# THE BEHAVIOUR OF A TWO-COMPONENT BACK-FILLING GROUT USED IN A TUNNEL-BORING MACHINE

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### Abstract

*The instantaneous filling of the annulus that is created behind the segment lining at the end of the tail during the TBM advance is an operation of paramount importance. Its main goal is to minimize the surface settlements due to any over-excavation generated by the passage of the TBM. To correctly achieve the goals, a simultaneous back-filling system and the injected material should satisfy the technical, operational and performance characteristics. A two-component system injection for the back-filling is progressively substituting the use of traditional mortars. In this paper different systems of back-filling grout and in particular the two-component system are analyzed and the results of laboratory tests are presented and discussed.*

### Keywords

tunneling, mechanized tunneling, segment lining, settlements, back-fill grouting

## 1 INTRODUCTION

Full-face shield machines have shown an ever increasing number of applications thanks to their ability to minimize and control surface subsidence when a tunnel is excavated with a low overburden. The excavation using these machines is made by a rotating cutter-head fitted with pick or disk cutters or a combination of both, while the face stability is guaranteed by the pressure in the bulk chamber, behind the cutter head, obtained or with a bentonite slurry (Slurry Shield and Hydroshield) or with conditioned soil [10 and 11] (Earth Pressure Balance Shields). The tunnel is then supported by a segmental lining that is installed continuously during the advance of the machine and this works as the final lining too. To permit the advance of the machine and of the shield, and for technological reasons, the excavation diameter is usually bigger than the external diameter of the final lining due to the overcutting necessary to permit the advancing of the shield, to the conicity of the shield itself and to the thickness of the shield (Fig. 1). For these reasons, around the lining there is an open space that must be continuously filled during the machine's advance.

The instantaneous filling of this "annulus", which is created behind the segment lining at the end of the shield tail, is an operation of paramount importance for the correct mechanized tunnelling procedure, particularly in an urban area. Its main goal is to minimize surface settlements due to any over-excavation generated by the passage of the TBM [4, 6, 7, 10]. Furthermore, the back-filling operation has to [2, 3, 4, 5, 8, 11, 12]:

- lock the segmental lining into position, avoiding movement owing to both segmental self-weight and the thrust forces, hoop stresses, generated by the TBM;
- bear the loads transmitted by the TBM back-up weight;
- ensure a uniform, homogeneous and immediate contact between the ground and the lining;
- avoid puncture loads by ensuring the application of symmetrical and homogeneous loading along the lining;
- complement the waterproofing of the tunnel with the concrete lining and gasketry (i.e., if the lining has cracks due to a wrong installation, back-fill grout should help to mitigate any water inflow).

