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Short term strength behavior of two-component backfilling in shield tunneling: comparison between standard penetrometer test results and UCS

Carmine Todaro*
Marco Bongiorno*
Andrea Carigi*
Daniele Martinelli*

* DIATI, Politecnico di Torino

The two-component backfilling system is the most frequently used method to fill the annular gap created during the shield machine advancement. This gap, due to the head overcut, the shield thickness and conicity and the tail brushes size should be filled continuously in order to avoid mainly surface displacement and linings movements. Nowadays this technology is the most chosen due to operative (both components are chemically and physically stable) and technical (mechanical performance start to grow up just immediately after the injection) advantages that mean money and time saving.
The main mechanical parameter used for the two-component grout characterization is the uniaxial compressive strength (UCS). In order to assess this parameter, a laboratory press and suitable hardened samples are needed but, expressly at short curing time, the penetrometer use is also diffused. This research pertains the study of two-component grout uniaxial compressive strength, its evolution in function of time and its correlation with penetrometer tests data.
Keywords: *two-component grout, backfilling, uniaxial compressive strength, penetrometer, shielded mechanized tunneling.*

Resistenza a breve termine delle miscele bicomponenti nello scavo con macchine scudate: confronto tra prova penetrometrica e resistenza a compressione monosassiale. *Il sistema di retroiniezione basato su miscele bicomponenti è il più utilizzato per l'intasamento a tergo del gap anulare che si viene a creare durante l'avanzamento della macchina. Questo gap, dovuto al sovrascavo della testa, allo spessore ed alla conicità dello scudo ed allo spessore delle spazzole di coda deve essere riempito in continuo al fine di evitare principalmente cedimenti superficiali e spostamenti relativi degli anelli di conci. Al giorno d'oggi questa tecnologia è la più utilizzata per vantaggi operativi (entrambi i componenti sono chimicamente e fisicamente stabili) e tecnici (le resistenze meccaniche iniziano ad aumentare immediatamente dopo l'iniezione) che si traducono in risparmi economici e di tempo.*
Il principale parametro di caratterizzazione meccanica utilizzato per le malte bicomponenti è la resistenza a compressione monoassiale (UCS). Al fine di verificare questo parametro sono necessari una pressa da laboratorio e campioni conformi anche se, per tempi di maturazione brevi, è diffuso anche l'uso del penetrometro. Questa ricerca verte sullo studio della resistenza a compressione monoassiale delle malte bicomponenti, la sua evoluzione nel tempo e la sua correlazione con i valori ottenuti da penetrometro.
Parole chiave: *malta bicomponente, retroiniezione, resistenza a compressione monoassiale, penetrometro, scavo meccanizzato di gallerie.*

1. Introduction

The filling of the void (herein called annulus) created behind the shield tail during the TBM advancement is a crucial operation in the mechanized tunnelling excavation process. A good backfilling allow the minimization of surface settlements ensuring an homogeneous, uniform and immediate contact between ground and lining. It is fundamental also for locking the segment linings into the designed position, avoiding movements due to both segments self-weight and the thrust forces generated by the TBM advancement. Furthermore, a well performed backfilling permits to bear the loads transmitted by the TBM back-up weight, avoiding yielding due to precast segments transport from outside to the machine head. If a homogeneous and uniform backfilling stratus is created, punctual loads on lining are avoided and the gaskets waterproofing action is improved (Thewes & Budach, 2009; Pelizza *et al.*, 2010; Peila *et al.*, 2011; Youn & Breitenbücher, 2014; Boscaro *et al.*, 2015; Ivantchev, A.J. & Del Rio, 2015).

For correctly achieving all the above mentioned goals, the injected material should start to harden ideally instantaneously after the nozzles exit and the annulus should be regularly and completely filled. On the other hand, from the operational point of view, the injection system should guarantee the reliability of the backfilling in terms of stability/transportability of both components and the choke pipes and nozzles avoidance (Dal Negro *et al.*, 2017).

