

Raising EPB Performance in Metro-Sized Machines

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ABSTRACT: Singapore is employing more than 29 earth pressure balance machines (EPBMs) to excavate a single 21 km metro line, Downtown Line 3. Moscow is adding 50 km of new metro line by 2016, 150 km by 2020. China will expand their metro lines tenfold by 2050 to more than 11,700 km. China's plans for the next two years require 250 EPBMs. With such extensive global metro expansion plans, increasing EPBM performance would have a monumentally positive economic impact, with tunnels being excavated in less time and at lower cost. EPBMs on several projects have recently set performance records. In this paper, the authors examine these and other projects, searching for clues as to why some EPBMs perform at higher rates than others and attempt to determine which causes are in the control of contractors, which in control of the machine designers and how one might replicate high performance on future projects.

1 INTRODUCTION

Labor cost is a large part of tunnel construction cost and it is substantially reduced when a project is completed faster. Other costs are also reduced when a project can be completed faster (i.e. land and office leasing, overheads, etc.) For the purposes of this paper, we have defined the "average weekly advance rate" as the measure of performance by which we judge the success of a project. We reviewed data from many projects, looking for the causes for "high" performance, and high average weekly advance rates.

This paper is based on the data gleaned from 46 EPB projects around the world. The complete source data cannot be made available publicly. Contractors, consultants, and machine manufacturers are protective of this knowledge because the knowledge is hard earned and valuable for the holder for the purposes of estimating future costs for project tendering, and for the successful excavation of future tunnels. In short, the knowledge which yields consistently high EPB advance rates is the tightly held, confidential, intellectual property

of the successful contractor. In the course of researching this paper, most of the contractors who were willing to share detailed information regarding specific projects including the production rates across all manufacturers' machines, EPBM specifications, geology and ground conditioning details, etc., did so only under condition that the specific details given to us not be revealed to third parties, including the names of the projects. They were willing to share their intellectual property only in order to see the results of this study, namely: are there any clear precursors which predict a successful high speed EPB project?

Unfortunately, not every one of the 46 projects studied would answer 100% of our questions, even with our agreeing to non-disclosure of those details. Therefore, the paper we are able to deliver at this time relied on a somewhat incomplete data set. Where possible, we also sought data from publicly available sources (i.e. industry periodicals and conference papers, etc.) The result is that some of the conclusions drawn are of a more general, indicative nature than the precise statistical

analysis that we had hoped to produce in all cases. Still, some clear conclusions can be drawn from the data. In some cases we will simply offer our opinions as to why some EPB's perform better than others, based on our knowledge, experience and communications with others.

2 THE PROJECTS AND THE TBMS

The 46 TBMs for which we reviewed performance (average weekly excavation in meters) were located in 11 different countries and worked on 22 different projects. 85% (39) of the TBMs were working on Metro tunnels, 2% (1) on a high speed rail tunnel, 11% (5) on sewer tunnels and 2% (1) on a gas pipeline tunnel. The geology on which the machines operated varies wildly from sedimentary rock, weathered rock through glacial till, gravel, sands, soils and clays. Ground pressure averaged approximately 3.8 bar with a single project operating, reportedly, at 13.5 bar. 28% (13) of the projects had ground pressure under 2 bar. 50% (23) of the projects reported ground pressures between 2 and 8 bar. 7 projects did not report the ground pressures encountered.

56% of the projects gave some information regarding ground conditioning employed. Several projects gave detailed information regarding ground conditioning, or that information is publicly available in articles published in industry periodicals and conferences. Unfortunately, no ground conditioning information was forthcoming or could be found in searches for nearly 40% of the projects. Given the apparent importance of this subject, and the currently fast growing knowledge on the subject of ground conditioning and its importance, it would be beneficial to have more details in this area for better statistical analysis of performance between machines employing state of the art ground conditioning and those that do not.