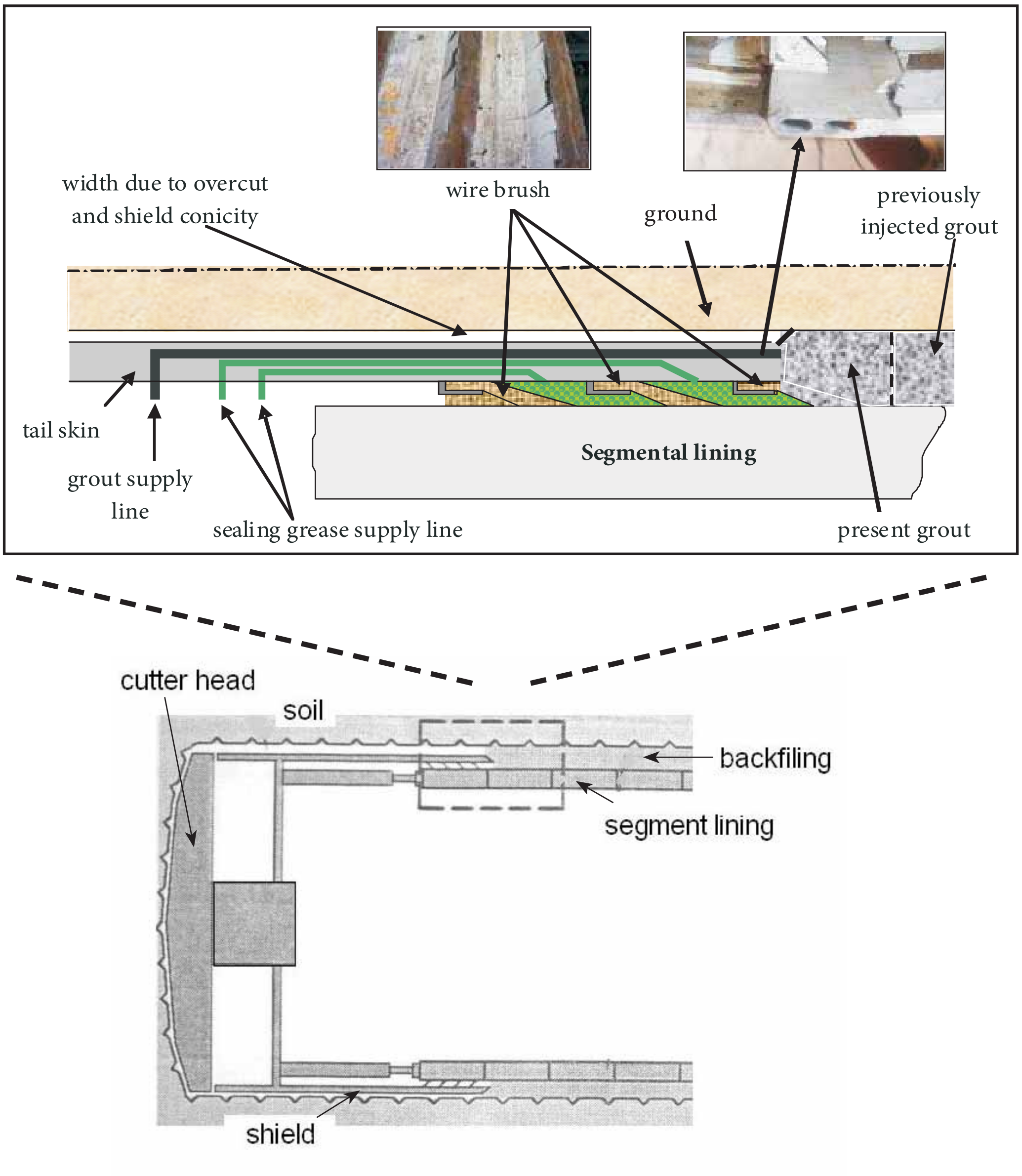


**Figure 1**. Scheme of the grouting through the tailskin.

To correctly achieve of all the above-mentioned goals, the simultaneous back-filling system and the injected material should satisfy the following technical, operational and performance characteristics:

– the back-filling has to be ideally instantaneous in order to avoid the presence of voids in the “annulus” while advancing with the TBM. For this reason, the back-filling is typically carried out through pipes located in the TBM’s tail skin;
– the “annulus” must be regularly and completely filled so that the lining is regularly linked to the surrounding ground (the system becomes monolithic);
– the reliability of the system must be guaranteed in terms of the transportability of the mix. The grout must therefore be designed in order to avoid choking of the injection pipes and the pumps’ segregation and bleeding in association with the time the grout is being transported and the distance from the batching to the injection;
– the injected material has to gel very quickly after injection (which is carried out progressively with the “annulus” generation) but without choking the injection pipes and nozzles (especially the ones for the accelerator admixture). The injection must always be carried out until either the maximum pressure is

achieved, which depends on the TBM face pressure, or the theoretical volume;
- the injection can be re-started and integrated with any previously injected material at any time;
- the injected material should be homogeneous with respect to the physical characteristics and mechanical behaviour throughout the "annulus";
- the injected material must be impossible to wash out with the ground water.

Back-filling requires that the longitudinal injection pressure should be higher than the pressure at the excavation face and it should be homogeneous during the whole injection process.

From the perspective of the structural design of the segmental lining these injections can actually be considered as a radial hydrostatic pressure, which acts simultaneously on the support structure and on the ground in opposite directions. This effect is very important because when the ring exits from the shield, during the machine advancement, it must be blocked in the ground by the backfilling. The backfilling material acts in order to completely fill the ring void and to give an external load to the segmental lining ring that "encloses" it and tends to limit or better eliminate any asymmetry of the load with a reduction of the bending moments and compress the ground at the boundary, thus eliminating any type of void that could have been created. The injected material, when passing from fluid to solid, should maintain the achieved static equilibrium; therefore, it should not be reduced in volume nor pressure-filtered into the ground.

## 2 TYPE OF MATERIAL FOR BACK-FILLING

The injected materials can have different characteristics and they are of different types and require different equipment, as summarized in Table 1, following the classification proposed by Thewes and Budach [8], following the scheme proposed by EFNARC [3]. Generally speaking, the three main types of injected materials can be divided into inert mixes, cement mixes and two-component mixes. The main properties of these mixes are reported in the following.

