

RESEARCH IN SOIL CONDITIONING FOR EPB TUNNELING THROUGH DIFFICULT SOILS

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ABSTRACT

The excavation of difficult soils by means of an Earth Pressure Balance Machine (EPBM) creates the potential for a reduced advance rate and increased downtime. EPBMs typically use soil conditioning to modify soil behavior to reduce abrasion, reduce cutterhead torque, control water, and ensure control of the spoil passing through the screw conveyor. Recent research is presented concerning two difficult soils for EPBM tunneling, which are sticky soils and coarse grained soils with low fines content. Soil conditioning tests were performed on several samples of difficult soils, which provide insight into how different polymers and additives can modify soil behavior to improve the performance of EPBM mining. During testing, the use of high density slurry to augment soils with low fines content was investigated. Results of investigation and a review of available literature is presented to help predict the potential for machine clogging and to help select useful soil conditioning agents in soils with low fines.

INTRODUCTION

The use of soil conditioning agents may be necessary in EPBM tunneling to modify soil behavior to control face pressure while excavating, to reduce abrasion, reduce cutterhead torque, control water, and ensure control of the spoil passing through the screw conveyor. The most difficult soils are those with an insufficient content of fine-grained material or those that clog the EPBM.

Samples of difficult soils from the Silicon Valley Rapid Transit (SVRT) project in San José, California, and from the North Dorchester Bay Tunnel (NDBT) project in Boston, Massachusetts, were tested in BASF laboratories in Cleveland, Ohio. The methods of identifying the difficult soils, the methods of testing and the results are included in this paper.

CLOGGING SOILS

The excavation of cohesive soils by means of an EPBM creates the potential for adhesion at the cutterhead, excavation chamber surfaces, in the screw conveyor and in the mucking system (belt conveyor or muck cars). If enough soil adhesion occurs, transport passages may become clogged, leading to delays and slower advance rates.

Identifying Clogging Soils

There are at least two methods available for evaluating the clogging potential of cohesive soil during EPBM tunneling. Each method is examined below:

- Analyzing in-situ soil moisture content in relation to Atterberg Limits; including the adhesion limit (Atterberg, 1974)
- Analyzing the relationship between soil consistency and soil plasticity (Thewes, 2004)

Adhesion limit. The adhesion limit test was first described by Atterberg in his 1911 paper (published in English in 1974). Several of the limits described in this paper were subsequently made into ASTM 4318 and are referred to as “Atterberg Limits”. The adhesion limit test was left out of the ASTM standard, but has been used in tunnel engineering to assess clogging potential. The more common application of adhesion limit is in the agricultural engineering field for which it was originally developed.

The terms stickiness and adherence are typically given to soil that adheres to metal. The sticky limit, or adhesion limit, is the lowest water content at which soil adheres to a nickel spatula when drawn lightly across the soil paste’s surface. Atterberg divides the plasticity range into a sticking plasticity and a non-sticking plasticity. This is illustrated in Figure 1.

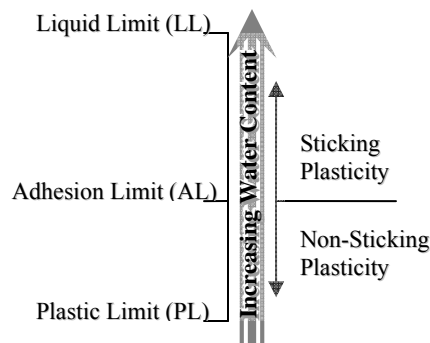


Figure 1 – Relationship of increasing water content to the adhesion limit

The soil consistency versus plasticity relationship. Detailed research in Thewes (1999) identifies the interaction of four mechanisms for the clogging potential:

- The adhesion of clay particles on a component surface; the most important single effect mechanism
- The bridging of clay particles over openings in the path of the spoil transport
- The cohesion of clay particles, sticking to each other
- The low tendency of clay towards dissolving in water

Thewes (2004) uses empirical data from slurry machine tunnel projects to highlight three categories of clay clogging potential based on the consistency (I_C) and plasticity (I_P) indices, and shows where each category exists on a plot of soil consistency versus plasticity illustrated in Figure 2. Soil samples from the field can be tested in the lab for Atterberg Limits and water content and then be plotted on the figure to find the associated category of clogging potential. The following equations show how each value is calculated:

$$I_C = (LL - \omega_c) / (LL - PL)$$

$$I_P = LL - PL$$

Where, LL = Liquid Limit
 PL = Plastic Limit
 ω_c = Water Content

Categories of clogging potential published by Thewes (2004) with proposed changes to apply to EPBM tunneling are as follows:

- Soils with **high clogging potential** lead to substantial problems during excavation and require daily cleaning works. Machine modifications only lead to a reduction, not a solution to the problem.
- Soils with **medium clogging potential** can be mastered after a number of mechanical modifications to the shield machine and soil transport system, along with changes in the operation of the machine
- Soils with **low clogging potential** require a reduction in the advance rate, but making major alterations to the EPBM is unnecessary

Differences between Prediction Methods

As an example to illustrate the difference between predictions based on adhesion limit and predictions based on the consistency/plasticity relationship, consider the high plasticity clay soil sample taken from approximately 50 foot depth on SVRT. Data for the same soil sample is plotted in Figure 2 for both prediction methods.

In this sample, the natural moisture content lies below the Adhesion Limit (AL) and above the PL; therefore indicating sticking behavior. Whereas, the empirical relationship graph by Thewes indicates a “high clogging risk”. The natural moisture content is expected to be altered during actual EPBM excavation because water is introduced as a component of foam soil conditioning through the injection ports. As water is mixed with the soil in the excavation chamber, the moisture content increases, thereby lowering the consistency. It is intuitive that this should lower the clogging risk as indicated by the Thewes graph, but this would move the soil into the sticking plasticity range using the adhesion limit prediction method (see Figure 2 for illustration). Through continued addition of water and foam, the conditioned spoil would ultimately reach the liquid limit where cohesion is rapidly reduced and clogging will become less of a concern as the spoil behaves more like a fluid.