The TBMs were manufactured by three different manufacturers. The maximum diameter of machines reviewed is 6.95 m and the minimum is 5.90 m. With an average diameter of 6.34 these machines can be taken to be "typical" metro TBMs. 44% of the machines

cutterheads were powered by Variable Frequency Drive (VFD), while only 17% reported using hydraulic cutterhead drive with the balance not reporting the type of cutterhead drive. However, the authors having generally good industry knowledge regarding prevalence of drive type by manufacturer, estimate that probably just over half the machines have VFD cutterhead drive and the balance are driven hydraulically.

3 OBSERVATIONS

With 100% of the projects reporting their average weekly production based on 2 x 12 hour shifts, 7 days per week, many of which could be verified through secondary sources, following is the summary of the average TBM weekly advance:

- Maximum: 184.8 m/week average
- Minimum: 33.7 m/week average
- Average: 85.5 m/week average
- Standard Deviation: 36.0 m/week average

We sorted the data several different ways looking for trends which would reveal why the EPBMs on certain projects performed much better than others. For example, we sorted the data by the following criteria and looked at each for correlation to the advance rate data:

- Machine diameter
- Cutterhead drive type (electric and hydraulic)
- Face pressure
- Tunnel length
- Country of project, and developed / developing nations

Relative to each of these criteria there appeared to be very little to no correlation with EPBM performance. For example, two of the top ten performers were in Canada, however so were two of the bottom ten performers. The top ten performers were about equally divided between developing and developed countries. It's notable that the top performer in our

sample, at an average of 184.8 m per week, was on the Moscow Metro Line 3.

3.1 Face Pressure

Face pressure seemed to have no correlation and, in fact, four machines operating at high face pressure (6 to 8 bar) achieved average weekly advance rates of 120 to 179 m/week on the Abu Dhabi Strategic Tunnel Enhancement Program (STEP).

3.2 Contractor Experience

Contractor experience appears to have some correlation with TBM performance. All of the machines which achieved average weekly performance in excess of 100 m/week had previously excavated at minimum 3 to 5 EPB tunnels, with some of them having completed scores of previous EPB projects. The bottom 15 performers were all operated by contractors with little EPB experience, with one exception.

3.3 Conveyor Mucking Systems

Conveyor mucking systems were used on only 15% of the projects (7 of 46). One was in the bottom quartile of performers, at 58 m/week, two were mid-performers at 70 and 72 m/week, two above average at 95 and 112 m/week and one topped the list at 184.8 m/week. Conveyor systems can assist in setting the stage for high performance, though conveyors alone cannot assure it, which should not be a surprise to any of our knowledgeable readers.

3.4 Ground Conditioning

From our analysis the factor most closely correlating to high performance is ground conditioning; the establishment of a ground conditioning plan for the specific project based on actual geological sample testing in coordination with the contractor, the EBM manufacturer and the ground conditioning chemical supplier. Planning for and executing a good ground conditioning regime with quality chemicals dispensed from properly designed systems on an EPBM is essential (see Figure 1).

Seven of the top ten performers used ground conditioning (GC) additives. Six of the top ten performers used GC agents, sourced them from experienced industry suppliers and used the services of those GC suppliers to specify the initial ground treatment regime before starting the TBM and later to adjust the GC regime for best performance. The contractor, GC supplier and EPB manufacturers also planned in advance together, to insure the EPBMs were properly fitted out for proper production and injection of GC agents.



Figure 1. EPB machine with severely clogged cutterhead in adhesive soil.

4 THE IMPORTANCE OF GROUND CONDITIONING

The correlation between high performance and execution of proper ground conditioning regime should not be a surprise to those who have been directly involved in EPB operations over the past decades. See Figure 2, a 1996 recommendation on the use of additives for EPBs from the Japanese Society of Civil Engineers. We have seen GC agents expand the range of geology in which EPBs can be successfully employed, from very adhesive clays to the other extreme of very coarse gravels under the water table, terrain which was formerly the sole domain of slurry machines.