### 2.1 INERT MIX

The inert mix is based on the sand transported in water with other constituents, such as filler, fly ash, etc. In the rock mass it is possible to use a simple mix of sand and gravel (pea gravel) just to fill the annulus void. Generally speaking, it is a cheap system. The absence of cement avoids the risk of clogging the pipes due to any premature setting [3, 5].

The sand has to be properly selected/graded and mixed: size and type anomalies significantly increase the possibility of an irregular and heterogeneous filling, leading to pipe clogging.

As the sand cannot pump readily, it is needed to inject behind the tailskin through the segments. Typically, this is carried out through either 1 or 2 propriety grout sockets that are cast into the segments. This has a counter effect of possibly adding to potential weak points from a waterproofing perspective.

The setting is very retarded (or it never occurs) and the final strength is very low (even when it is not important to achieve any such strength). The inert mix is often chosen by French designers and contractors, as briefly described by the Working Group n.4 of the AFTES [1]: "The control of the injected material and of its hardening during the production and injection are really complex, and the progressive renunciation of the cement mix is in favour of products with a postponed grip (the pozzolanic reaction) and poor compression strength. This product is injected directly and continuously throughout the pipes that are placed in the thickness of the tail behind the last ring in the annular space, directly behind this one".

### 2.2 CEMENTITIOUS MIX

The cementitious mix is made up of water, cement, bentonite and the chemical admixtures necessary to modify the water/binder ratio and the initial and final setting times. It is an active mix with a very high fluidity. It has to be easily pumpable, and is usually retarded (some hours) to avoid the risks of choking the pipes during transportation and injection.

The presence of cement helps in the development of mechanical strength, which can reach high values (15-20 MPa at 28 days, even if it is not really necessary for good back-filling). Also, this type of mix is very negatively influenced by variations in its ingredients, which can lead to the pipes choking. This mix should be injected as near to the face as possible to provide quick support to the segmental ring. Injection through the tailskin into the "annulus" can cause serious problems with choking.

Thewes and Budach [8] and EFNARC [3] have described these types of mixes in reduced active systems. Reduced active systems have a fraction of cement, usually varying between 50 kg/m$^3$ and 100 kg/m$^3$, while only in active systems does the binder component develop full hydration with a cement content of over 200 kg/m$^3$.

## 2.3 TWO-COMPONENT MIX

The two-component mix is typically a super fluid grout, stabilized in order to guarantee its workability for a long time (from batching, to transport and injection), to which an accelerator admixture is added at the injection point into the “annulus”. The mix gels a few seconds after the addition of the accelerator (normally 10-12 seconds, during which the TBM advances approximately 10-15 mm), The gel exhibits a thixotropic consistency and starts developing mechanical strength almost instantaneously (weak but sufficient for the purpose: 50 kPa at 1 hour is typical).

This system is injected under pressure throughout the “annulus” and is able to penetrate into any voids that are present. Also, it can penetrate into the surrounding ground (depending on its permeability).

Furthermore, the retarding agent has a plasticizing effect and is able to inhibit the mix from setting, thereby guaranteeing its workability up to 72 hours after batching: this facilitates stockpiling grout in the mixer-containers that are bigger than the theoretical volume of material to be injected for every ring. This is useful for avoiding one of the most common mistakes, i.e., batching and stockpiling only the theoretical amount and not more. If eventually a bigger void is found that needs to be filled in, you would leave the crown unsupported for too long, so leading to potentially serious consequences.

The addition of the accelerator admixture to the fluid mortar leads to an almost immediate gel formation, which starts developing mechanical strength. Such gels are homogeneous and therefore avoid the point loading of the segments.

The constituents of the two-component back-fill grout are sourced from “industrial” production and so should be perfectly controlled: this guarantees its regularity, with obvious advantages in the constancy of the fresh and hardened mixes. No constituent should exhibit variable characteristics (such as sand might).

By using a proper mix-design and specifically designed equipment the risks of choking can be minimized. Some problems could arise with the nozzle of the accelerator line choking: this can normally be attributed to an improper cleaning regime or simple wear and tear of the injection outlet mechanism.

The bentonite significantly increases the homogeneity and impermeability of the hardened mix. Furthermore, it minimises the bleeding, helps in achieving the thixotropic consistency when the flow stops because the “annulus” is full and so helps in the gelling process, conferring higher impermeability to the system (less than $10^{-8}$ m/s).