In the last decades, the use of two-component grout is spreading in many job sites (Novin *et al.*, 2015; Peila *et al.*, 2015; Shah *et al.*, 2018), despite a limited amount of researches have been carried out on these new material. The two-component mix is composed by a super fluid grout (component A), stabilized in order to guarantee its workability for a long time, to which an accelerator admixture (component B) is added at the injection points, located at the shield tail. Few seconds after the addition of the accelerator and the turbulent mix of both components (normally ranged between 8 and 25 seconds, during which the TBM advances approximately 2-15 mm), the mix becomes a gel and exhibiting a thixotropic consistency it starts to developing its mechanical strength almost instantaneously. The component A is typically made up of cement, bentonite, retarding/fluidifying agent and water also if in the last years blast furnace slag, fly ash and metacaolin are also added (Schulte-Schrepping & Breitenbucher, 2019), while component B is commonly a silicate solution. Cement guarantees the mix strength while the bentonite gives stability to the grouting mix, reducing the bleeding phenomenon (separation between water and cement particles). The retarding agent adding is due to inhibit the mix from setting thereby guaranteeing its workability for very long time after batching (up to 72 hours if necessary) and to facilitate stockpiling grout in the mixer-containers (Hashimoto *et al.*, 2004; Pellegrini & Peruzza, 2009; Pelizza *et al.*, 2012; Dal Negro *et al.*, 2017).

No standardized requirements in terms of mechanical properties that the final grout should reach are available in scientific literature and also tests or procedures concerning the component A properties are not standardized. Despite study approaches are different for each case study, all papers available in scientific literature recognize the uniaxial compressive strength (UCS) as the main mechanical parameter of the hardened grout. Particularly, the attention of all the stakeholders is today focused on the strength developed just few hours after the injection (short curing time). Requirements and engineer prescriptions concerning UCS at short curing time are often fulfilled by tests carried out with a penetrometer (Peila *et al.*, 2011). This procedure is faster and simpler than by using a concrete press, but outcomes are different physical quantities even if often both tests are identified equal and results are confused and not easily overlapped (Antunes, 2012).

In this paper a common two-component grout is studied in terms of mechanical compressive strength. The use of penetrometer for this goal is also described and introduced. Outcomes are showed and put in relation with real UCS values obtained by using a laboratory press.

2. Laboratory tests and equipment

In order to assess the properties of the two-component grout, specific tests are becoming in last years frequently used. Concerning the component A, Peila *et al.* (2011), Zarrin *et al.* (2015), Pellegrini & Peruzza (2009), Shah *et al.* (2018) and Antunes (2012) introduced a protocol made up of simple tests (specific weight, flowability and bleeding) that permit to assess the suitability of the component A with the technical requirement in terms of physical and chemical stability, homogeneity and pompability.

Regarding the interaction between the component A and the component B, the gel time assessment is an experimental procedure that permits the computing of the reciprocal volume percentage of both components suitable for a certain time of jellification (Todaro *et al.* 2019). On the hardened grout compressive tests are usually performed by press (Chieregato *et al.*, 2014). Furthermore, the penetrometer test has been recently introduced for the short term strength assessment.

In the following a test campaign carried out on hardened two-component grout samples cured at different time is discussed. Only the short curing time has been analysed, with tests assessed after 60, 65 70, 90, 100, 120, 125, 130 and 180 curing minutes with penetrometer and press both. This approach has permitted to provide a comparison between the two different methodologies and relative outcomes.

