Back-fill grout with two component mix in EPB tunneling to minimize surface settlements: Rome Metro—Line C case history

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ABSTRACT: The instantaneous filling of the annulus created behind the segment lining at the end of the tail shield during TBM advance is an operation of paramount importance. Its main goal is to minimize displacements around the tunnel and induced surface settlements due to lost volume at the tail shield. For correctly achieving these goals, the simultaneous back-filling system and the injected material should satisfy technical, operational and performance characteristics. The two-component injection system for back-filling while excavating with shielded TBMs is progressively replacing the traditional use of cementitious mortars.

In the paper different systems of back-filling grout and in particular the two-component system are analyzed and discussed together with a description of the Rome Metro (Line C) case history where this type of back-filling was widely applied.

1 INTRODUCTION

The instantaneous filling of the “annulus” created behind the segment lining at the end of the tail shield during TBM advance (Fig. 1) is an operation of paramount importance. Its main goal is to minimize displacements around the tunnel and induced surface settlements due to lost volume at the tail shield [1, 2, 3]. The management and control of settlements induced by the construction of tunnels in urban areas is very important since they can damage nearby the buildings. Furthermore, the back-filling operation must [1, 4, 5, 6, 7, 8, 9, 12]:

- lock the segmental lining into the right position, avoiding movement owing to both segmental self-weight and the thrust forces and 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 mitigate any water inflow).

For correctly achieving the above goals, the simultaneous back-filling system and the injected material should satisfy the following technical, operational and performance characteristics:

- the back-filling should ideally be 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 inserted inside the TBM tail skin, uniformly distributed around the tail skin (Fig. 1);
- the “annulus” must be regularly and completely filled so that the lining is fully 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 be designed to avoid choking off the injection pipes, segregating in pumps and bleeding, in conjunction 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 generation of the “annulus”) but without choking the injection pipes and nozzles (especially the ones for the accelerator admixture). The injection must always be carried out until either achieving the maximum pressure that is a function of 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 behavior throughout the “annulus”;
• the injected material must not be able to be washed out by ground water.

2 TYPE OF MATERIAL FOR BACK-FILLING

Injected materials can have different characteristics and mechanical behavior. Different backfill types require different equipment as summarized in Table 1 following the classification proposed by Thewes and Budach [9] following the scheme proposed by EFNARC [6]. Generically speaking the three main types of injected materials are inert mix, cement mix and two component mix. The main properties of these mixes are reported below.

2.1 Inert mix

Inert mix is based on sand transported in water with other constituents, such as filler, fly ash, etc.

2.2 Cementitious mix

Cementitious mix is constituted by water, cement, bentonite and chemical admixtures (also named mortar) 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 delivery pipes during transportation and injection.

The presence of cement helps develop 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 choking the pipes. The mix should be injected as close to the face as possible.
possible to provide rapid support to the segment ring. Injection through the tail skin into the “annulus” can cause serious problems with choking. The high frequency of choking of grout supply lines involves discontinuity in the back-filling operation. This creates voids and joints that do not allow the grout to completely fill the annulus thus not performing the design requirements.

Thewes and Budach [7] and EFNARC [6] have described these types of mortar in reduced active systems. Reduced active systems have a fraction of cement usually varying between 50 kg/m³ and 100 kg/m³ while in active systems the binder component develops full hydration with a cement content of over 200 kg/m³.

2.3 Two-component mix

Two-component mix is typically a super fluid mortar, stabilized in order to guarantee its workability for a long time, usually at least 72 hours (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 (Fig. 2), 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).

The main characteristic of the two-component mix is the quick development of its mechanical properties thus permitting the best filling of the void.

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 mortar from setting thereby guaranteeing its workability up to 72 hours after batching. This facilitates stockpiling grout in mixer-containers that are bigger than the theoretical volume of material to be injected per 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, you could leave the crown unsupported for too long, leading to potentially serious consequences.

The accelerator admixture is based on sodium silicate. Its addition to the fluid mortar leads to an almost immediate gel formation which starts developing mechanical strength. 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. This guarantees its regularity with obvious advantages in the consistent quality of fresh and hardened mixes. No constituent should exhibit variable characteristics (such as sand).

Using a proper mix-design and specifically designed equipment the risks of blockage can be minimized. Some problems can arise with the nozzle of the accelerator line blocking. 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 minimizes the bleeding, helps in achieving a thixotropic consistency when the flow stops because the “annulus” is full and so helps in the gelling process, conferring greater impermeability to the system (less than 10⁻⁸ m/s).
3 PERFORMANCE ANALYSIS OF THE TWO-COMPONENT SYSTEM

3.1 Creation of an annular incompressible bubble

The injected material for a two-component system is an ultra-fluid slurry which, due to addition of an accelerator admixture just before its injection, gets a thixotropic consistency in a few seconds. As it is made up of a huge amount of water (approximately 800 litres per cubic meter of material), it is an incompressible fluid, just like water.

The consequence of this is that the annulus void created behind the TBM tail skin is a closed annular bubble, 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 a reaction-pressure inside the fluid, uniform throughout the volume and around all the surfaces of the volume, avoiding any deformation.