**Table 1**. Field of application of various backfilling technologies (redrawn from [8]).

| Material | Application range | | Backfilling system | | Required equipment | | | | Specific/remarks |
|---|---|---|---|---|---|---|---|---|---|
| | Hard rock | soil | A | B | a | b | c* | d | |
| Mortar active system | • | • | • | • | • | | | | Conventional mortar, stiffness behaviour depends on using of additives |
| Mortar reduced active system | • | • | | • | • | | | | stiffness behaviour depends on using of additives |
| Mortar inert system | | • | | • | • | | | | stiffness behaviour depends on using of additives |
| Two-component grout | | • | • | • | | O | • | | stiffness behaviour just after mixing |
| Deforming mortar | • | | • | | | | • | | Only usable in hard rock (material under development) |
| Pea gravel | • | | • | | | | | • | Often used in hard rock, increased bedding by using mortar at the bottom, normally lower modulus of deformation and lower properties of embedment than for an active mortar |

Key:
• : applicable - O : limited applicability
A: Backfilling through the grout holes in the lining segments, B: Backfilling through the tailskin-
a: piston pump; b: peristaltic pump; c*: progressive cavity pump; d: pressurized air

In an Italian subway-station excavation we can see, once the "dummy" segments have been removed, the presence of the "annulus" filled with the gel. The photograph allows us to see the presence of the back-fill under the invert segments (Fig. 2) that demonstrates the complete filling of the voids.

## 3 TWO-COMPONENTS MIX: EXAMPLES OF APPLICATIONS

Here are some significant examples of tunnelling projects in different countries where the two-component system was and is currently being used for the back-filling operation.

### 3.1 METRO LINE C - ROME (ITALY)

The Metro Line C is currently under construction in Rome. Two EPB machines (6.7m diameter) finished excavating the first part of the line (approx. 4km), while the other two have just started. In the first part of the line, the ground where the machines were excavating was a low-permeable, stable "pozzolana", but later the TBMs will drive into a permeable and soft ground. Although the first project dealt with the injection of a traditional cementitious grout for the back-filling operation, the chosen method was finally a two-component system. The first component is an ultra-fluid mortar, with the following characteristics:

- it is stable and does not present any separation between the water and the solid contents, despite the very high water/binder ratio. This is important to avoid problems of clogging in the injection lines, even during long breaks, and to allow the transportation of the mortar, even for long distances;
- it is able to guarantee the workability for at least 72 hours from its batching. Immediately before its injection, the mortar is admixed with an accelerator, which leads to an almost immediate creation of the thixotropic gel. The gel is able to fill in completely the annular space around the concrete lining (as proved by the several core samples extracted through the segments) and to improve the waterproofing features of the tunnel (the permeability coefficient of the hardened material is comparable that of a clay). The ingredients of the two-component mix are reported in Table 2.

**Table 2**. Two-component mix adopted in Metro C Line in Rome (values per m$^3$ of hardened material).

| | |
|---|---|
| Water | 770-820 kg |
| Bentonite | 30-60 kg |
| Cement | 310-350 kg |
| Retarding agent by Mapei | 3-7 l |
| Accelerator admixture by Mapei | 50-100 l |

The right dosage of each ingredient depends on several factors, such as the desired pumpability: for example, in those machines where the mix is pumped from the batching plant directly to the TBM, the material must have great pumpability properties and the bleeding must be minimised; therefore, the percentage of bentonite is increased.

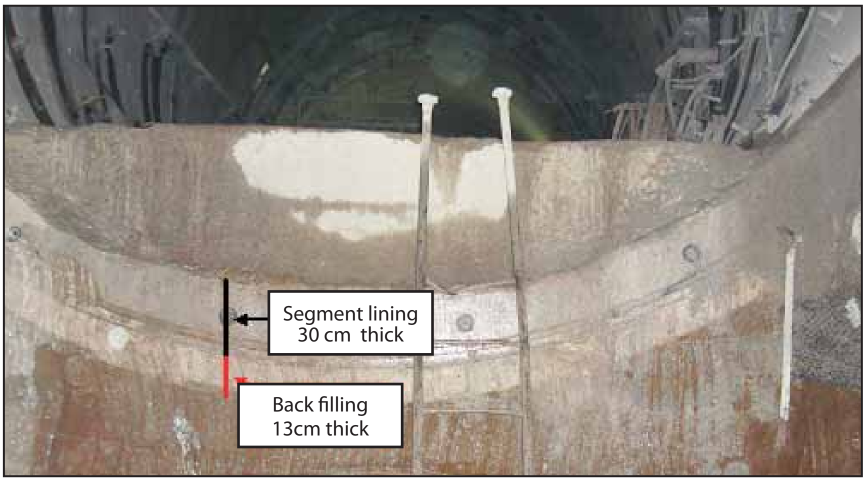


**Figure 2**. Example of backfilling in a metro tunnel in Italy (Prof. Pelizza's picture archive).

The project requirements about the development of mechanical strengths only deal with the very early and early stages (up to 24 hours), which means when the TBM tail passes over and the back-filling material comes into contact with the surrounding ground.