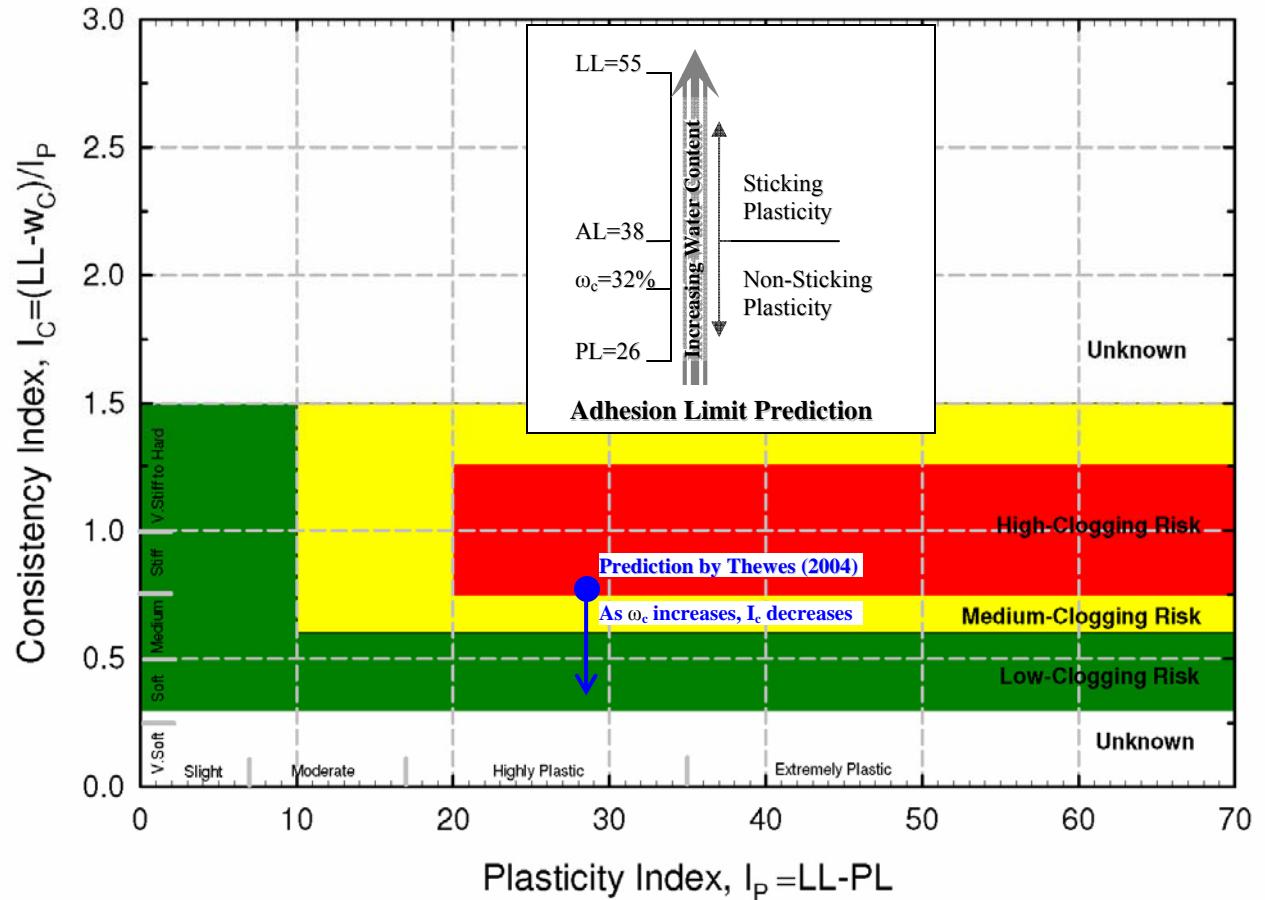


Figure 2 – Comparison of prediction methods for clogging soils

The simplicity of the adhesion limit test leads to a drawback for predicting EPBM clogging potential. Research published by Kooistra (1998) and Ziminik (1999) has shown that real world effects such as high normal stress, contact time between clay and steel, steel roughness, differential pore pressure/capillary pressure, and variations in clay mineral composition are relevant to clogging of an EPBM, and these factors are not considered in the adhesion limit test.

Assessing the Suitability of Anti-Clay Soil Conditioners for Clogging Soils

Once potentially clogging soils have been identified on the tunnel alignment, the next step is to find a soil conditioner that will reduce or eliminate the clogging risk. The various soil conditioner suppliers have each developed procedures for evaluating anti-clay conditioners and the correct dosage. Standard practice has been for the soil conditioner suppliers to grab soil from the site (usually from early shaft excavations) that is assumed to represent the conditions along the tunnel alignment and to perform their own testing, and then recommend a product and a dosage rate. On the SVRT project which is currently in the design phase, extra soil samples from the design phase geotechnical investigations at tunnel depth were made available for this testing. Laboratory testing for the SVRT project and also for the NDBT project is described below.

Sample Selection for SVRT. The SVRT extension of the existing Bay Area Rapid Transit (BART) system includes five miles of twin bore tunneling by EPBM through San José. During the subsurface investigation soil samples were supplied to BASF laboratory, at their request, and testing was performed to establish suitable quantities of soil conditioners for estimating purposes. The offer is available to other soil conditioner suppliers who may request soils samples. Soil samples were tested for the effectiveness of soil conditioners on different soil types to be encountered during tunneling. The soil samples sent to be tested were taken from a geotechnical sonic boring. In order to mimic the mixing of materials within the excavation chamber of the EPBM machines, some soils samples were blends of soils from different intervals along the boring.

A potentially clogging soil sample was identified within the sonic boring for testing. The vast majority (~80%) of this clay was taken from a layer of CH at a shallow depth. The remaining portion (added to increase volume) was taken from a marine clay layer (CL type material) at approximately 90 feet depth. The samples were aggregated and mixed in the sample container. Trace amounts of fine sand were present in the CH material, and one piece of fine gravel was discovered in the mixer during testing at the lab. The total sample volume was approximately 2.5 gallons.

Clogging soil testing. No dilatancy or water segregation was noted in the sampled soils prior to testing. The initial soil material was very cohesive and therefore no slump testing was conducted during the testing. A small, measured quantity of soil was placed in a Hobart Model N-50A mixer for testing and soil condition agents were then added. Methods to reduce clogging include the addition of water and the use of foam and anti-clay agents.