2.1. Two-component grout samples manufacturing

Due to the lack of standards pertaining the compressive strength assessment on the two-component grout (more similar to a hard clay at short time and more alike a weak concrete at long time) the standard UNI EN 196-1:16 (Methods of testing cement. Determination of strength) has been chosen as guideline. The reason that led authors to choose this document comes from the backfilling history. It is known that before the spreading of the two-component technology, the most frequently used method for fill the annulus was the mono-component, a mortar with fine aggregate perfectly aligned to be tested with UNI EN 196-1:16. Nowadays, nevertheless the mono-component technology is not the most popular, all stakeholders involved in the tunnelling word still follow that guidelines. Indeed, taking into account contract specifications (mostly in Europe job fields), requirements concerning compressive strength are usually asked to be assessed following the UNI EN 196-1:16. According to this technical standard, moulds with dimensions of 40*40*160mm have been used although is clearly explained in the text that is not applicable to mortars with very short setting times and without aggregates.

Adaptations and specific adjustments in order to use the UNI EN 196-1:16 for the two-component grouts have been taken and discussed in the following.

It is important to highlight that the sample preparation of the two-component mix is quite complex since it requires to fill the mould in a very short time (the gelling process starts in few seconds). Two containers are filled, one with component A and the other one with component B (the amount of which is computed based on the mix design). Component A is poured into component B (on the contrary the right turbulence is not generated), the operation is repeated and finally the mix is poured inside the mould, trying to create a continuous and homogeneous flow. It is very important to fill all the sample mould in a single layer, indeed every subsequent casting corrections lead to an inhomogeneous sample, unsuitable for testing.

Concerning the computation of the right amount of component A suitable for a good casting, it is strictly discouraged to use a volume equal to the mould one (0.256 L). Authors suggest to increase this value at least of 20%. It should take into account that mixing the two components by creating the turbulence according to the abovementioned procedure, inevitably air bubbles inside the still liquid mix will be created. Certainly, bubbles tend to ascend toward the upper surface (the casting surface) till the liquid phase is preserved but due to the fast gelling reaction, not all bubbles can leave the grout and weakness points may be present on the tested surface leading to unreliable outcomes (fig. 1).

Another practical aspect that cannot be neglected in the casting phase consists in the impossibility to pour the whole prepared mixed volume in the mould, due to the fast gelling process between the components. Unavoidably, a certain amount of gelled material will be stuck in the tank used after the mould casting.

In conclusion, the drawback related to an unsuitable casting can be avoided deliberately using a bigger volume of components compared to the mould one and scraping with a spatula the surplus material as showing in Figure 2. The scraping operation should be carry out in the successive 60 seconds after the casting in order to avoid samples damages. On the left the gelled surplus material is clearly visible, characterized by bubble prints, while on the right the weak layer is agilely removed with a spatula. The obtaining of a complete filled mould with a whole, intact and flat surface is a crucial step for the reliability of outcomes.

After the casting phase, moulds are hermetically sealed (in order to avoid water losses due to evaporation) without demoulding and are cured for scheduled time (with a fix environmental air temperature of 23±2°C).

More details regarding the samples manufacturing and the UNI EN 196-1:16 adopted changes can be found in Todaro *et al.* (2019).

2.2. Penetrometer tests (surface compressive strength)

The penetrometer is commonly used for the time setting determination of concrete. As reference, the ASTM C403/C403M-16 can be taken into account. This standard has been drown up for concretes, made up with aggregates in the matrix that must be sieved through 4.75mm. Prescriptions strictly related to concrete phenomena are reported, like for instance the consolidation of the mortar by stroking the mould and the bleeded water removing on the casting surface. Also the penetrometer bit dimensions (in the reference called needles) change in

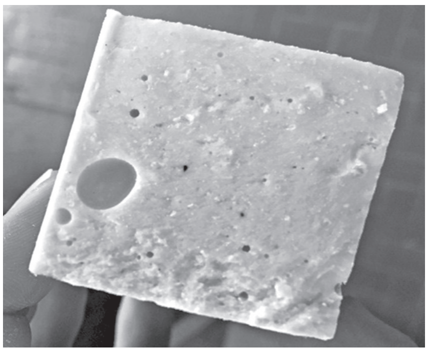

Fig. 1. Example of a big air bubble trapped inside the medium, close to the casting surface. Sample discarded.