Shield type		EPBM			Slurry
Soil Type		SPT N	Without Additives	With Additives	
Alluvial Cohesive Sand	Silt and Clay	0 - 2	Y	Y	Y
	Sandy Silt, Sandy Clay	0 - 5	Y	Y	Y
Pleistocene cohesive soil	Loam and Clay	5 - 10	Y	Y	Y
	Sandy loam, sandy clay	10 - 20	N	Y	Y
		15 - 25	N	Y	Y
Sandy Soil	over 25	N	Y	Y	
	Sand with silty clay	10 - 15	Y	Y	Y
	Loose sandy soil	10 - 30	N	Y	Y
	Consolidated sand	over 30	N	Y	Y
Gravel with Boulders	Loose gravel	10 - 40	N	Y	Y
	Consolidated gravel	over 40	N	Y	Y
	Gravel with boulders	N/A	N	Y	N
	Boulder gravel, boulders	N/A	N	N	N

Figure 2. Table from Japanese Society of Civil Engineers (1996) with recommendations regarding use of additives for EPB applications.

Soil states range in consistency from solid and semi-solid to plastic and liquid. Obviously, EPB machines are not capable of efficiently, economically and safely excavating materials at the extremes of these states, especially so when under the water table. It is therefore necessary to treat the soil in order to transform the soil into material which can be efficiently excavated.

4.1 GC guidelines to get started

A good place to start an understanding of the basics of ground conditioning is the “Specifications and Guidelines for the use of specialist products for Mechanised Tunnelling” published in 2001 by EFNARC, the European federation focused on specialist construction chemicals and concrete systems. In 2005 the document was updated to include hard rock TBMs as well. EFNARC engages with the European Commission and technical committees as well as other groups participating in the European Harmonization of Specifications and Standards. We recommend the EFNARC document to our readers for its considerable valuable information (see Figure 3).

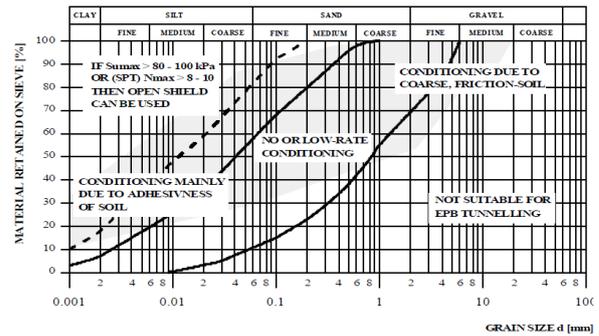


Figure 3. EFNARC guideline for particle size distribution in which EPB can be employed and soil conditioning needs in different ground types (Boundaries are only indicative), EFNARC, 2005.

EFNARC suggests there are three primary types of foam ground conditioners (see Figure 4):

- Type A: High dispersing capacity (breaking clay bonds) and / or coating capacity (reduce swelling effects)
- Type B: General purpose with medium stability
- Type C: High Stability and anti-segregation properties to develop and maintain a cohesive soil as impermeable as possible

Tender documents for most metro projects include a comprehensive Geotechnical Baseline Report (GBR). The GBR typically will contain a general description of the geology, photographs of samples, rock types and strengths, ground water information, particle size distribution analysis, moisture content of clays, permeability, etc. With the GBR in hand, the EFNARC guidelines relating to soil conditioning are an excellent starting point. In discussions with GC suppliers, a tendering contractor with the GBR should be able to arrive at an initial plan for GC chemicals and the associated cost. Additionally, the contractor with the GC supplier can coordinate with the prospective EPBM manufacturer to insure that the EPBM is fitted with GC delivery systems that meet the requirements of the GC plan.

Soil	Foam types			FIR	Polymer additives
	A	B	C		
Clay	↑			30-80	Anti clogging polymer
Sandy clay – silt	↓	↑		40-60	Anti clogging polymer
Sand – clayey silt		↓		20-40	Polymer for consistency control
Sand			↓	30-40	Polymer for cohesiveness and consistency control
Clayey sands			↑	25-50	Polymer for cohesiveness and consistency control
Sandy sands			↓	30-60	Polymer for cohesiveness and consistency control

Figure 4. EFNARC guidelines for product types, foam and polymer, relative to different soils (FIR values are indicative only), EFNARC, 2005

In addition to information in the contract documents, it is recommended to take things a step further, with testing in the laboratory.

