Analysis of the Performance of Two Component Back-filling Grout in Tunnel Boring Machines Operating under Face Pressure

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1. Introduction

The instantaneous filling of the "annulus", which is created behind the segment lining at the end of the shield tail (Fig. 1), is an operation of paramount importance. Its main goal is to minimise surface settlements due to over-excavation generated by the passage of the TBM [1, 2, 3].Furthermore, the back-filling operation has to [1, 4, 5, 6, 7, 8, 9]:

- 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 ground and 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 wrong installation, back-fill grout should help to mitigate any water inflow).

For correctly achieving 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, back-filling is typically carried out through pipes located into the TBM 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 transportability of the mix. The grout must therefore be designed avoid choking of the injection pipes and pumps segregation and bleeding in collaboration with the time the grout is being transported and distance from batching to 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 be always carried out until either achieving the maximum pressure, that 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 in respect to physical characteristics and mechanical behaviour throughout the "annulus";
- the injected material must be unable to be washed out by ground water.

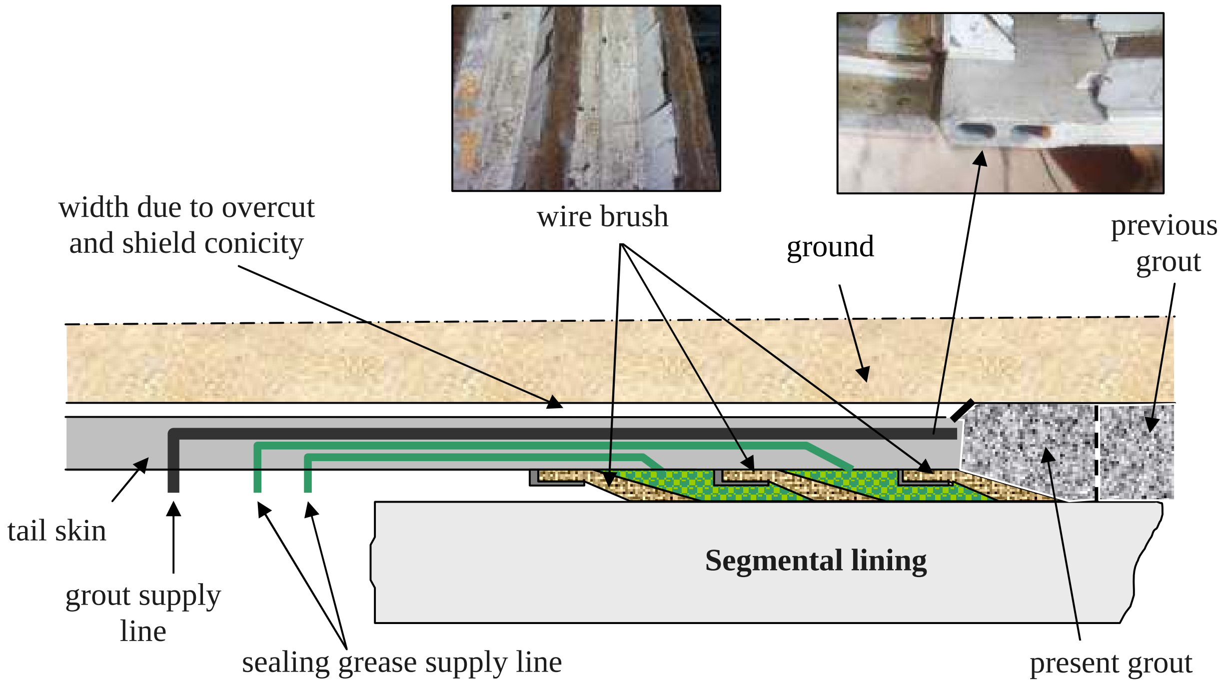

Figure 1 – scheme of the grouting through the tailskin

2. Type of material for back-filling

The injected materials can have different characteristics and they are of different types and require different equipments as summarized in Table 1, following the classification proposed by Thewes and Budach [9] following the scheme proposed by EFNARC [6]. Generally speaking the three main types of injected materials can be divided in 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 sand transported in water with other constituents, such as filler, fly ash, etc. In 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 premature setting [6, 7].
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 cast into the segments. This has a counter effect of possibly adding to potential weak points from a waterproofing perspective.
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 [10]: "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 postponed grip (pozzolanic reaction) and poor compression strength. This product is injected directly and continuously throughout the pipes 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 constituted by water, cement, bentonite and 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 risks of choking the pipes during transportation and injection.

