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Sao Paulo Metro Project – Control Of Settlements In Variable Soil Conditions Through EPB Pressure And Bicomponent Backfill Grout.

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ABSTRACT

The respect of EPB reference pressure during TBM advance and hyperbaric activities, the complete and effective filling of the annular gap between tunnel lining extrados and the excavation section and a well organized monitoring system, to control surface settlements and ground distortion, are items of utmost importance in EPB tunnelling process.
The paper describes how these concepts have been applied while excavating in the difficult underground conditions found at Sao Paulo (Brazil) during the execution of the Sao Paulo Metro Line 4 – Lot 1.
In this project, the annular gap has been filled by two components type, cement grouting. The back feed of the extensive monitoring campaign carried out to check the surface settlements during the excavation and hyperbaric maintenance operations will also be described in the paper.

INTRODUCTION

The execution of a Metro tunnel in a city such as Sao Paulo do Brazil is a big challenge either due to technical or economical reasons.
Sao Paulo, at the moment, is the financial and economical capital of Latin America and contends to Mexico City and NY the lead as the most populated city of the continent.

The city has grown very fast in the last 40 years reaching the number of 18 ML people in between Sao Paulo and the suburb areas (Grande Sao Paulo). Although the first metro project dates late 60's, same as Mexico City, from there on Sao Paulo has seen the execution of only 61 km of Metro lines compared to the 202 km of Mexico DF.

The Line 4 project connects the west side of the city (Villa Sonia) with the centre (Luz) interconnecting tree of the four existing lines; Blue (Line1), Green (Line 2) and Red (Line 3).
The new line crosses line 2 (6 m below it) close to Paulista station and crosses line 3 inside Republica station. Line 1 is intercepted at the far end, at Luz station.

The city is characterized by continuous follow of modern high buildings (over 40 stores) and old low private houses (two or three stores).

The Sao Paulo Metro Company awarded to the local Joint Venture CVA (Consorcio Via Amarela) the execution of 12,8 km of tunnel, 12 stations, and 12 ventilation shafts.

Half of the total length of tunnel is excavated by TBM while the rest by NATM.

CVA is a Joint Venture leaded by CBPO Odebrecht and includes the fifth bigger company of Brazil. The JV has contracted SELI as supplier of the equipment and to assist the Company for the excavation of the tunnel by TBM.

<Figure 1. Dense populated area – view from site installation>

GEOLOGY DESCRIPTION

The area interested by the Metro Line 4 Project, see figure 1.A, is characterized by four different geological formations:

- Gneiss rock basement
- Tertiary sediments characteristics of Sao Paulo region
- Quaternary alluvial deposits
- Filling basement material

More specifically the TBM has operated in three different geological formations:

- Soil derived from the alteration of gneiss of the basement encountered in a limited area of the Faria Lima region
- Soil of the Resende formation characterized by high to medium plasticity, clay and sandy layers inter-bedded, incorporating gravel
- Soil of the Sao Paulo formation characterized by intercalation of red clay layers having medium to hard consistency and red fine to coarse sand layers

<Figure 1.A Geological profile Sao Paulo Metro Line 4 – Lot 1>

Soil Conditioning

As it is well know to TBM EPB operators, a good soil conditioning is of outmost importance in the operation of the TBM, either to easily muck out the excavated material and to maintain homogeneous EPB pressure in the tunnel face.

For the Sao Paulo project two special foams have been developed in the Innotek factory, in Italy, according to the specific geology to be encountered.
The first one, Inntens TK70, have been used in sandy grounds, while the second Inntens TK57 have been used where saturated clay were predominant.

During the excavation, the conditioning parameters, FER, FIR and conditioning agent concentration, have been modified according to the characteristics of the materials being excavated, in particular to their plasticity and fineness modulus.