Esempio di grande bolla d'aria inglobata all'interno del materiale, vicino alla superficie di getto. Campione scartato.

Fig. 2. Samples casted computing a bigger whole volume of material. Bobbles are clearly visible on the casting surface (on the left). Samples trimming performed by a spatula (on the right).

Provini gettati usando un volume maggiore di materiale. Le bolle sono chiaramente visibili sulla superficie di getto (a sinistra). Spatolatura dei provini (a destra).

function of the cured time. Considering that the two-component technology is completely different, some prescriptions reported in the abovementioned reference can be smartly adopted, since the base studied phenomenon is the same. In the following, the used procedure concerning the study of two-component mix is described.

Penetrometer tests have been carried out using a SAUTER GmbH Ziegelei 1 D-72336 Balingen digital model dynamometer (max force of 1000 N, 0.5N of resolution) equipped with a flat circular bit with an area of 177.9 mm^2 and 5 mm of thickness (fig. 3).

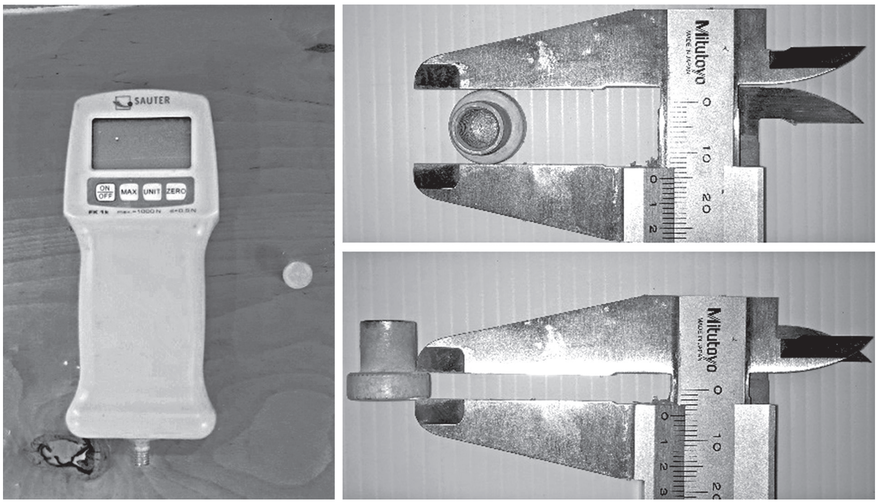

Fig. 3. Used penetrometer (on the left) and bit details (on the right).
Penetrometro utilizzato (a sinistra) e dettagli della punta (a destra).

Both bit area and the penetration thickness are different from ASTM regulation. In particular, the required depth of 25mm has been reduced to 5mm in order to avoid that the shear strength virtually developed on the lateral bit surface and the board effect due to the tank bottom could negatively affect the determination. According to ASTM C403/C403M-16 the instrument is placed perpendicularly to sample casting surface and a growing pressure is applied manually with a constant advancement speed suitable for end the test in 10 seconds. The peak force that allows to penetrate the bit thickness for 5mm into the two-component mortar ($F_{p\text{-}pen}$) is measured.

For each grout sample, 3 tests distributed along the casting surface of the specimen have been performed. In Figure 4, a simple testing scheme is depicted. Despite the minimum distance between bit impressions should be at least of 25mm, the three obtained values for each samples have showed no dependence between the designed smaller distance from the boundary.

In order to facilitate the penetration operation, two steel guides can be used to prevent the penetration overcoming beyond the chosen length (fig. 5). The used mould (made of PVC) has to be rigid in order to avoid any deformation due to the load application. Moulds made of different material can also be used (polystyrene) but all mould displacements must be constrained (fig. 5).