4.2 Specialist, EPB GC laboratory testing

Today there are a growing number of laboratories, in private companies and at universities, which can perform a number of tests aimed specifically at defining a ground conditioning regime for an EPB project. Typically, these laboratories mix actual soil samples from the job site, at their in situ moisture content, with various foams and polymers and then test the treated samples (see Figure 5). One such simple test is a slump test, such as is typically performed on wet concrete to determine its workability. (This test can also be done on the job site, if the correct equipment is made available at the site). As written in the paper Characterization of Soil Conditioning for Mechanized Tunneling: "...the carried out tests show that the slump test is a good indicator to define the global behavior of a conditioned soil and due to its simplicity, can be used in the preliminary design stage but in particular on the job site to keep the conditioning development under control during excavation." (Borio 2007).



Figure 5. Testing fixture. Treated sample is placed in barrel on left and subjected to pressure and extracted from barrel through screw conveyor on right. (Photo courtesy of Mapei-UTT)

The results of such tests can give a very good indication for the starting point for soil conditioning additives at the beginning of a project, including the foam and polymer types recommended along with:

- **Cf** – the concentration of foam product in water, which can be measured either as percent volume (1986 Japanese standard) or percent weight (EFNARC). This value varies anywhere from 0.1 to 8%, and it is dependent upon the ground conditions and the specific foam product selected.
- **FER** – the Foam Expansion Ratio. Values are typically 6 to 18, being expressed as the ratio of air to foam, where 18 is 17 parts air and 1 part foam/water solution.
- **FIR** – the Foam Injection Ratio. This is the ratio of foam injected into the cutting head and the in situ volume of soil being excavated. This is typically in the range of 10 to 80% per EFNARC guidelines, but in the Japanese standard goes beyond 100% up to 130% foam/in situ soil volume. (The reader should bear in mind that the actual ratio of foam to soil in the chamber will be dependent upon the pressure in the chamber, as the air in the foam compresses under pressure.)
- **Cp** – the concentration of Polymer product in water, typically in the 0.1 to 2.0% range.

For foam/polymer solutions, this is between 0.3 and 10%

Some foam products are provided with polymers so that only the foam guidelines need be followed.

The wear tests provided by the laboratory will give the contractor an indication of the level of wear improvement offered by the foam and polymers recommended. While the test will not provide definitive numbers, it will give an indication. For example, if the wear test shows a reduction in wear of the test specimen of 25% due to the additives, then one can hope to see a proportional reduction in wear on the cutters, bits and cutterhead. Given the danger, time and cost of hyperbaric interventions, reduction in wear is one of the stronger motivations for having a properly planned GC regime.

5 EPBM DESIGN FOR GROUND CONDITIONING

It is imperative that the EPBM manufacturer is aware of the GC regime plan and that appropriate foam generators, polymer plant, air compressors and bentonite systems are included, as well as proper distribution and injection points on the cutterhead, in the cutting chamber and in the screw conveyor. These systems should be fully tested and accepted prior to boring. Results from the 46 projects reviewed and anecdotal evidence points to this being an area of coordination which is often overlooked and where a little effort early in the TBM design can result in vastly improved performance for the duration of a project.

A properly designed EPBM GC system requires input from the contractor and the GC additives supplier (see Figure 6). That being said, ground conditioning is not an exact science—variations and changes to the conditions can result in changes to the initial requirements. Thus having a plan for each anticipated soil group is important, as well as how changes will be implemented.