<Figure 2. Conditioned muck at disposal area>

Equipment Description

The execution of the Metro tunnel must avoid interfering with existing transportation system in order to minimize the risk of paralyzing the city. More specifically surface settlements and distortion have to be minimized. Therefore the choice of the excavation system has been oriented to an EPB TBM and the related simultaneous backfilling system to the bi-component cement grout.

The TBM selected is the Herrenknecht S-336 EPB, sizing 9,5 m diameter.
The backup and all the relevant auxiliary equipment are SELI.

The bi-component grouting system is composed by six eccentric screw pumps having a capacity of 200l/min each to supply grout liquid A to the tailskin injection ports and six eccentric screw pumps each with capacity of 20 l/min to supply the accelerator (liquid B) to the tailskin injection port. All pumps are feed through FVD.

The grout system can operate in manual, semi automatic or fully automatic mode, setting all relevant parameters on a touch screen panel.
A dedicated PLC, receiving the input commands from the grouting operator panel and the back feed information from the flow meters and the pressure transducers, installed on each grouting lines, ensure that the system works according to the values set.

The grout is blended at the portal area by an automatic batching plant.

The component A and B of the grout are pumped from the portal area to the respective tanks on board of the TBM backup through 1.1/4" and 1" pipe respectively. A maximum distance of 3,5 km have been reached with a pressure of 80 bar measured at the portal.

Work Execution

To avoid surface settlements or heave, during the TBM advancing, reference EPB and grout injection pressure have to be strictly followed.

For the EPB pressure, two reference values have to be provided by the designer for the whole tunnel length:

- Ground stability pressure
- Minimum ground deformation pressure

The first value ensures the stability of the tunnel face and the second has the goal of minimize the deformations of the ground before and after the TBM approaches the specific location.

While the first point is the most important in terms of safety of the people leaving in the buildings on the surface and the users of all surface and underground structure, is the second point the most interesting in terms of fine tuning of the TBM.

The TBM has seven EPB sensors distributed at various heights inside the working chamber.

Playing with the screw conveyor, the advance speed, and the flux of soil conditioning agents, the TBM operator has to keep the pressure on sensor no.1 (the top one) as close as possible to the reference pressure. Moreover, he has to ensure that the distribution of pressure inside the working chamber is rising with the depth with a gamma factor ranging in between 1,2 and 1,4 ton/m^3.

The grouting pressure is a consequence of the EPB pressure. To ensure that the grout will fill completely the cavity behind the rings, a pressure slightly higher than the EPB pressure has to be applied.

Since this pressure is read at some distance from the delivery point, this concept has to be interpreted by the operator of the TBM according to the specific grouting system adopted. The reason is that grouting pressure reading may suffer other influences apart from the EPB pressure at the TBM working chamber, such as: grout flow (depending to the TBM advance speed); grout line length, section and obstruction; grout viscosity etc.

The TBM Manager, the Monitoring Manager and the Design Engineer have to continuously share all the information in order to optimize the EPB and grout pressure to be applied so to minimize the final ground distortion.
For the Sao Paulo Metro Line 4 Lot 1, the TBM parameters have been supplied by the Company Figueredo Ferraz. Latina Company is in charge of the monitoring, while SELI manages the TBM excavation.

Ground stability pressure at the tunnel face has been calculated following the method suggested by Anagnoustou and Kovari (1996) at each 50 m, starting from the information available at the beginning of the project such as geological description, water table level and surface loads.

The foreseen ground deformation has been calculated starting from the methods suggested by Peck (1969). Peck method has been chosen due to its simplicity that allows a rapid and simple evaluation of the settlements in a continuous form all along the tunnel alignment. With the retro-analysis of the residual settlements behind the TBM shield, the method is continuously re-calibrated for the evaluation of the future distortion while the TBM advances in different geology.

Back feed From Monitoring

While TBM advances in ground a huge amount of information is stored by the computer connected to the TBM PLC.
Some of this information has to be re-interpreted with the support of the back feed of the surface monitoring to optimize the EPB operations.