Computing the ratio between the peak force ($F_{p\text{-}pen}$) expressed in N and the bit area (A_b) expressed in mm^2 it is possible to obtain a physical quantity equal to a pressure, expressed in MPa (Equation 1). This quantity is herein called surface compression strength (SCS).

$$SCS = \frac{F_{p-pen}}{A_b}(\text{MPa}) \qquad (1)$$

Despite the ASTM C403/C403M-16 called the same quantity Penetration Resistance, authors decided to rename this pressure Surface Compression Strength

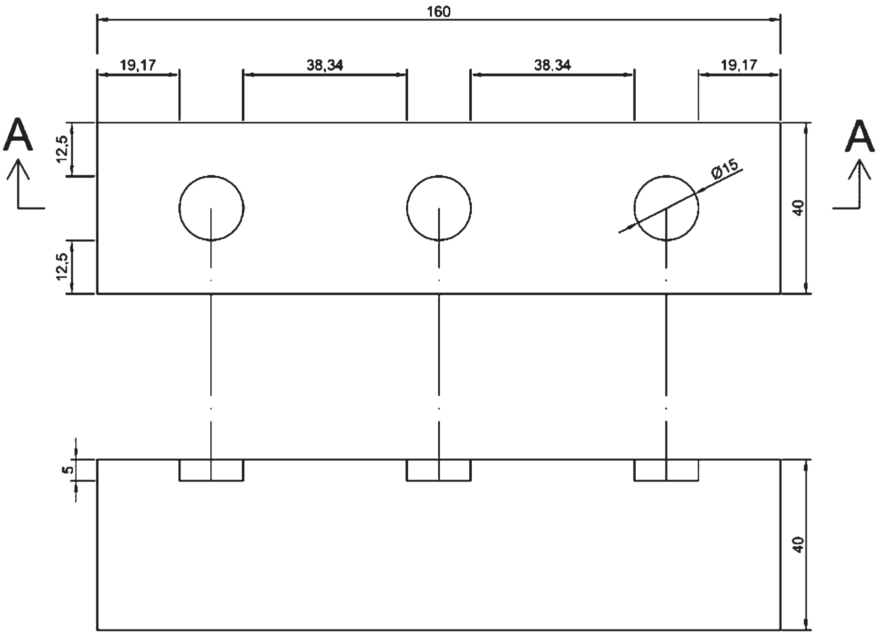

Fig. 4. Scheme of a grout two-component sample and geometrical disposition of the bit prints. All distances are expressed in mm.
Schema di un campione di malta bicomponente e disposizione geometrica delle impronte della punta. Tutte le distanze sono espresse in mm.

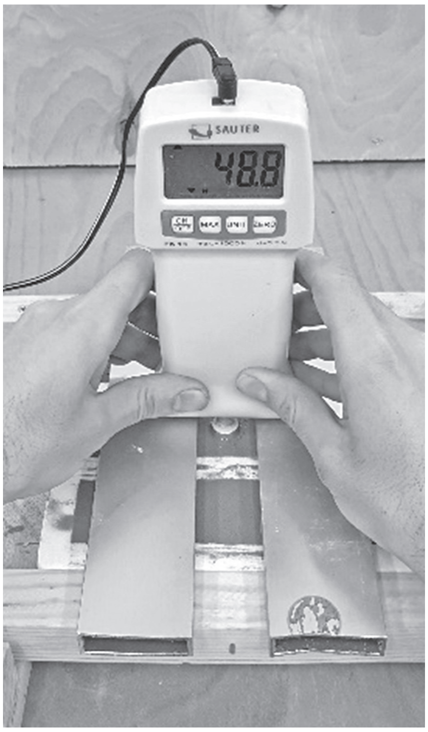

Fig. 5. Penetration phase carried out by using the steel guides designed to prevent the penetration overcoming over 5 mm.The depicted mould is made of polystyrene and the displacements are constrained with a wood block device.
Fase di penetrazione con utilizzo delle guide in acciaio per il blocco della profondità ai 5 mm. Lo stampo riportato in figura è realizzato in polistirolo e gli spostamenti sono impediti da un sistema di bloccaggio in legno.