Figure 6. Silty Clay prior to and following GC treatment (Photo courtesy of Condat)

The project team must agree to the GC plan and insure that the EPBM design and GC equipment supply will fully support the GC plan. Some things which must be considered:

- Probable quantities of foam agent, polymers and bentonite (or other fine material) to be consumed, consumption rates and estimated TBM production rates.
- Package sizes to be used for each GC agent
- Logistics; movement and handling of GC agents / packages into and out of the tunnel
- Specification of the dosing units
- Specification of the foam generator
- Specification of dedicated air compressor
- Specification of bentonite plants
- Locations of the above systems on the TBM and backup
- Quantity and location of Foam injection nozzles (cutterhead and screw conveyor)
- Quantity and Location of Bentonite injection points (cutterhead, mixing chamber, screw, shield)
- Control systems for manual, semi-automatic and fully automatic control.
- Location of system adjustment controls and ability to “lockout” to prevent unauthorized adjustments
- Quantity and placement of additional water lines into mixing chamber

Regarding this last point, it is important to have the capability to inject water into the chamber in addition to GC agents. When the ground is too dry, it is far less expensive to use water to wet the soil, and then use the GC agents to condition the soil, than to use the GC agents alone.

In general, it is best to inject all GC agents from the cutterhead because this provides the best possibility for GC agents to flow with and become thoroughly mixed with the excavated material. However, there are times when it might be advantageous to inject GC agents into the mixing chamber. For example it is prudent to inject bentonite during a machine stoppage because foam will collapse, eventually leaving an air bubble in the top of the chamber and water in the bottom. Under certain conditions it might be necessary to inject directly into the screw conveyor to form a plug, or to reduce friction and torque at the screw conveyor. When designing the EPBM for GC use, it is important that the systems be designed for flexibility and with redundancy. A properly designed EPBM will offer the user opportunities to employ all of the GC agents (water, foam, polymers and bentonite) in any combination and at an array of injection points on the cutterhead, into the mixing chamber and into the screw conveyor. In addition, because of the danger and difficulty associated with effecting repairs beyond the pressure bulkhead, distribution line redundancy is advisable.

5.1 Cutterhead Foam Injection Ports

EPB cutterheads should be designed with certain port sizes and locations and minimum quantities. Figure 7 shows an example of additive injection port locations on a Ø6.6m EPB cutterhead. These injection ports should be capable of injecting foam, polymer, bentonite, or any mix of these and should be located with the first port as close to the center of the cutterhead as possible. Remaining ports should be located with decreased radial spacing as they near the outer periphery of the cutterhead. It is not necessary for the ports to reach the outermost radius of the cutterhead, this being the area of fastest motion and therefore best mixing. For “metro sized” cutterheads 6 to 7 m in diameter, a minimum of five injection ports is standard, with all piping having an internal diameter of about 40 mm (1.5 inches). For each injection port on EPB cutterheads, protection bits with tungsten carbide inserts and hard facing should be placed on both sides of the port

for protection in both directions of cutterhead rotation.

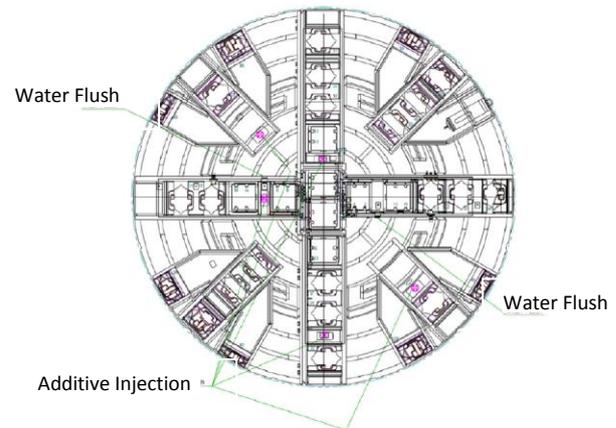


Figure 7. Ø6.6 meter EPB cutterhead with five additive injection ports shown in pink, and two water injection ports to prevent clogging

As EPB cutterheads get larger, more ports are of course needed. For example, in the Ø9m and Ø10m range EPB cutterheads, seven additive injection ports are used, with piping having an internal diameter of about 50 mm (2 inches).