To be able to do this work in real time we create a figure in the job site, the ATO or Site Technical Assistant. The ATO receives all the information from the TBM and the monitoring and makes the first screaming, 24 hr per day.

As soon as the ATO detects a deviation from the normal behavior of the TBM or monitoring parameters or a deviation from the designed parameters, he informs immediately the TBM Manager.

The TBM Manager will immediately take the pr-established actions to bring the situation inside the normal range of work (e.g. lifting up EPB and/or grouting pressure). If these actions will not succeed then the TBM

Manager contacts the Designer that will recalculate the proper pressures and foreseen settlements on the base of the new information available.

Hyperbaric Activities

As well as reference pressure, need for the tunnel excavation, the Designer supplies the relative reference pressure for hyperbaric activity.
Hyperbaric operations are needed in order to check the cutter head conditions and to carry out the maintenance of the cutting tools.

SELI's policy is to keep continuously under control the cutter head condition. For this reason a very rigid plan of programmed maintenance has been installed. This plan foresees two hyperbaric interventions per week to control the CH conditions.

Programmed hyperbaric interventions where carried out usually every Tuesday and Friday.
Dates may vary according to the geological ground conditions of the particular location or closeness to dangerous structures, such as tunnels, high buildings or deep foundations.

Up to date 63 hyperbaric interventions have been carried out with pressure ranging in between 0,8 and 2,5 bar.

Thanks to this plan we were able to keep the cutter head in perfect conditions reducing to zero any time lost associated to CH wearing. We believe that the exceptional performance achieved by our TBM (such as 80 mm/min advance speed) have been reached also thanks to the strict plan of CH maintenance.

Monitoring Instrumentation

The instrumentation chosen for the monitoring of the ground response to the TBM advance, have been the most simple and with faster reply as possible for an urban environment such as Sao Paulo city.

Therefore such instrumentation consists in:

- Ground marker
- Tassometers
- Convergence anchoring pin and levelling
- Clinometers
- Inclinometer
- Piezometers

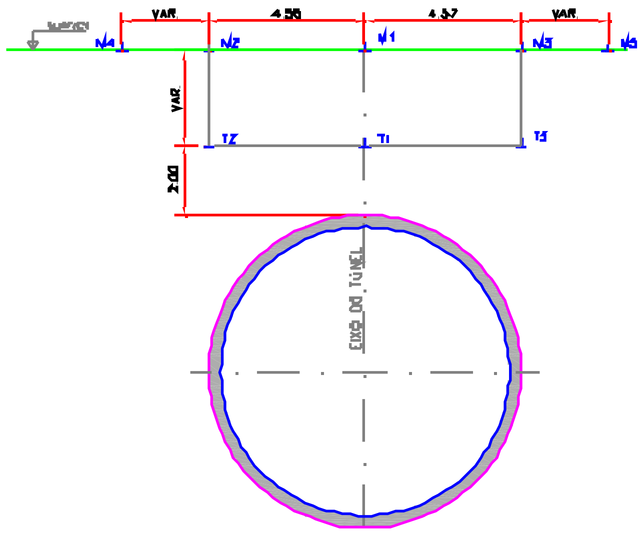
Monitoring sections have been located at each 25 m of the tunnel alignment, for a total number of 200 sections.

Four different sections have been prepared, called type A, B, C and D.

Sections type A and B are used to monitor the ground as well the aerial and underground structure. Sections type C and D are used to monitor the ground behaviour only.

Sections A, B and C give information of the average behaviour of the ground all along the tunnel length. Section D is applied in the critic zones where a more detailed monitoring campaign is recommended.

Section A consists of five Ground Markers M (see fig.1), three Tassometers T and four Convergence Pins P; B consists of three M, one T, and four P; C consists of three M and finally sections D consists of two T only.



<Figure 3. Section type A>

Frequency Of Readings

Sections type A, B and C frequency of reading is shown in the following diagram no.1. The point "zero" represents the position of the TBM cutter head and the other numbers represents the distance in meters ahead and behind the TBM.
Different frequency may be applied according to the needs of special situations such as detected ground movement, proximity of infrastructure or buildings etc.