For longer stages, the requirements only regard the durability of the hardened material (ensured by the natural humidity of the ground) and its impermeability.

## 3.2 ORAKI MAIN SEWER HOBSON DIVERSION (OMSHD) - AUCKLAND (NEW ZEALAND)

This project concerns the excavation of a 4.3-m-diameter Mixed-face Shield. The average productions were 114 metres of bored and lined tunnel per week. The project requirements were particularly high in terms of the mechanical strengths to be achieved, even at long stages. In particular, the two-component material had to achieve: 0.1 MPa at 30 minutes and 5 MPa at 28 days.

The only way to achieve such great values was to use an amount of cement that was higher than typically used (480 kg per cubic metre of hardened material). At the same time, the grout was not pumpable enough with such an amount of cement and the addition of a super-plasticizer admixture was necessary (Table 3).

Such a mix guaranteed proper pumpability and stability properties to the fresh grout and was able to achieve average values of compressive strength at 28 days from batching of 5.1 MPa.

**Table 3**. Two-component mix adopted in Oraki Main Sewer Hobson Diversion (OMSHD) – Auckland (values per m$^3$ of hardened material).

| | |
|---|---|
| Water | 730 kg |
| Bentonite | 30kg |
| Cement | 480 kg |
| Retarding agent by Mapei | 1 l |
| Super-plasticizer by Mapei | 5 l |
| Accelerator admixture by Mapei | 50 l |

It is important to underline that such a high compressive-strength request is not strictly necessary for a proper back-filling, as already mentioned. In fact, the back-filling material cannot have structural tasks at long stages, when all the external loads (ground, water) are supported by the segmental lining. The two-component mortar should just act as an "interface" between the surrounding ground and concrete, in order to homogenously discharge the pressures on the lining.

## 3.3 METRO LINE IN SOFIA (BULGARIA)

This project concerns the construction of two 3.47-km - long parallel tunnels, which were completed at the beginning of 2009 and were excavated by an EPB machine with a diameter of 5.82 m.

The alluvium ground where the tunnel was bored was subject to many and frequent geological and geotechnical variations. The composition of the material used to fill the annular voids behind the segmental lining is summarized in Table 4 [9].

**Table 4**. Two component mix adopted in the metro line of Sofia (values per m$^3$ of hardened material).

| | |
|---|---|
| Water | 795 kg |
| Bentonite | 25 kg |
| Cement | 290 kg |
| Retarding agent by Mapei | 2.5 l |
| Accelerator admixture by Mapei | 74 l |

Such a material was able to gel in approximately 12 seconds and to achieve 0.03 MPa of compressive strength at 1 hours and 1.5 MPa at 24 hours.

Nothing was requested in terms of the mechanical behaviour for longer stages. The injection ratio was varying, depending mainly on the infiltration of material into the surrounding ground: the average values were 120-130% of the theoretical volumes.

## 3.4 METRO LINE 1 IN BRESCIA (ITALY)

The project concerns the construction of a metro-line tunnel in alluvial ground with a tunnel diameter of 9.15m, excavated by an EPB machine. The composition of the two-component mix used is summarized in Table 5.

**Table 5**. Two-component mix adopted in the metro line of Brescia (values per m$^3$ of hardened material).

| | |
|---|---|
| Water | 816 kg |
| Bentonite | 42 kg |
| Cement | 315 kg |
| Retarding agent | 3 l |
| Accelerator admixture | 60 l |

## 3.5 LTA BORED TUNNEL CONTRACTS - SINGAPORE

Another important reference, regarding the use of the two-component mix, is the construction of the LTA

Bored Tunnel in Singapore, which included approximately 20 Lots for a total of more than 50 km of tunnels. In every Lot, the use of the traditional cementitious grout was substituted by the injection of an ultra-fluid grout able to gel in a few seconds of the injection and to completely fill in all the annular space around the segmental ring.

The use of such a material was successful in all the tunnels, which were bored with different types of TBMs (EPB, Slurry Shields), manufactured by different suppliers, and in different geological conditions (clay, alluvium ground, fluvial deposits, granite, gravel, etc.).

This also proves the flexibility of the two-component back-filling and its adaptability to very different and changing conditions of boring.