Two tests were conducted on this material. For the first test, no water was initially added to the clay soils during mixing. The clay stuck to the mixing paddle stiffly, and the adhesion had fully obscured the windows through the paddle completely. A 30% Foam Injection Ratio (FIR) of Meyco SLF 30 foam [at a Foam Expansion Ratio (FER) of 7] was added to the sample and the result was a reduction in the clogging of the mixing paddle, and a slightly visible reduction in the adhesion of the clay to the paddle. The basics of soil conditioner mix design are described by the European federation dedicated to specialist construction chemicals and concrete systems (EFNARC), (2005) and this document can be referenced for additional information. Next, 1.5% by weight of an anti-clay agent (Rheosoil 211) was added to the mix and the resulting clay soil mix was still sticky and the paddle remained thoroughly loaded with adhered clay soil, but mixer motor effort was audibly reduced and the mix became more plastic in appearance. After the addition of water, the resulting soil mix had lost its ability to bridge the gaps in the mixing paddle, becoming fluid like a thin pudding. The original foam matrix had been destroyed prior to this point due to the amount of previous mixing that had taken place, so a second test was run, with the foam added last.

For the second test of this material, illustrated in Figure 3, 7.5% by weight of water was initially added to the second sample and mixed thoroughly. The resulting clay mix was still very sticky, but was slightly more plastic than the sample in the first round at this point. Next, 1.5% of Rheosoil 211 (R211) was added (by weight) while mixing. The effect on adhesion was immediate, and was at a similar state to where the first test ended exhibiting low bridging ability of the clay across the paddle openings. Motor effort was

also audibly reduced. Then, 15% FIR of the SLF 30 foam was added to the mix, which resulted in visible fluffing (bulking). The mix was now more fluid and required even less torque from the mixer to agitate. An additional 15% FIR was then added, bringing the total to 30% by volume. The soil mix now had the appearance and viscosity of a mousse, and could be described as very fluffy (notable air entrainment) almost immediately. It required very little mixing effort. The soil mix also now had a dilatant quality when shaken, and vibrated like mousse or jello in a mold.

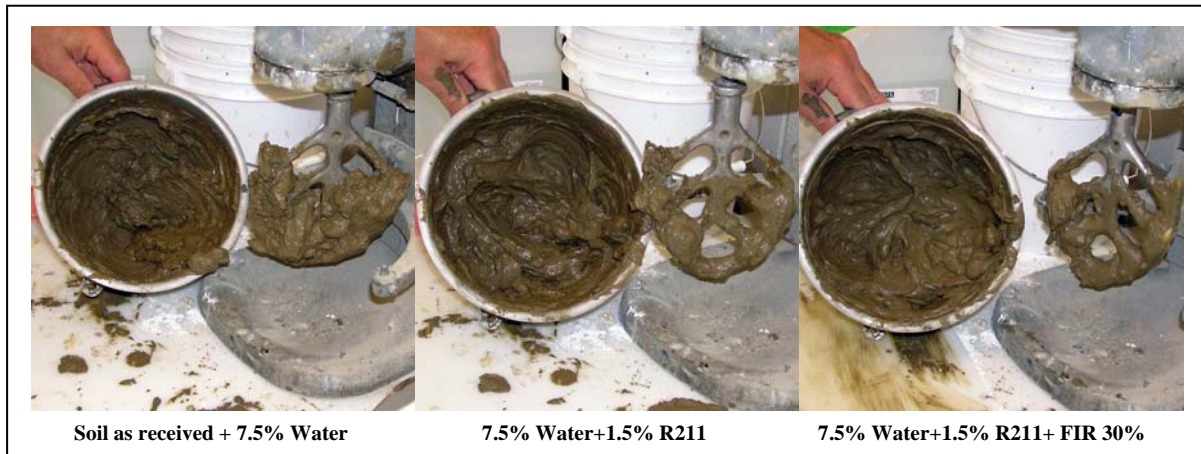


Figure 3 –Soil conditioning for clogging soil

The addition of water with soil using the small lab mixer seemed to improve the ability to mix the other ingredients. The Rheosoil 211 appeared effective in small quantities at reducing the adhesion of the clay. During actual tunneling, Rheosoil 211 and the foam would be mixed and introduced at the same time. The mixer did not allow clods of material to be present at the time of addition, and it is unknown how capable this chemical is of reducing clods that may occur in the cutting chamber. The occurrence of clods of clay material may require higher dosing of Rheosoil 211 during mining than that presented in lab testing if the agent is capable of reducing clod size. The addition of the foam served to fluidify the mix, reduce torque for mixing, while bulking and aiding in making the mix very homogeneous.