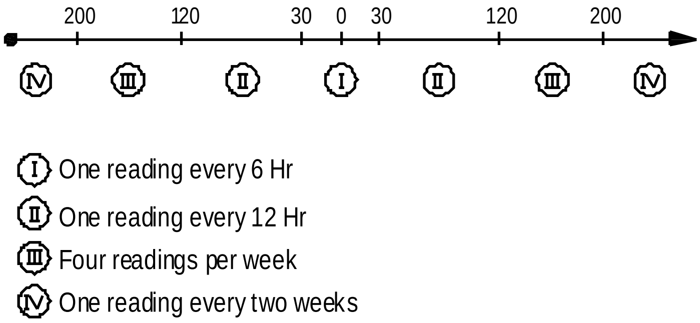


Diagram 1 - Frequency of reading for section type A, B, C

Section type D frequency of reading is shown in the following diagram no.2.

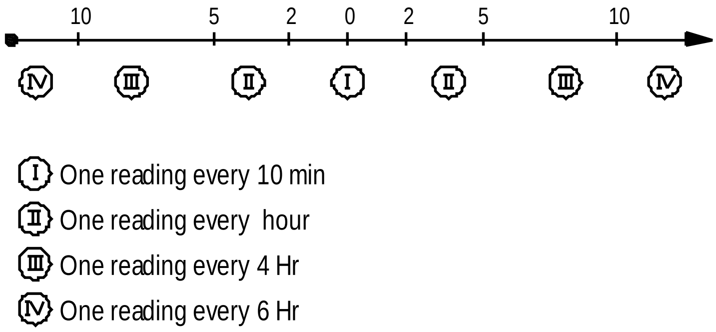


Diagram 2 - Frequency of reading for section type D

Alert Levels

Four reference levels of alert have been set according to settlement detected by the surface monitoring.
At each level different pre-established interventions have to be followed until the situation is considered under control again. The interventions going from lifting up, step by step, the EPB and grouting pressure (without stopping the mining activities) to a more drastic solutions such as stoppage of the excavation and post grouting or soil consolidation interventions.

At the beginning of the project an average settlement corresponding to a lost of ground volume ranging in between 0,3 and 0,7% have been considered absolutely acceptable.

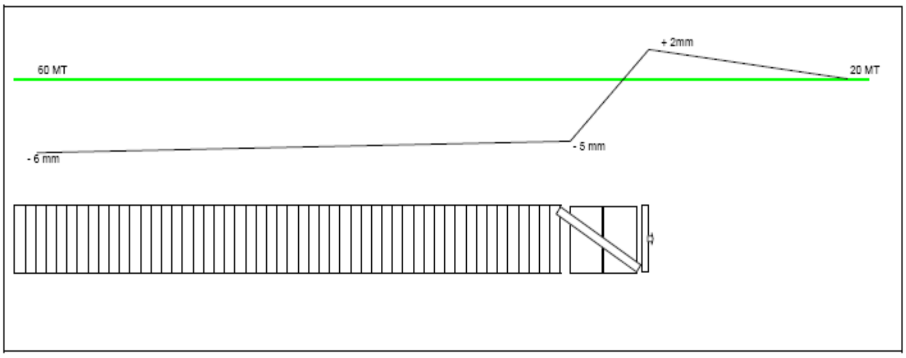
It is clear that depending on the local geology, water table level, and tunnel coverage, different settlements may occur for a same value of volume lost.

First level of alert corresponds to settlements induced by a volume lost higher than 0,7%.
Second, third and fourth level correspond respectively to volume lost of 1%, 1,5% and 2,5%.

At the present stage of the work average settlements corresponding to 0,17% of volume lost have been recorded. Average settlement is 6 mm while average distortion is 1:1700.