due to the different adopted testing procedure. In this research, by using the flat bit (ratio diameter/depth = 3), the shear strength developed on the lateral surface is neglectable, so the main strength that the material opposes to penetration is a compression one exerted only from the upper part of the specimen. On the other hand, the ASTM procedure suggests the use of different bits (in function of curing times) that inserted for a depth of 25mm lead to a ratio diameter/depth between 1.14 and 0.18. In this case, the shear strength plays an unneglectable role, so in conclusion the computed pressures can be considered physically different and named differently than the ASTM nomenclature.

2.3. Press tests (uniaxial compressive strength)

Uniaxial compressive tests have been carried out according to UNI EN 196-1:16 with some adaptations. This guideline indeed appoints that before carrying out compression tests, three point flexural tests should be performed on each single sample obtaining the flexural strength and the two halves of the sample. Once upon all samples are split, compression tests can be performed on each half by using a suitable comprimitor (fig. 6).

Specifically with the two-component grout at short curing time (less than 24 hours), it has been observed the impossibility to obtain two half-samples by means of three point flexural tests. Firstly it is marked difficult demoulding samples without damages and secondly a phenomena of supports indentations on the weak sample surfaces has been observed assessing the flexural tests (fig. 7, on the left). Therefore, in order to obtain in any case samples suitable for the comprimitor use, special moulds have been designed with waterproof plastic layers used as partition walls, obtaining 3 useful mini-samples (fig. 7, on the right).

Fig. 6. Used comprimitor according to UNI EN 196-1:16.
Comprimitore utilizzato conforme alla normativa UNI EN 196-1:16.

It is important to highlight that the location of the plastic layers along the mould can be done roughly, ensuring only that the mini-samples main dimension must be bigger than 40 mm. Hence, not all the obtained mini-samples

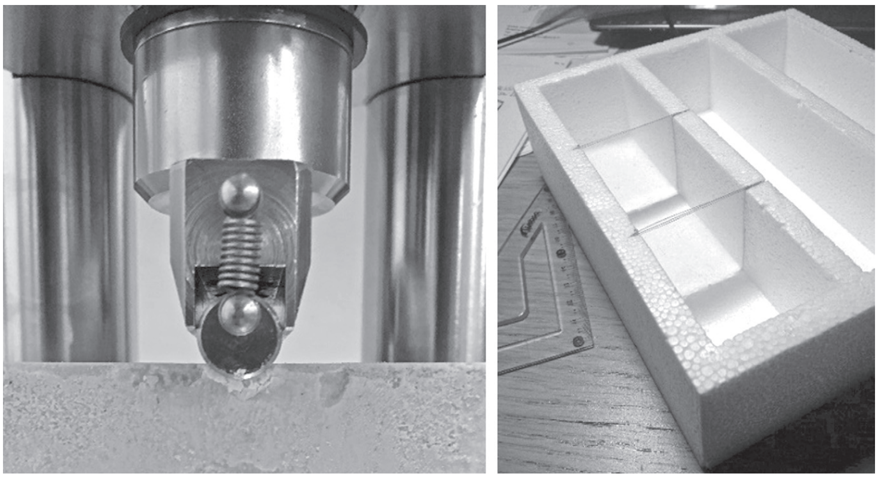

Fig. 7. Indentation phenomenon observed on a two-component sample cured less than 24 hours (on the left). Special polystyrene mould expressly designed with waterproof plastic layers as partition walls (on the right).
Fenomeno di indentazione osservato su provino di malta bicomponente maturato meno di 24 ore (a sinistra). Stampo in polistirolo con setti di separazione in plastica espressamente progettato (a destra).

must be exactly equal and possible variations in length do not affect compression test outcomes, as it has been proved from authors during the preliminary test campaign.