Laboratory testing for NDBT. Part of the NDBT excavation was through the Boston Blue Clay (BBC), a marine clay deposit. Laboratory tests were performed to determine the effects of foam and anti-clay agents on the clay. Included in these tests were rheology measurements using an Anton Parr Physica MCR 301 type rheometer with a 12 mm measuring bob. Initially, shear rate and torque measurements were made on four mixtures to illustrate the effects of foam addition. The foaming agent concentration (CF) of the foam solution was 10%, the FER was 10, and the FIR was variable. Testing was run in the following order:

1. BBC as received
2. BBC, 10% addition of water
3. BBC, 10% water, Meyco SLF 30 (0.5kg/m^3 of soil), R211 (0.5kg/m^3 of soil)
4. BBC, 10% water, Meyco SLF 30 (1.5kg/m^3 of soil), R211 (0.5kg/m^3 of soil)

The addition of water decreased the torque required to move the bob through the clay but did not significantly reduce stickiness. The addition of foam lowered the torque further

and lessened the stickiness of the clay. The shear rate used in these tests was limited due to the amount of torque needed to test the clay as received; it rapidly reached the limit of the Rheometer. A graphic representation of the tests is shown in Figure 4.

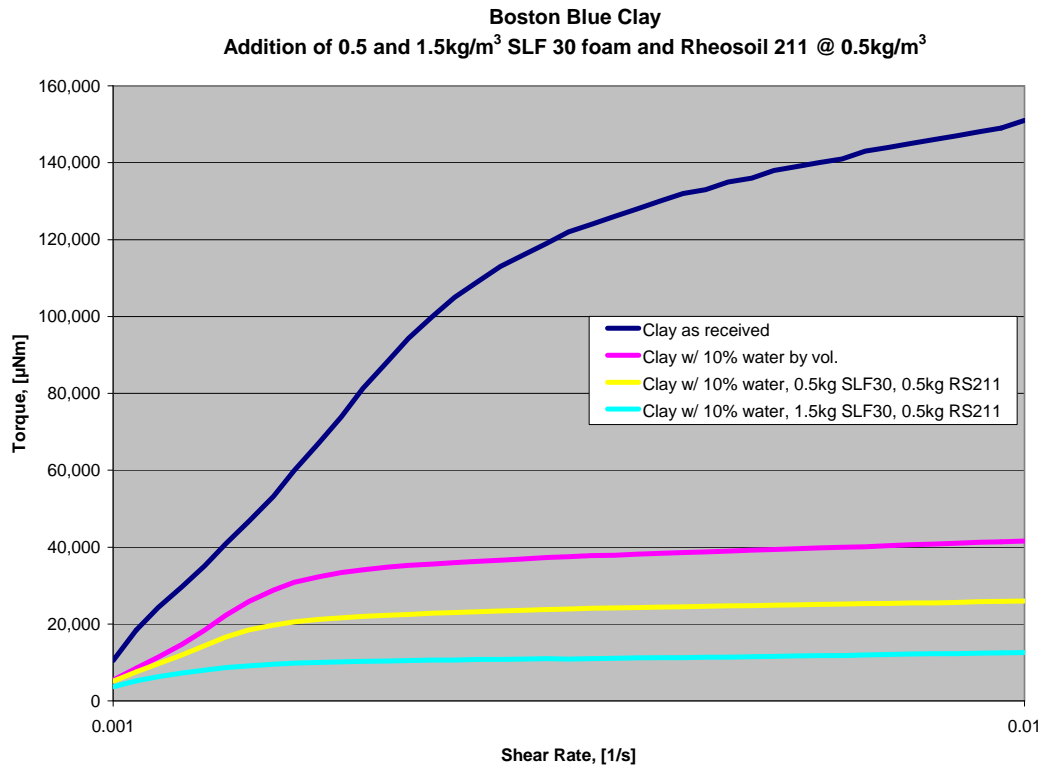


Figure 4 – Rheometer testing in Boston Blue Clay

To illustrate the effects of anti-clay agent (Rheosoil 211), tests were made using three mixtures. The FIR was kept low to better show the effects of the dispersant.