The normal behaviour of the ground observed while the TBM passes through a monitoring section has been as follows. Starting from 20 m ahead of the TBM cutter head, the soil starts to lift few decimals of mm. Once the forward shield reaches the monitoring section is recorded the faster settlement which occurs until the tail skin after reaches the same section. At that point settlement tends to stabilize, see figure 4.

A completed stabilization of the settlements is reached about 60 m behind the cutter head position, two or three days after the TBM passed below the specific section.



<Figure 4. Surface ground movement while TBM approaches a monitoring section.>

Bi-component grouting system

The complete and effective filling of the annular gap is of utmost importance in EBP tunnel excavation.

The complete annular gap filling mitigates the tunnel excavation induced settlement and is also the mechanism whereby ground and other loads are applied in controlled mode to the tunnel lining. The continuous backfilling provides an impermeable membrane all around the tunnel lining that, jointly with segment gaskets, enhances waterproofing of the tunnel.

Simultaneous two component backfilling grouting, abbreviation 2CBG, from injection pipes located on the TBM tailskin, has great effectiveness.
This system uses two different liquids: liquid A composed by cement, bentonite, water, and retarder; and liquid B or liquid sodium silicate.

Few seconds after mixing the two liquid components, a semi-solid jelly consistency material, in plastic state, is formed. The cement grout keeps this jelly state for about half an hour, then start hardening and reaches 0,05 – 0,1 Mpa in one hour. The strength at this stage depends on cement and sodium silicate dosage.

Grouting pressure starts acting on the extrados of lining immediately after the passage of the tail shield. Thanks to the liquid/plastic state of the grout mixture the grouting pressure distribution becomes quickly uniform moving away to the grouting ports.

After hardening, the grout holds the earth pressure and the ground water pressure, and conveys the load to the tunnel lining.

Comparison Between The Mortar Backfilling And Two Component Backfilling Grouting

For many years, in Europe, where EPB TBMs were used, traditional mortar cement has been adopted. Even if there is no doubt that traditional mortar can fulfil its task, we consider that 2CBG bring more vantages.

Below are listed some of them compared to traditional mortar.

The mortar backfilling grout requires 4 to 5 hours to set and takes long time, 12 to 24 hours, to achieve a compressive strength between 0,05 and 0,1MPa. During this time, the grout can be washed away by groundwater. Meantime the precast lining floats inside the mortar grout and it can easily lower especially in permeable soil above the water table.

The 2CBG take 6 to 12sec to gel and approximately 1hour to harden reaching up to 0,05 to 0,1MPa; the gel time can be chemically varied directly onboard the TBM, changing the percentage of silicate injected. The gelled material gives an immediate support to precast lining avoiding sinking or floating of the ring, also in impermeable ground.

Traditional mortar requires a sophisticated batching plant for its preparation, heavy wagons for the transport, and a double system of pumps to transfer the mortar from the wagon to the storage tank and from the tank to the tail skin.
The mortar easily clogs the pipes of the tail skin, so the lines have to be cleaned frequently.
It loses its workability easily even using chemically retarded, especially during prolonged excavation stops, therefore it cannot be kept inside the storage tank for long time.

The 2CBG system requires a very easy colloidal mixing plant for the component A only. The two components are transferred separately directly from the external plant to the storage tank onboard the TBM through two dedicated pipelines.
The cement/bentonite slurry is injected inside the annular gap by six screw pumps assembled under the storage thank, the accelerator is added to component A by six screw pumps as well.
The component A doesn't clog easily the lines and the pipes are easy to be cleaned by water.
The cement slurry is chemically retarded and can be kept inside the storage thank for more than 8hours without sedimentation.

Pressure control of traditional mortar grout is very difficult to be carried out, since pistons pumps always make pecks of pressure while pumping. With 2CBG the flow is absolutely constant and so the pressure read at the pressure transducers.

Using the traditional mortar grout is difficult to control the ground volume lost due to TBM advance, while with the 2CBG, in the Sao Paulo Metro Line 4 Project, the average ground volume lost has been kept lower than 0,4%.

