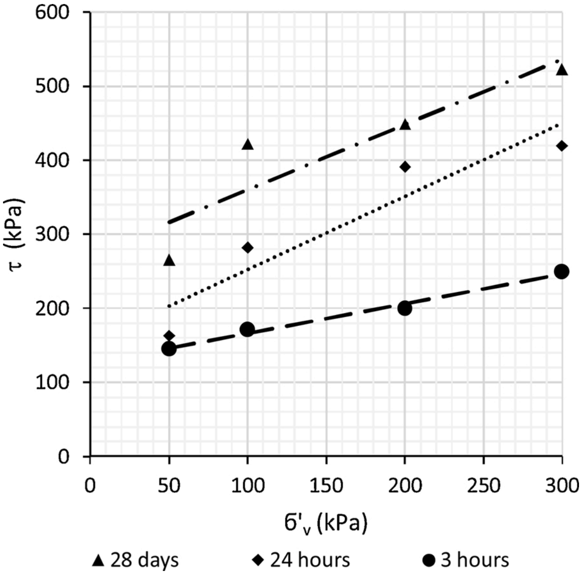

Fig. 16. Mohr-Coulomb failure criteria envelopes of the two-component grout cured for 3 and 24 h and 28 days.

Table 4
Cohesion and friction angle values of the two-component grout cured for 3 and 24 h and 28 days.

Curing time	c' (kPa)	φ' (°)
3 h	126	22
24 h	154	45
28 days	272	41

order of magnitude can be considered as a valid datum by designers.

For 1 h of curing, the direct shear test is not a correct testing methodology. According to the obtained results, the only method able to provide a reliable value of the shear strength is the undrained approach.

In conclusion, this study highlights the potential use of the direct shear test for assessing the shear strength of two-component grout. The authors conclude that the direct shear test is a valuable tool that provides consistent results and could be potentially integrated in the checking protocol of construction sites. Furthermore, for designers, the provided order of magnitude of the cohesion and friction angle in function of the curing time are an important data for verify, at the preliminary design phase, the stability of linings.

A last consideration pertains to the consolidation process. As discussed, the curing time of 3 h was taken into account for the determination of the shear rate because it allows the longest consolidation phase. Samples cured for a longer time, indeed, exhibited a shorter t_c. This aspect should be investigated in view of the potential dependence of the hydraulic conductivity on the curing time of the grout.

CRediT authorship contribution statement

Carmine Todaro: Conceptualization, Methodology, Investigation, Writing – Review & Editing, Resources, Original Draft. **Andrea Carigi:** Investigation, Methodology, Writing - Review & Editing. **Daniele Martinelli:** Methodology, Writing – Review & Editing. **Daniele Peila:** Supervision, Writing – Review & Editing, Funding.

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Declaration of Competing Interest

The authors report no declarations of interest.

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