1. BBC, 10% water, Meyco SLF 30 (0.5kg/m³ of soil), R211 (0.5kg/m³ of soil)
2. BBC, 10% water, Meyco SLF 30 (0.5kg/m³ of soil), R211 (0.75kg/m³ of soil)
3. BBC, 10% water, Meyco SLF 30 (0.5kg/m³ of soil), R211 (1.0kg/m³ of soil)

The shear rate on these mixtures was increased by three decades (each decade is a ten fold increase in the shear rate) as the torque values were lowered due to the soil conditioning. The incremental increase of Rheosoil did decrease the torque of the mixtures. A graphic representation of the results is shown in Figure 5.

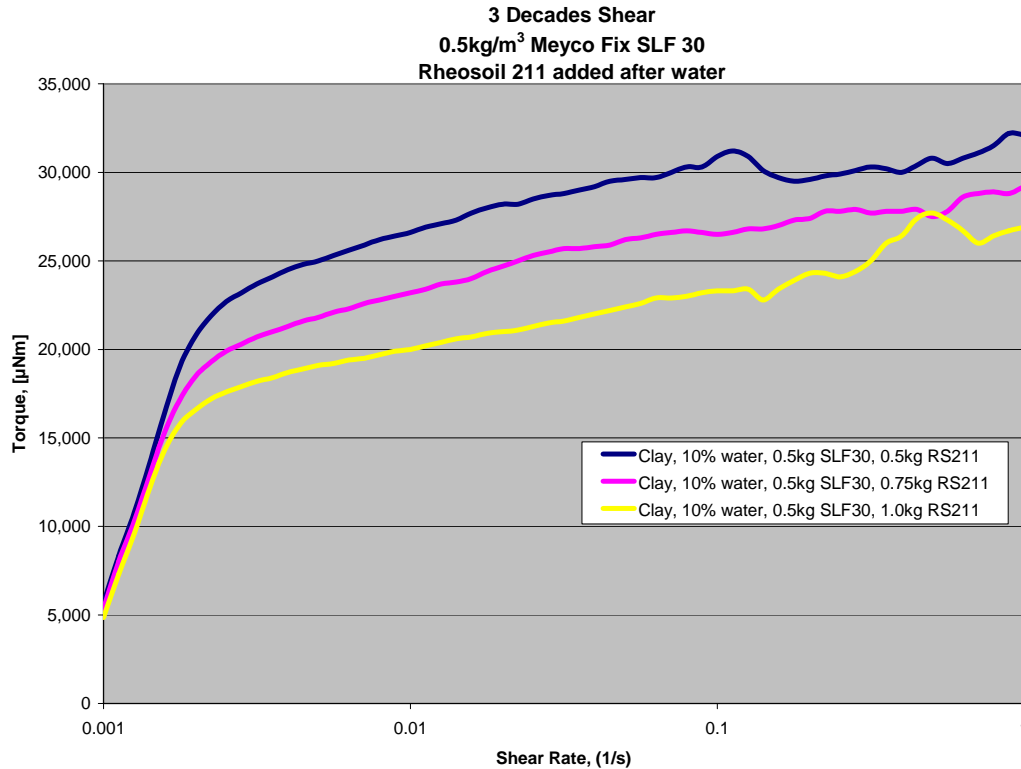


Figure 5 – Rheometer testing in Boston Blue Clay with three decades of shear

The results show the value of foam and Rheosoil on the rheology of the clay. Both lessened the adhesion of the clay and lowered the torque required to move through the clay as measured by the Rheometer.

Both the foam and clay dispersant technologies were utilized in the NDBT.

Case Histories

Analyzing empirical data from completed EPBM tunnel drives is one of the most valuable methods to evaluate the usefulness of the adhesion limit and the Thewes method to predict clogging.

Although the Thewes paper does not specifically describe its application to EPBMs, there is limited other published empirical data found in this regard. Langmaack (2007) applies the Thewes paper to the soil data from the Toulouse Metro Line B EPBM drive completed in France in 2007. During the EPBM drive on this project the machine experience significant clogging even working in dry ground conditions under compressed air. The difficult soil, “Toulouse molasses”, plots in the medium to high clogging risk zones. By the addition of water, foam and an anti-clay agent to the soil mix, the project was able to stay on track by reducing clay clogging problems.