Choosing The Back Filling Grouting System

After the experience had in Vancouver Metro Project and the good results obtained in terms of filling ratio, residual settlements and ground volume lost, SELI proposed to replace the traditional mortar backfilling system with two component backfilling grout system for the Sao Paulo Metro Line 4 Project.

In Sao Paulo the 2CBG system looked even more appropriate to be applied due the local geological formations, the presence of a watertable constantly above the tunnel crown, the overburden and the importance of the structures along the project and, consequently, the low residual settlements and distortions to be maintained during the whole TBM progress.

Some times technical choices, such as this one, are in conflict with project budgets.
Actually, after laboratory trials and the search of the proper materials on the local market, we came to a grout materials prize higher than the traditional mortar. But grouting costs is not only to be considered as material costs. Comparing equipment costs and more specifically TBM excavation time lost, due to grout lines clogging, of two precedent SELI's Projects (Athens Attilko Metro and Vancouver Projects), we find out that the 2CBG is far better than traditional mortar grouting even in terms of final project cost.

The use of this type of grout provides greater flexibility to the TBM operator. Varying the ratio of two components A:B, the setting time of the grout can be varied directly onboard the TBM giving to the operator the possibility to control how the grout material will penetrate the annular gap and the ground.

Grouting Process

As we said the effectiveness of 2CBG system, filling the ring annulus void, is higher than using the traditional mortar grouting method as the shorter setting time of the first helps to minimize the lost of grout diluted or segregated by the ground water.

The ring annulus void is grouted through injection ports located at the end of the TBM tailskin perimeter using constant pressure grout injection.
On our TBM there are six available injection ports in total, and during the regular mining process all the ports are used.

The injection of component A starts with the beginning of the TBM advance cycle. The retarded grout (liquid A) is pumped via the 2'' line from the storage tank, onboard the backup, to the TBM tailskin.

Following a minimal delay (e.g. 10 seconds time) the accelerator (liquid B) is pumped via the 1”, reduced to 3/8”, line to the injection nozzle. The accelerator flows through separate hose contained in the elliptical shape pipe of the component A in the tailskin. At the end of liquid B hose is located the injection nozzle. It is only at that point, located at the tailskin far end that the accelerator and retarded grout get in contact mixing together forming the gel.

2CBG Specification

The 2 component backfilling grouting performances haven't been standardized yet. According to the experience held in other projects we have been able to fix some characteristics and parameters that we want to be respected for the fresh component A and the gelled grout. The sodium silicate characteristics vary according to the gel time required the final compressive strength, the pumping distance and the material available locally.

The component A has been designed to match the following characteristics:

- Efficient flow ability
- Early generation of strength
- Waterproofing
- Resistance to segregation
- Ability to be transported (pumped) at long distance
- Resistance to dilution by groundwater
- Very low volume reduction

The following values have been considered crucial to be achieved for the correct backfilling grouting:

- Marsh viscosity > 35sec <45sec
- Lost of viscosity after 4h < 0,5%
- Bleeding:
  - After 1h < 0,5%
  - After 2h < 1%
  - After 24h < 4%
- Initial setting time > 24h
- Gel time > 6sec <12sec
- Sodium silicate dosage > 6% calculated on the mix weight
- Compressive strength:
  - After 1h > 0,1Mpa
  - After 24h > 0,5Mpa
  - After 28days > 2,5Mpa

Mix Design For Component A And Accelerator Characteristics

The mixture of the tixotropic gel grout has been designed for the characteristics above mentioned using cement, bentonite, liquid retarder and sodium silicate all available on the local market.

Cement. Different classes and types of cement have been tested with particular interest in finding the best solution in terms of gel time, early and late compressive strength, sodium silicate consumption and, of course, prize. Cement type V ARI RS from Votoran has been chosen; this cement is an early strength sulphate resistant Portland cement.