Once obtained the mini-samples, the uniaxial compression test campaign has been started by using a Wykeham-Ferrance press and a comprimitor in accordance with EN 196-1:16. A press speed of 0.25 mm/min has been set up for all test campaign. Outcomes were force – displacement graphs where, once recognized the peak force $F_{p\text{-}press}$ expressed in N, the uniaxial compressive strength has been computed considering an area of 40*40mm^2 (Equation 2). This value corresponds to the area of the plates that the comprimitor applies on the sample surfaces.

$$UCS = \frac{F_{p-press}}{1600} (\text{MPa}) \qquad (2)$$

2.4. Used mix design

In scientific literature it is possible to find different mix designs used in different job sites spread in all the world (Peila *et al.*, 2015) with different quantities or type of each components strictly connected to the specific engineering requirement that the final grout should satisfy.

The chosen mix design, given in Table 1, has been used in a French job field and it has been selected because the appointed amount of each component is close to the average concerning its typical ranges.

3. Results and comment

Considering the chosen mix design, both UCS and SCS test campaigns have been scheduled taking into account 9 different curing times: 60, 65, 70, 90, 100, 120, 125 and 180 minutes.

Tab. 1. Used mix design.
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Component A	water (kg)	853
	bentonite Clariant Bentonil CV15 (kg)	30
	cement Buzzi CEM I 54.2 R (kg)	230
	retarding/fluidifying agent Mapei CBS1 (kg)	3.5
Component B	accelerator Mapei CBS3 (kg)	81

For each curing time, 5 samples have been tested, obtaining 5 and 15 outcomes for UCS and SCS respectively (for tests concerning the penetrometer use, each tested sample has provided 3 value of strength, according with procedure above described).

Curves of average strength values have been drawn and are reported in Figure 8. The first observed aspect concerns the highest values of penetrometer outcomes. The reason could be explained in the different failure mechanisms that occur in a confined way for SCS while for the UCS there are no confining forces. It should be also highlighted that in the real two-component backfilling applications, the grout is constrained triaxially and that both UCS and penetrometer tests does not reflect the real stress state applied to the backfilling material and thus provide conservative outcomes.

In Figure 9 the ratio SCS/UCS is reported in function of the curing time and it is relevant to assume that the trend is almost constant, close to the value of 5.

In Antunes (2012), 3 different mix designs have been tested by means of a laboratory press and the penetrometer at 1 hour of curing. Despite tests have been performed following different standards, also in that research the ratio between UCS and penetrometer test is close to 5 for each tested mix.