It is advisable to fit the screw conveyor with a minimum of three 50 to 100mm (2 to 4 inch) diameter injection ports with one located as near the pressure bulkhead as possible and the others located along the conveyor. The pressure bulkhead should have a minimum of ten 50mm (2 inch) diameter injection ports with at least one located immediately each side of the screw conveyor intake and the remaining distributed roughly evenly around the bulkhead.

It should be noted that GC systems (Foam generators, polymer pumps, bentonite pumps and water lines) will not be connected to all of the ports fitted to the EPBM. There will be a substantial surplus of ports when the quantity is compared to the quantity of GC injection lines. What is important is, again, flexibility and redundancy so the contractor can make adjustments to the ground treatment as needed to achieve success based on actual results.

5.2 Operator's Station and Software

The operator's station for the EPBM, with the usual Human Machine Interface (HMI)

touch screens, typically has several screens dedicated to GC systems (see Figure 8). The foam system will generally have one screen for setup (to set Cf, FIR and FER) and one screen for operation where the operator can monitor status in automatic mode, or control the system in manual mode.

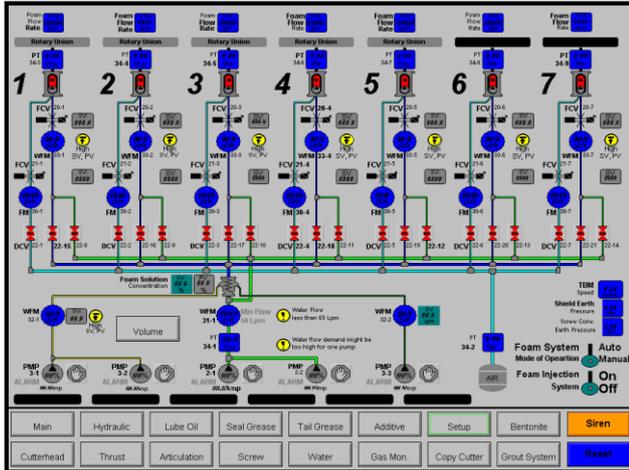


Figure 8. Main foam system screen on HMI screen (Photo courtesy of Robbins)

FIR, again, is the ratio of foam injected as a percent of the in situ volume of soil being excavated. Since the rate of volume of soil being excavated is dependent upon the EPBMs advance rate, the rate at which the foam is injected must vary with the EPB advance rate in order to maintain a constant FIR, that is, the same proportion of foam to soil at all times. This being the case, it is advantageous to operate in automatic mode in order to maintain a consistent state of soil conditioning.

Of course, there are similar options on the operator’s control screens for setting the parameters for polymer, Cp and FIR.

The HMI may have an additional screen which shows the total volumes of air, water, foam and polymers which have been injected over some period of time which can, of course, be reset.

The geology anticipated on a project effects the final design of a number of components of an EPBM; cutterhead, cutting tools, screw conveyor(s), ground conditioning systems, grout systems, etc. However, it is worth noting that if the contractor, the GC chemical supplier and TBM designers work together, the design of

cutterheads and conveyors can be positively impacted for improved TBM performance and reduced component wear (see Figure 9).



Figure 9. Well-conditioned clay leaving the screw conveyor onto the belt conveyor (photo courtesy of Mapei UTT)

6 CONCLUSIONS

It was our intention at the outset to attempt to derive some simple, high-level guidelines that if followed would provide the highest probability of an EPBM reaching the best possible performance in metro-sized tunnels. Following are those guidelines, some of which are simply common sense, known already by experienced EPBM users and some of which have been suggested by several other recent authors on the subject of ground conditioning:

1. **GEOLOGICAL SAMPLES:** Prior to tendering, the project owner should engage an experienced geological / hydrological testing firm to perform as many tests and obtain test samples from as many points as reasonably possible along the tunnel alignment, and if possible from the actual tunnel depth. Sufficient sample quantities should be obtained to provide the tendering contractors the possibility to perform laboratory testing on the samples prior to bid. If that is not possible, then the owner or their consultants should have such

laboratory testing performed, which can establish a baseline initial ground conditioning recommendation by one or several chemical suppliers. This will allow the tendering contractors to make adjustments in their commercial budgets and schedules for the improvement in performance they may reasonably expect to see on the project with the proper use of ground conditioning.