Bentonite. Scope of the bentonite is to stabilize the slurry, reducing the bleeding, and increasing the viscosity. Therefore drilling grade bentonite (following the API specification 13/A – ISO 13500) has been added in the component A blend.

Liquid retarder. In order to extend the component A setting time a natural sugar solution has been added in the mix as retarder.

Water. Water from local artesian wells has been utilized.

<Figure 5. Component A after mixing>

Accelerator. To gel the component A, achieving the specifications previously indicated, we have tested many liquid sodium silicate accelerator.
When it is added to Liquid A, the sodium silicate quickly causes the jellification of the water content in the mixture A itself. The gelling time, that is the time needed to form the gel within the mixture A, depends on various factors, where the most important are: the cement type, the water/cement ratio, the amount and type of silicate used and the humidity
and temperature of the environment.

For our mixture we found out that the proper sodium silicate has the following characteristics:

- Density @ 20°c, 38° Baumè
- Viscosity @ 20°c 40 Cp
- Content of solid 34,4%
- SiO_2/Na_2O ratio 3,22

- @20°c 1,355 t/m^3

Trial Mix Test Results

The tests performed in laboratory are not standardized yet and they are empirical but at the same time are very practical and give the idea of what happen inside the annular gap when the 2CBG is injected.

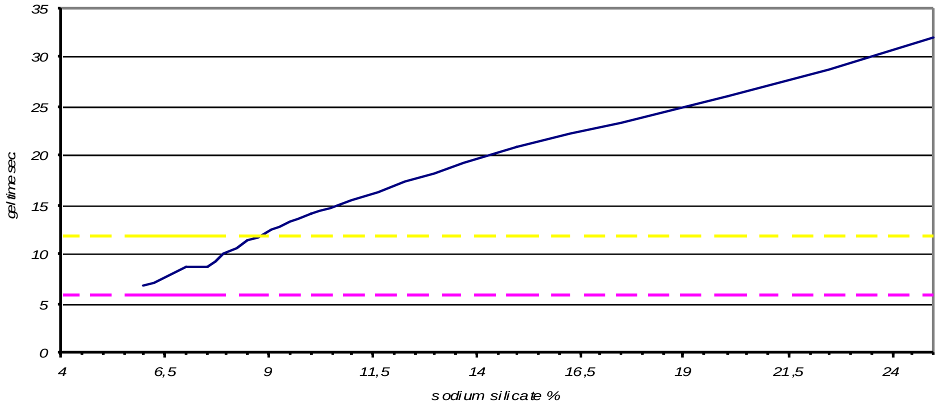
Here below are reported the results obtained using the materials adopted for the component A of the Sao Paulo Metro Line 4 Project:

- Marsh viscosity - viscosity of component A, measured @ 20°c with Marsh cone having an opening of 4,76mm, range between 38 and 40sec
- Bleeding - bleeding measured in the laboratory, using a 250cc glass cylinder, gave the following results:
  - After 1h is none
  - After 2h < 1%
  - After 24h < 4%

<Figure 6. Component A bleeding after 24h>

- Setting time - no component A setting has been measured in 24h
- Gelling time - the gelling time has been determined just mixing the component A with component B, sodium silicate, by two plastic glasses. The procedure has been repeated with different accelerator percentage until the specified gelling time has been achieved, see diagram 3. Eight to nine seconds

gelling time have been reached adding 7% of sodium silicate to the component A.