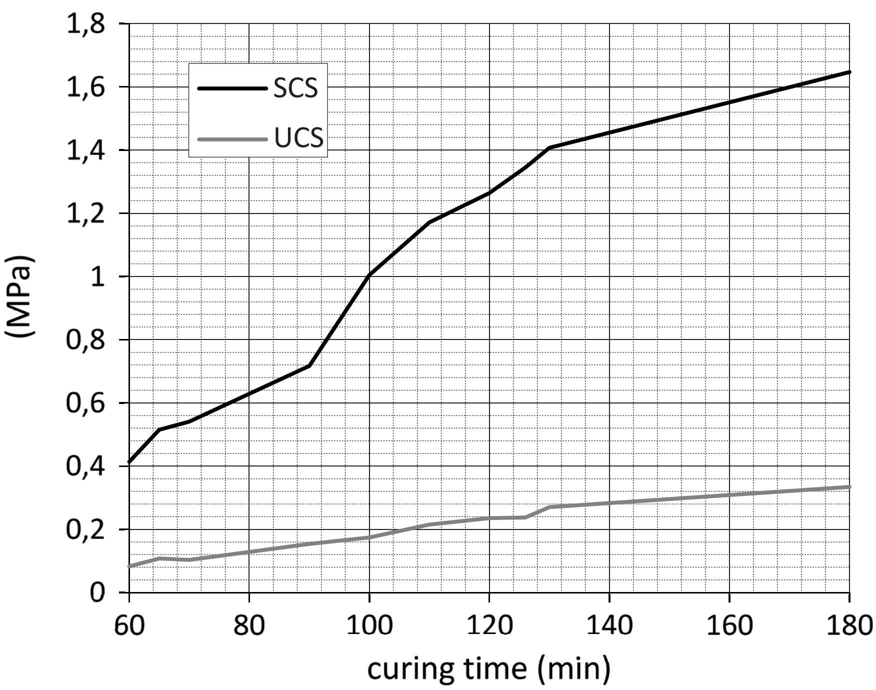

Fig. 8. SCS and UCS outcomes in function of the curing time.
Risultati relativi a SCS e UCS in funzione del tempo di maturazione.

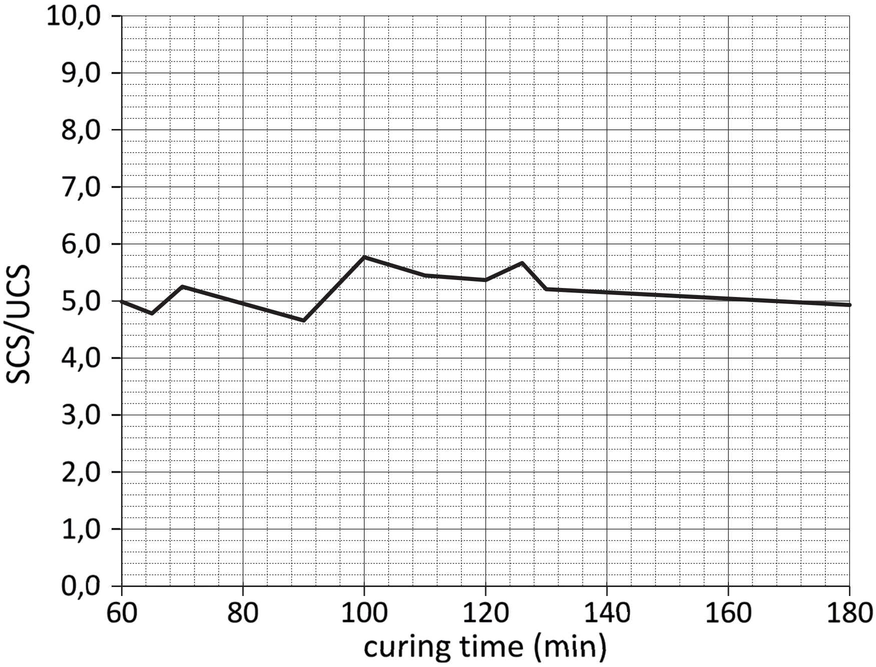

Fig. 9. Trend of SCS/UCS in function of curing time.
Andamento del rapporto SCS/UCS in funzione del tempo di maturazione.

4 Conclusions and future developments

The two-component backfilling system is the most frequently used method to fill the annular gap created during shield machine advancement behind the segment lining. In a tunnel project, a preliminary laboratory test phase is necessary in order to set-up the mix design for the two-component backfilling.

The evaluation of short-term behaviour in terms of compressive strength is an operation of paramount importance and requires a carefu analysis. Frequently the penetrometer test is used and outcomes are wrongly considered equivalent to uniaxial compression test results. According with result obtained in this research, it appears that penetrometer results cannot be directly compared with the standard uniaxial compressive strength but a correlation factor should be used. This correlation factor could bring the penetrometer use to estimate a fundamental parameter such as uniaxial compressive strength using a quicker and more agile test.

Eventually authors want to highlight that the obtained correlation factor should not be used indifferently for each two component mix design project because the dependence concerning the mix design and the geometry (between bit and mould in the penetrometer test) may studied in deep detail. The research is in progress to extend the results to a wider range of mix designs.

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