### 3.6 CONCLUSIONS OBTAINED FROM CASE HISTORIES

All the mentioned examples prove that the current tendency is to privilege the back-filling of ultra-fluid two-component mixes, activated with an accelerator and able to generate a thixotropic gel in a few seconds. This system avoids all negative aspects correlated with the use of traditional cementitious grouts and is able to achieve all the technical requests demanded for the back-filling of injected material.

All these examples prove the efficacy of back-filling using ultra-fluid two-component mixes, activated with an accelerator. The fluid is able to penetrate into the earth and annulus, subsequently generating a thixotropic gel in a few seconds.

## 4 PERFORMANCE ANALYSIS OF THE TWO-COMPONENT SYSTEM

### 4.1 CREATION OF AN ANNULAR UNCOMPRESSIBLE BUBBLE

As the injected material for the two-component system is an ultra-fluid liquid which, thanks to the addition of an accelerator admixture just before its injection, obtains a thixotropic consistency in a few seconds, and as it is made up of a huge amount of water (approximately 800 litres per cubic metre of material), it is without doubt an uncompressible fluid, just like water.

The consequence is that the annulus void that is created, after the TBM tail-skin passage, has to be considered as a closed annular bubble that is filled, instant per instant, with an uncompressible fluid.

Therefore, every movement of the surrounding ground that tends to enter in the bubble or any movement of the concrete lining which tends to reduce the bubble volume, instantaneously leads to the creation of another reaction-pressure in the ball, uniform along all the volume and above all the surfaces of the volume, which avoids any type of deformation.

Therefore, the uncompressible ball of gel confines perfectly and completely everywhere the concrete rings already installed and the new concrete ring that has to be installed.

In order that this can be effectively real, it is necessary that the following conditions are met:

- the injected material must remain uncompressible;
- the fluid cannot escape from the bubble:
  - it cannot permeate through the surrounding ground (this is avoided by the underground water that exerts a hydrostatic pressure on the injected material).
  - it cannot escape through the space between the tail and the excavation profile, that is avoided by a correct balance between the tunnel face pressure and the injection pressure (which must be approx. 0.2 bar higher, not more);
- if the surrounding ground in bad condition tends to close towards the bubble, it cannot be allowed to move with excessive pressures, otherwise the pressure needed to advance the machine would increase too much. This has to be balanced and controlled with the right equilibrium between the pressure in the excavation chamber and the injection pressure. This can be aided by lubrication of the extrados of the tailskin with a bentonite slurry. It is suggested that the bentonite slurry injection takes place exactly where the tail is blocked and weighs on the ground, which means behind the invert of the lining and in the final part of the tail;
- the segment ring just installed cannot have deformations (in general, without ovalization) due to its own weight, which could lead to an anomalous installation of the rings or a too low pressure on the upper segments;
- the gel cannot be leeched by the underground water.

It is evident from the above reasons that it is necessary to inject a fluid that does not harden instantaneously, but that becomes a gel quickly and progressively without avoiding the formation of an uncompressible ball at constant volume.

The long-term mechanical strength of the back-fill material does not have any meaning, because it does not give any structural contribution to bearing the hydrostatic and geostatic loads (these are completely supported by the concrete lining), but the gel has to be as homogeneous as possible in order to mitigate the external loads (a closed ball!).

To achieve this goal it is doubtless necessary that the gel cannot decompose after its injection: its durability must guarantee that the uncompressible annular ball is kept permanently.

Therefore, all the attention should be paid to the behaviour of the injected material at early stages (from the first seconds to some hours), which includes the injection and installation of some segment rings. It is evident that the existence of a closed uncompressible ball is the most efficient and important factor.

## 4.2 DURABILITY

The durability of the gel that totally fills the annular bubble is guaranteed in the normal humidity conditions of the ground (even more when the tunnel is drilled under the water table). During the construction of many Metro Lines in Singapore the authors understand that since the two-component system has started to be used, more than ten years ago, there has only been a positive indication of the grout's durability. A comprehensive proof of the behaviour for the future does not exist, but the gel must have two features that indicate its durability:

- the undeformability: this parameter immediately appears as the most significant, as the gel is made up principally of water. If the water is not lost (due to evaporation or filtration), the material will remain stable. It is, therefore, essential that the hosting ground keeps its natural humidity;
- the technical impermeability of the ground ($10^{-8}$ m/sec). This is the physical parameter that favours the creation of the situation described above.

Both the mentioned characteristics can be measured in the laboratory and can be assumed as indicators of durability.

## 4.3 CONSISTENCY AND COMPRESSION STRENGTH OF THE HARDENED MIX

The first important consideration deriving from what has been written above is that, when a super-fluid two-component mix is used, the early-stages mechanical strengths are more important than the latter stages: in fact, the concrete lining, not the back-filling, must bear all the hydrostatic and geostatic pressures.