<Diagram 3. Grout gel time vs percentage of sodium silicate..>

<Figure 7. Component A gelled in the glass during the mixing>

<Figure 8. Component A gelled>

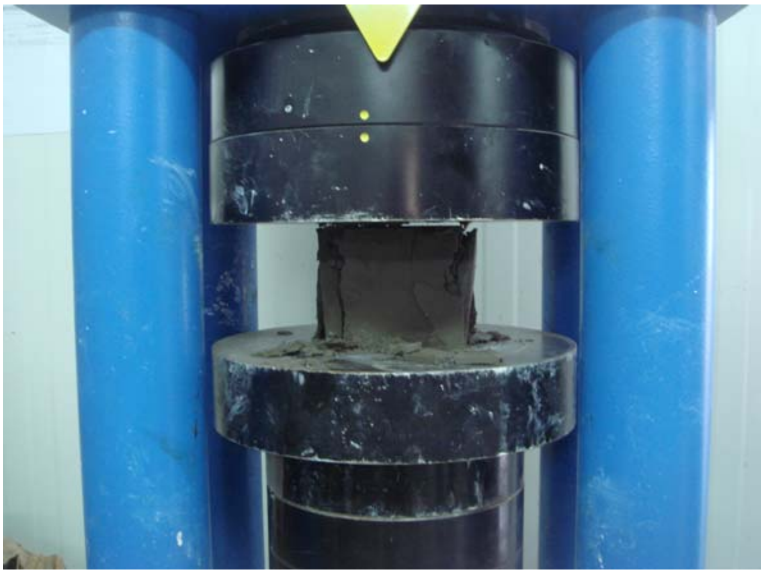
- Compressive strength - due to the difficulty to measure the compressive strength of the jelly material and to the lack of specifications, we have utilized a no-standard method that is empirical but effective. In order to be able to measure a compressive strength of 0,1Mpa, we have modified the Vicat apparatus applying on the top of it a weight able to exercise directly on the consistency plunger and consequently on the component A being hardened, a pressure equivalent to $1kg/cm^2$. 0,1 Mpa compressive strength is achieved when the Vicat consistency plunger doesn't penetrate the sample as shown in the photos.

<Figure 9. Modified Vicat apparatus>

<Figure 10. 0,1 Mpa compressive strength is achieved>

<Figure 11. 2CBG hardened removed from the glasses>

To verify the compressive strength after 2 Hr and 28 days, cubic samples, 100x100x100mm, have been prepared and cured at 20°c and >90% humidity.



<Figure 12. 28 days compressive strength>

Summarizing, the required compressive strength values have been achieved adding to the component A 7% of 38° Baumè sodium silicate in weight.

Following are listed the compressive strength obtained:

- after 1h		> 0,1Mpa
- after 2h		0,7Mpa
- after 28days		3,8Mpa

<Figure 13. Hardened backfilling cores>

Two Component Batching And Delivering Plant

Component liquid A of the grout is batched on the surface in the dedicated mixing plant designed by SELI and fabricated by Innotek Italia.

<Figure 14. Component A turbomixer>

<Figure 15. Component A agitator>

The component A is pumped by duplex pump into a tank onboard the TBM backup gantry, through a dedicated 1.1/4” pipeline installed along the entire tunnel length.

<Figure 16. Pumping station for component A>

The sodium silicate (accelerator liquid B) is stored on the surface (as well onboard the TBM) and pumped by single stroke vertical pump inside the tunnel to the TBM backup gantry through a dedicate 1” pipeline installed along the tunnel. Two more pipelines 1.1/4” and 1” are installed as spare.

<Figure 17. Component B – sodium silicate – pumping station>

The two components are mixed together only at the six injection ports in the tailskin of the TBM.

<Figure 18. Component A and B grouting line plus flushing port>

CONCLUSION

SELI Company have been contracted by CVA (Consorcio Via Amarela) Joint Venture to supply and manage a 9,5 m diameter EPB for the excavation of Lot 1 of the Sao Paulo Metro Line 4 Project.
An extensive monitoring system both for the TBM parameters and for the ground distortion has been implemented.
Due to the restriction of settlements imposed by the particular urban environment such as the city of Sao Paulo, SELI decided to install onboard the TBM the two component back filling grouting system.
The system, already tested in previous projects run by SELI, results much better in terms of final soil volume lost and so in terms of residual settlements.
Thanks to the rapid share of information coming from the TBM and the back feed of the monitoring, the site personnel could quickly take all the proper actions to maintain the final ground settlements and distortion inside the foreseen limits.