The presence of cement helps 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 [7] and EFNARC [6] have descried these type of mix 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 the binder component develop full hydration with a cement content of over 200 kg/m^3.

Material	Application range		Backfilling system		Required equipment				Specific/remarks
	Hard rock	**soil**	**A**	**B**	**a**	**b**	**c**	**d**	
Mortar active system	O	O	O	O	O				Conventional mortar, stiffness behaviour depends on using of additives
Mortar reduced active system	O	O		O	O				stiffness behaviour depends on using of additives
Mortar inert system		O		O	O				stiffness behaviour depends on using of additives
Two component grout		O	O	O		X	O		stiffness behaviour just after mixing
Deforming mortar	O		O				O		Only usable in hard rock (material under development)
Pea gravel	O		O					O	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

Table 1 – Field of application of various backfilling technologies (redrawn from [1]).
Key: O *: applicable -* X*: 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

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 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 in avoiding one of the most common mistakes, that is, 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 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 strengths. Such gels are homogeneous and therefore avoid point loading of the segments.
The constituents of two-component back-fill grout are sourced from “industrial” production and so should be perfectly controlled: that 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).

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 increases significantly 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).

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

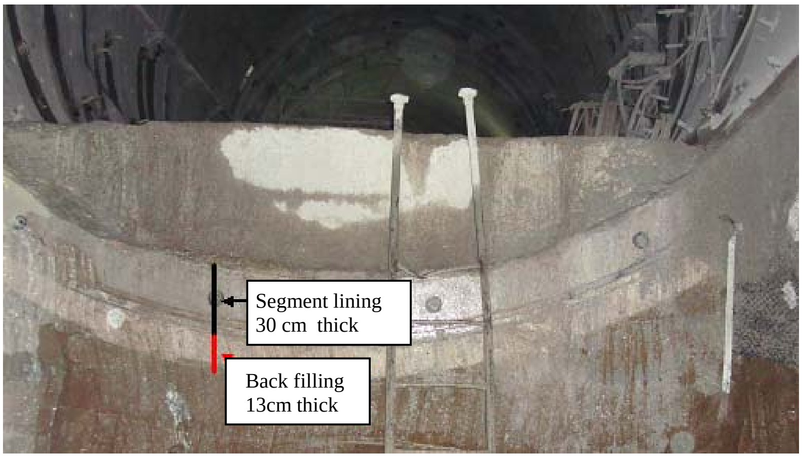

Figure 2 – Example of backfilling in a metro tunnel in Italy (Prof. Pelizza's pictures archive)

3. Two components mix examples of applications

Hereunder 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), whilst 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 in 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 separation between water and the solid contents, despite of the very high water/binder ratio. This is important to avoid problems of clogging in the injection line
- it is able to guarantee the workability for at least 72 hours from its batching using a retarding agent by Mapei SpA. Immediately before its injection, the mortar is admixed with an accelerator admixture (developed by Mapei SpA), which leads to an almost immediate creation of a 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 the one of a clay). The ingredients of the two-component mix are reported in Table 2.