2. LABORATORY TESTING FOR GROUND CONDITIONING SPECIFICATION:

Should the owner not provide the contractors with laboratory test results of the geological sample testing, then the contractor would be well advised to have such tests carried out at their own expense in order to obtain a recommended ground conditioning regime from an experienced EPB chemicals supplier. The results of such tests will go far toward providing the best possibility of high performance on the project, as well as giving the tendering contractor much information regarding probable costs for ground conditioning agents.

3. EPBM DESIGN: Though ground conditioning is extremely important, it is equally important that the contractor and machine manufacturer review the probable geology, hydrology and face pressures of the project in detail and discuss the impact on the EPBM design, which might include:

- Dress of cutterhead: disc cutters, scrapers, picks, bits, etc.
- Opening ratio of cutterhead
- Type of screw conveyors: ribbon or shafted
- Quantity and length of screw conveyors
- Abrasion-resistant cladding requirements: cutterhead, mixing chamber, mixing bars, screw conveyor flights and casing, etc.
- Face pressure related design: pressure bulkhead, thrust ram sizing, articulation

ram sizing, tail shield seals, main bearing seals, man-lock and tool-lock, breathable air design, air compressors, etc.

- Ground conditioning foam, polymer and bentonite systems, air compressors, etc.

4. COORDINATION AND EQUIPMENT SPECIFICATION FOR GROUND CONDITIONING:

Early in the EPBM procurement / design phase, the contractor, chemical supplier and EPBM supplier should meet and discuss the results of the ground conditioning laboratory results. There should be agreement regarding the systems required on the EPBM to properly inject the agreed upon chemicals into the proper locations on the EPBM (e.g., cutterhead, pressure bulkhead / mixing chamber, screw conveyor points, etc.). There should be agreement on foam generation plant specifications, probable ranges for Cf, Cp, FER, FIR, and it should be ensured that those calculations for the sizing of plants (e.g., air compressors) consider the likely face pressures under which the EPBM will be working.

5. ON-SITE GROUND CONDITIONING TESTING:

The job site should have the ability to do on-site testing of ground conditioning agents in order to make adjustments throughout the tunnel drive without undue downtime for the machine. At minimum this should include:

- A laboratory scale foam generator
- A 5 liter heavy duty mixer with 3 speeds and standard paddles
- DIN flow table (30 cm table) with standard mortar cone (slump test)
- A graduated container of 1 or 2 liters capacity (plastic or non-breaking)
- Weighing balance accurate to 0.1 gram
- Stop watch
- Calibrated glass or clear plastic cylinder, with perforated base, 1 liter capacity

- Various calibrated plastic containers up to 2 liters
- A 50 ml graduated cylinder
- A filter – funnel of 1 liter capacity with non-absorbent filter

6. EPBM LAUNCH, GROUND CONDITIONING ADJUSTMENT & SITE LAB SETUP: At the start of boring, on the job site, there should be representatives from the chemical supplier and the EPBM supplier to work with the contractor to make any adjustments to the ground conditioning regime to obtain optimal EPBM performance. In addition, this time can be used to ensure that the ground conditioning testing that is done on site is done properly, including the training of personnel as may be required.

Ground conditioning, as the main factor explored here affecting advance rate, is the first line of influence for the contractor/additive supplier/equipment supplier to influence how material is excavated. The GC plan, implemented in front of the cutterhead, impacts the entire operation as the material must flow through the machine, out the heading, over the surface and off the site. It affects every part of the job from the number of tool changes required to the amount of cleanup in the heading and on the surface due to spillage. When this global impact of ground conditioning is taken into account, it makes good sense that advance rates are closely correlated. The authors believe that it is this overarching influence that makes a good GC plan, in combination with an EPBM properly designed for executing the plan, one of the most powerful tools available in achieving good project success.

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