In the example of the Sofia Metro Line, it is clear from the table that the requested data are 0.03 MPa at 1 hour and 1.5 MPa at 24 hours and nothing is said about longer stages.

This position appears to be absolutely correct because it is in the first hours (8 rather than 24 when the TBM advances regularly) that the gel must fill every void in the "annulus" (and eventually in the surrounding ground) and protect the segment lining. This is carried out thanks to the high fluidity of the injected material and its quick gel creation. Furthermore, the gel must block the ring in its projected position (avoiding the formation of point loads) and at the same time avoid the last installed rings deforming due to the TBM thrust and cutting-wheel rotation.

It is of paramount importance that the mix creates a gel after a few seconds and so an incompressible closed ball is generated: therefore, the gel creation must be tested (at 0.5 and 8 hours stages the measures of mechanical strengths are suitable, for example, with a pocket penetrometer). The rationale of the half hour can be adjusted to suit the time taken to build one ring should be long enough for the grout to achieve sufficient strength to avoid floating around in the grout.

Measures above the 24 hours are only suitable for checking that the gel does not decompose, but increases its strength in order to allow the extraction of cores through the segments, useful to directly check the effective total filling of the "annulus".

It is without doubt that a measure of the compressive strengths on cores extracted in situ (even if the coring partially disturbs the samples) is the most reliable and significant, because the material is injected into the "annulus" at pressure and there remains in environmentally natural conditions.

# 5 TESTS ON THE TWO-COMPONENT BACK-FILLING GROUT MIX

In the following the results of a series of tests regarding the physical and mechanical behaviour of a two-component injection grout for filling the annular voids behind the segmental lining during mechanized tunnelling with EPB machines are presented, showing how this mix works properly for the mechanized tunnelling purposes.

**Figure 3**. Phases of preparation of the hardened grout samples.

The tests were carried out both on a fresh and on a hardened mix. The technical procedure (Fig. 3) that was used to obtain the samples of hardened material is:

- 10 litres of fresh and ultra-fluid grout were prepared in a bucket;
- the right amount of accelerator admixture was added and mixed to the grout for some seconds to properly distribute the accelerator in the whole grout volume;
- when the material starts hardening, the mixing is stopped;

while the mix quantities are reported in Table 6.

**Table 6**. Two-component mix adopted for the tests.

| Component | Average quantities [kg/m$^3$] |
|---|---|
| Water | 796 |
| Bentonite | 35 |
| Cement type IV/B-P 32.5 R | 350 |
| MAPEQUICK CBS SYSTEM 1 | 6.4 |
| MAPEQUICK CBS SYSTEM 2 | 84.8 |

## 5.1 TESTS ON FRESH GROUT

To check the suitability of the fresh grout for the EPB tunneling procedure, the following tests were carried out:

- bleeding test (ASTM C940). This test is carried out by leaving undisturbed 500 ml of mix for three hours and after measuring the percentage of water separation. This value for a good mix should not exceed 3%;
- Marsh cone test (ASTM C185). The test makes it possible to evaluate the fluidity and viscosity of the mix. It is carried out using a standardized cone (Fig. 4) and measuring the time request by 1000 ml of mix to flow. The optimal value for the tunneling purposes should be about 30-45 s;
- hardening time evaluation. This test was carried out by mixing 500 ml of grout and 48 g of accelerator. The hardening time is fixed when the mix is no longer workable (Fig. 5).

These tests make it possible to evaluate whether the mix can be easily and safely pumped through the tail

**Figure 4**. Execution of Marsh cone test.

**Figure 5**. Grout mix after hardening.

skin and also provide the maximum time while the not accelerated mix remains stable without separation of the solid phase (mainly cement grains). The obtained results are reported in Table 7, showing the good behavior of the studied mix.

**Table 7**. Results of the bleeding tests on different samples.

| Sample | Time since the grout was prepared [h] | Bleeding value [%] | Marsh cone time [s] | Hardening time [s] |
|---|---|---|---|---|
| A | 0 | 3 | 33 | 12 |
| B | 12 | 2 | 32 | 12 |
| C | 24 | 2 | 32 | 13.5 |

## 5.2 TESTS ON HARDENED GROUT MIX

After seven days from the mix preparation, the sample was cored (Ø 54 mm, diameter/height ratio=1) and the uniaxial compressive strength of the grout mix was measured at different curing times, keeping the samples under soil with its natural humidity. From Figure 6, where all the results are summarized, it is possible to see how the grout mix hardens in time and that it reaches values greater than 4.5 MPa.