Component 1	Water	770-820 kg
	Bentonite	30-60 kg
	Cement	310-350 kg
	Retarding agent	3-7 l
Component 2	Accelerator admixture	50-100 l

Table 2 – two component mix adopted in Metro C Line in Rome (values per m^3 of hardened material)

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.
The project requirements about the development of mechanical strengths only deal with the very-early and early stage (up to 24 hours), that means when the TBM tail passes over and the back-filling material gets in 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)

The project concerns the excavation of a 4.3 m diameter mixed-face Shield. The average productions were 114 meters of bored and lined tunnel per week. The project requirements were particularly high in terms of mechanical strengths to be achieved, even at long stages. In particular the two-component mix, with the retarding agent and the accelerator admixture developed by Mapei SpA, had to achieve: 0.1 MPa at 30 minutes and 5 MPa at 28 days.
The only way to achieve so great values was to use an amount of cement higher than typically (480 kg per cubic meter 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 developed by Mapei SpA was necessary (Table 3).

Component 1	Water	730 kg
	Bentonite	30 kg
	Cement	480 kg
	Retarding agent	1 l
	Super-plasticizer	5 l
Component 2	Accelerator admixture	50 l

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

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.
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 just should act as an “interface” between surrounding ground and concrete, in order to homogenously discharge the pressures on the lining.

3.3 Metro Line in Sofia (Bulgaria)

The project concerns the construction of two 3.47 kg long parallel tunnels, which were completed at the beginning of 2009 and that 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 two-component mix, with the retarding agent and the accelerator admixture developed by Mapei SpA, used to fill the annular voids behind the segmental lining is summarized in table 4 [11].

Component 1	Water	795 kg
	Bentonite	25 kg
	Cement	290 kg
	Retarding agent	2.5 l
Component 2	Accelerator admixture	74 l

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

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 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:

Component 1	Water	816 kg
	Bentonite	42 kg
	Cement	315 kg
	Retarding agent	3 l
Component 2	Accelerator admixture	60 l

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

3.5 LTA Bored Tunnel Contracts - Singapore

Other important references, regarding the use of the two-component mix, is the construction of the LTA Bored Tunnel in Singapore, which included approx. 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 after 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 diverse 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 to the use of traditional cementitious grouts and is able to achieve all the technical requests demanded to the back-filling 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 two-component system is an ultra-fluid liquid which, thanks to the addition of an accelerator admixture just before its injection, gets a thixotropic consistency in a few seconds, and as it is made up of a huge amount of water (approximately 800 litres per cubic meter 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 tailskin 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 which 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 which has to be installed.
In order that this can be effectively real, it is necessary that the following conditions are achieved:

- 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 conditions 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 a 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, that 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 leached 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 strengths 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 more homogeneous as possible in order to mitigate the external loads (a closed ball!).

For 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 on 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 which fills totally 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 grouts durability. A comprehensive proof of the behaviour for the future does not exist, but the gel must have two features which 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 (for evaporation or filtration), the material will remain stable for ever. It is therefore essential that the hosting ground keeps its natural humidity.
- the technical impermeability of the ground (10^{-8} m/sec). It is the physical parameter that favours the creation of the situation above described.

Both the mentioned characteristics can be measured in 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 can be noticed in 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 that 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 uncompressible closed ball is generated: therefore the gel creation must be tested (at 0.5 and 8 hours stages the measure 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 a strength enough to avoid floating around in the grout.
Measures above the 24 hours are only suitable to check 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 the measure of compressive strengths on cores extracted in situ (even if the coring can disturb partially the samples) is the most trustable and significant, because the material is injected in the “annulus” at pressure and there remains in environmental natural conditions.

5. Conclusions

The two-component system injection for the 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 pressure of all the annular voids created after the TBM tail passage, thus avoiding surrounding movements. The main features of such a material are: super-fluid initial consistency, 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 the attention on the last 2-3 installed rings and not more.
Consequently, also according to the international ways, 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 that event inside the “annulus”, it is needed to simulate that by preparing samples in 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 mechanical strength does not influence the structural behaviour of the tunnel lining if the “annulus” is actually completely filled in.

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