Therefore the incompressible zone of gel perfectly confines the concrete rings already installed and the new concrete ring which has to be installed.

So this can be carried out the following conditions must be achieved:

− the injected material must remain incompressible;
− the fluid must not escape from the annulus void:
  − it must not permeate through the surrounding ground (this is avoided by the ground water that exerts a hydrostatic pressure on the injected material);
  − it must not escape through the space between the tail and the tunnel face, which 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 is in poor condition, it tends to squeeze towards the annulus. It cannot be allowed to move with excessive pressure, otherwise the force required to advance the machine would increase too much. This has to be balanced and controlled with equilibrium between the pressure in the excavation chamber and the injection pressure. This can be aided by lubrication of the extrados of the tail skin with a bentonite slurry. Bentonite slurry injection should take place exactly where the tail is blocked and bears on the ground, i.e. behind the invert of the lining and in the rear part of the tail;
− the segment ring just installed must not be deformed (i.e., without ovalization) due to its own weight, which could lead to an anomalous installation of the rings or too low a pressure on the upper segments;
− the gel must not be leached by the underground water.

From the above, it is evident 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 incompressible annulus at constant volume.

The long term mechanical strength of the backfill 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 to mitigate the external punching loads.

To achieve this goal the gel must not decompose after its injection: its durability must guarantee that the incompressible annular filling is maintained permanently.

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

3.2 Durability

The durability of the gel which totally fills the annular void is guaranteed in the normal humidity conditions of the ground (even more so 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 positive indication of grout durability. Comprehensive proof of grout behavior 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 (by evaporation or filtration), the material will remain stable for ever. It is therefore essential that the host ground maintains its natural humidity;
− the technical impermeability of the ground ($10^{-8}$ m/sec). This is the physical parameter that favors the creation of the situation described above.

Both these characteristics can be measured in the laboratory and can be assumed as indicators of durability.
3.3 Consistency and compression strength of the hardened mix

An important consideration from the above is that, when a super-fluid two-component mix is used, the early stage mechanical strength is more important than the latter stage strength. The concrete lining, not the back-filling grout, must bear the applied long term hydrostatic and geostatic pressures.

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 achieved by the high fluidity of the injected material and its rapid gel setting time. Furthermore the gel must hold the ring in its built position (avoiding the formation of punching loads) and at the same time avoiding 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 an incompressible annulus is generated: therefore the gel set must be tested (at 0.5 and 8 hour stages) to confirm that the strength is suitable, for example with a pocket penetrometer. The selection of the half hour test time can be adjusted to suit the time taken to build one ring. The first test time should be long enough for the grout to achieve a strength adequate to avoid the lining floating around in the grout.

Tests after 24 hours are only suitable to check that the gel does not decompose, but increases its strength over time in order to allow the extraction of cores through the segments. This may be useful to directly check the effective total filling of the “annulus”.

Testing of compressive strength on cores extracted in situ (even if the coring can partially disturb the sample) is the most reliable method because the material is injected in the “annulus” at pressure and remains there in environmentally natural conditions.

4 TWO COMPONENT MIX. EXAMPLE OF APPLICATIONS—ROME METRO—LINE C (ITALY)

The tunnels of Metro Line C are under construction in Rome using four EPB machines and will constitute the third line of Rome metro.

Metro C S.c.p.a. is the General Contractor for the engineering and construction, formed by Astaldi S.p.a. (leader of the joint venture), Vianini Lavori, Ansaldo STS, Cooperativa Muratori e Braccianti di Carpi and Consorzio Cooperative Costruzioni.

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The layout of the Line (Fig. 3) is 25 km long (18 km underground) with 29 stations. It crosses Rome from south-east to north-west.

Line C will have three connections with the other two existing metro lines, the A Line (in San Giovanni and Ottaviano stations) and the B Line (in Fori Imperiali-Colosseo station).

Presently Line C has been built in the first sections called T7, T6A, T5 e T4, between the Montecompatri-Pantano station (south-east) and the San Giovanni station, for a length of about 18.5 km of which 10 km are underground with 22 stations.

The Line C will be operated driverless with a Total Automation System. The Central Direction of Operations is located at Graniti train depot (at the south-east end of the line) and the stations will contain automatic doors synchronized with the train’s doors.

When operating this metro line will have the largest passenger transport in Europe with a maximum capacity of 24000 passengers/hour in each direction. Each direction is managed with a single tunnel with 5.8 m inner diameter and with a lining thickness of 0.30 m. The segmental lining is universal (Fig. 4, Tab 1).

The main geological formations encountered by the tunnels are volcanic soils with properties ranging from loose soils to soft rocks (Fig. 5 and Tab. 2). All the tunnels are below water table, which can be higher than 15 m over the tunnel crown.

Four EPB machines were used for the construction of the tunnels with an excavation diameter of 6.71 m (Fig. 6 and Fig. 7). Since the lining has an outer diameter of 6.40 m, the thickness of the backfilling annulus is about 150 mm.

Backfilling was carried out with a two component mix. This mix was studied by Metro C
using special tests and research carried out by the Department of Land Environment and Geoengineering of Politecnico di Torino.