To study the effect of the curing condition it is possible to compare the samples that were maintained inside a soil with its natural humidity and those that were maintained in the open air.

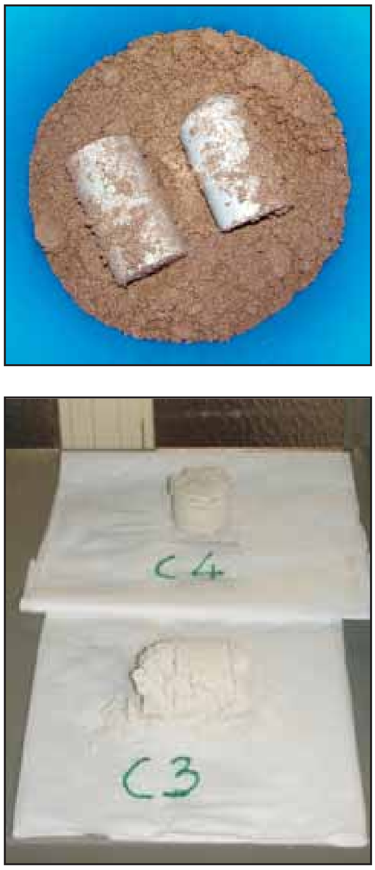


**Figure 7**. Example of two samples cured under natural soil and two cured in the open air. The difference in behaviour is clear.

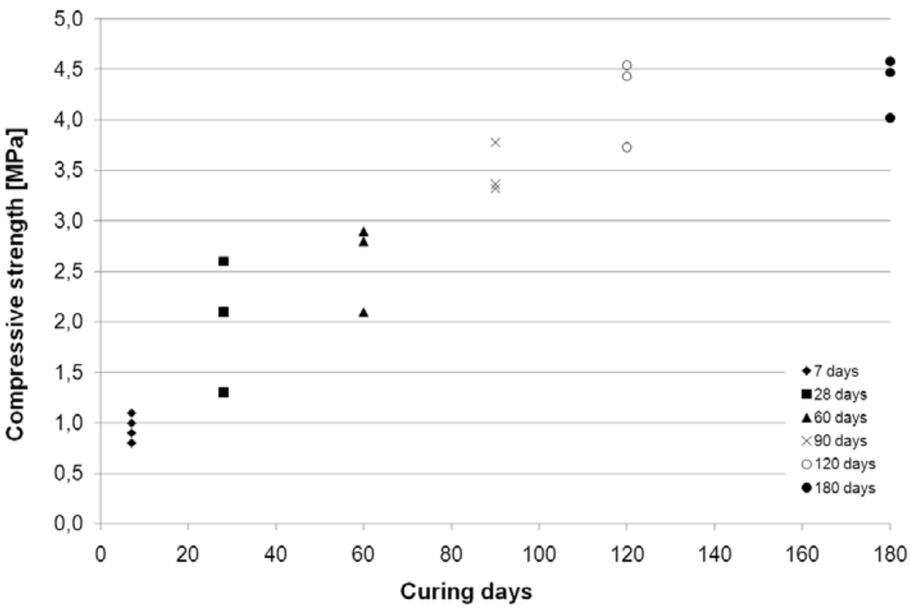


**Figure 6**. Uniaxial compressive strength of the two-component tested mix.

From the photographs it is clear, the great difference of behaviour: if the sample loses its natural water it then loses its mechanical properties.

## 6 CONCLUSIONS

The two-component system injection for back-filling while excavating with shielded TBMs is progressively substituting the traditional use of cementitious mortars for two main reasons: it reduces the risks of choking pipes and pumps (typical when pumping cementitious systems) and guarantees a complete filling at the pressure of all the annular voids created after the TBM tail passage, thus avoiding the surrounding movements. The main features of such a material are: super-fluid initial consistency, the creation of a gel after a few seconds from the injection, compressive strengths from approx. 0.1 to 1 MPa at early stages.

Effectively, the goal of the back-filling is carried out in the first minutes after its injection; therefore, it is important to focus attention on the last 2-3 installed rings, and not more.

Consequently, also according to international methods, it is important to verify that the mix actually makes a gel quickly, in order to confine homogeneously the segment ring.

As it is impossible to verify the event inside the "annulus", it is necessary to simulate that by preparing samples in the laboratory, with which it is possible to determine the consistency achieved by the gel in the first hours and later. The latter stages are meaningless, because the gel's mechanical strength does not influence the structural behaviour of the tunnel lining if the "annulus" is actually completely filled in.

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