The first mix component is an ultra-fluid mortar, with the following characteristics:

- it is stable and does not cause separation of water and solid contents, despite the very high water/binder ratio. This is important to avoid clogging in the injection lines, especially during long breaks, and to allow the transportation of the mortar over long distances.
- It is able to guarantee the workability for at least 72 hours after batching. Immediately before
injection, the mortar is admixed with an accelerator, based on modified sodium silicate, which leads to an almost immediate creation of a thixotropic gel. The gel is able to completely fill in the annular space around the concrete lining (as proved by the several core samples extracted through the segments) and to improve the water-proofing features of the tunnel (the permeability coefficient of the hardened material is comparable to that of a clay).

The ingredients of the two-component mix are reported in Table 3.

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 good pumpability properties and the bleeding must be a minimum, therefore the percentage of bentonite is increased. The project requirements for the development of mechanical strength only deal with the very-early and early stage (up to 24 hours), when the TBM tail passes over and the back-filling material gets in contact with the surrounding ground.

For later stages, the requirement only concerns the durability of the hardened material (ensured by the natural moisture of the ground) and its impermeability.

The accelerator admixture is based on sodium silicate enriched SiO\textsubscript{2} and characterized by an optimal ratio SiO\textsubscript{2}/Na\textsubscript{2}O. The SiO\textsubscript{2} content improves the strength and durability properties of the hardened mix. The main properties of the mix are: gel time: 5–15 s; uniaxial compression strength after 1 h: ≥50 kPa; after 8 h: ≥100 kPa; after 24 h: ≥450 kPa and permeability coefficient: ≤1.0 × 10\textsuperscript{-8} m/s.

Many tests, also required in the tender documents, were carried out to check both the quality of the hardened mix and the thickness of the annulus. Special attention was given to checking the complete filling of the annulus gap, particularly over the crown of the segment lining.

These investigations were developed using georadar tests (Fig. 8, Fig. 9 and Fig. 10), direct core drilling of the lining and the back-filling (Fig. 11) and visual check where the tunnel was successively

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Amount (kg)</th>
<th>Amount (l)</th>
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<tbody>
<tr>
<td>Water</td>
<td>770–820</td>
<td></td>
</tr>
<tr>
<td>Bentonite</td>
<td>30–60</td>
<td></td>
</tr>
<tr>
<td>Cement</td>
<td>310–350</td>
<td></td>
</tr>
<tr>
<td>Retarding agent</td>
<td>3–7</td>
<td></td>
</tr>
<tr>
<td>Accelerator admixture</td>
<td>50–100</td>
<td></td>
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</tbody>
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Table 3. Two component mix adopted in Metro C Line in Rome (values per m\textsuperscript{3} of hardened material).

Figure 8. Execution of Georadar Tests above the machine backup.

Figure 9. Example of transverse section that was investigated with georadar.

Figure 10. Example of the result of the georadar investigation along an arch as indicated in Fig. 9.

Figure 11. Photograph of a core sample of the lining and of the back-filling grout.
The investigations showed good backfilling along the whole line. An other indirect check of the quality of backfilling (both of the operation of injection and of the type of mix used) was provided by the displacement monitoring around the tunnel and on the ground surface. The surface settlements along 8 km of excavated tunnel were generally smaller than one order of magnitude less than the values forecasted in the design stage.

With reference to the strength properties of the hardened mix the carried out tests have shown the following average values of monaxial compressive strength: 0.05 MPa at 1 hour, 0.01 MPa at 8 hour and 4.5 MPa at 24 hours. After longer hardening time the specific tests requested by the client have provided values of uniaxial compressive strength bigger than 5 MPa after 180 curing days.

5 CONCLUSIONS

The two-component injection system for backfilling while excavating with face pressure applied by shielded TBMs is progressively replacing the traditional use of cementitious mortars. There are two main reasons for this: it reduces the risks of blocking pipes and pumps (common when pumping cementitious systems) and guarantees complete filling of the annular void created after the TBM tail passage, thus avoiding surrounding ground movements. The main features of such a material are: super-fluid initial consistency, creation of a gel a few seconds after the injection, compressive strengths ranging approx. 0.1 to 1 MPa. The goal of the backfilling is effectively carried out in the first minutes after injection, therefore it is important to focus the attention on the last 2–3 installed rings and not more.

Consequently, and according to international experience, it is important to verify that the mix actually gels quickly, in order to homogeneously confine the segment ring.

As it is impossible to verify all this inside the “annulus”, it is necessary to prepare and test samples in the laboratory, determine the consistency achieved by the gel in the first few hours and later. Investigating the latter stages is meaningless, because the gel mechanical strength does not influence the structural behaviour of the tunnel lining if the “annulus” is completely filled in.

The example application of Rome metro-Line C clearly shows the advantages of backfilling using ultra-fluid two-component mixes, activated with an accelerator. This type of fluid is able to completely fill the annulus due to the fluidity of the mix and speed of hardening (a thixotropic gel is formed in a few seconds) thus permitting correct management and control of surface settlements that are important when tunneling in urban areas.

REFERENCES