The Beacon Hill Project, recently under construction, was a tunnel excavated by EPBM primarily in glacial till. During this project, adhesion limit tests were performed along with Atterberg Limits and the Natural Moisture Content (NMC). Each test plotted the NMC between the plastic limit and the adhesion limit, and below the liquid limit. Based

on this data alone, the clay at its NMC is not prone to sticking in the manner the test was done. The project Geotechnical Baseline Report (GBR) baselined 25% of all very stiff to hard clay soils to be sticky clays based on the designer's related tunneling experience and the owner's allocation of risk rather than the adhesion test results alone. Although it was not considered at the time of writing the GBR, the Thewes method does indicate a high potential of clogging for some soils in the tunnel drive. When construction took place, EPBM clogging was apparent during the Beacon Hill drives, lending credibility to the Thewes method. Clay adhesion was reported in the cutterhead, screw and muck conveyance equipment along with other surfaces the clay came into contact with.

Until more soil properties, including adhesion limit, from a large database of past tunnel projects can be interpreted into meaningful relationships to predict EPBM clogging, the tunnel engineer's tools are limited. The Thewes method is one tool that does provide a relationship between soil properties and case histories of TBM clogging. While this method was originally developed based on slurry TBM experience, the basic principles making this method valid for assessing slurry TBM drives are also valid for EPBM drives. EPBM case histories from Beacon Hill and Toulouse Metro appear to confirm this.

SOILS WITH LOW FINES

Another difficult soil is coarse-grained soil with insufficient fines combined with free water for EPBM tunneling. In order for an EPBM to properly control face pressure while excavating, it must dissipate the face pressure along the length of the screw conveyor. "Toothpaste" is a term often used to describe the ideal consistency of conditioned soil mixture for an EPBM. The material in the screw must be a stiff viscous fluid like toothpaste in order to properly dissipate the face pressure. Some sands and gravels have insufficient fines to achieve the consistency of toothpaste. Instead, they tend to drain free water and segregate, which are undesirable spoil characteristics for EPBM spoil. Sands and gravels that segregate and drain free water do not behave like a viscous fluid, and could not be expected to dissipate pressure along a screw conveyor. How much fines are needed is a point of discussion. In the British Tunneling Society (BTS) guideline for closed face tunneling, a minimum value of 10% is recommended (BTS, 2005), but this would rely on the addition of polymer. Without the addition of polymer, 20% fines is considered a minimum.

Identifying Soils with Low Fines

Identification of low fines soils can be done with sieve analyses during the subsurface investigation that measure particles smaller than 75 μm or particles able to pass through a No. 200 sieve. Fines contents of soil layers in the face are averaged because the EPBM cutterhead, cutterhead arms and screw conveyor will at least partially mix the soil from each soil layer. It is this average fines content of soil in the excavation and screw conveyor that influences the ability to control face pressure while excavating.

Mitigating Soils with Low Fines

In soils with low fines, sole use of foam may not be enough to provide the desired plasticity to the soil. Segregation risks persist, even with stable foam. Various polymers

can be combined with foam technology to control segregation and improve plasticity and work by binding the water in the soil matrix and decreasing the slump. However, if the fines content is less than 10%, additional fines may need to be added in the excavation chamber because extensive polymer addition to achieve the desired plasticity may prove uneconomical. The addition of fines along with foam and a polymer can provide a more economical solution. The addition of fines, made at the cutterhead, changes the characteristics of the soil in the working chamber, providing sufficient cohesion to the soil. This is traditionally achieved using bentonite slurry. An alternative to bentonite slurry is High Density Limestone Slurry (HDLS) which has a number of advantages over bentonite. As well as being capable of achieving higher density than bentonite slurry, HDLS is more economical and does not require the special handling and disposal measures for the spoil that is required for bentonite contaminated spoil.

HDLS, comprised of approximately 70% pulverized limestone by weight, when combined with a fluidifier to control bleed, produces a viscous fluid which can be pumped and delivered to the excavation chamber. Higher percentages of pulverized limestone may result in nozzle clogging.

Using this method, the excavation chamber spoil is treated with enough HDLS and polymer to enhance the fines content and consistency of the spoil such that:

- The permeability is significantly reduced to prevent free water flow through spoil in the screw conveyor
- The spoil has sufficient cohesion and friction within the screw conveyor for plug formation to resist excavation chamber pressure without induced slippage within the screw conveyor
- Spoil texture is consistent and exhibits enough cohesion to prevent free flowing or very low slump material on the conveyor or spoil removal system

The amount of HDLS being added, and when it is needed, will generally be controlled through visual observation at the screw conveyor discharge point. A slump test can be used, but careful attention must be paid to how well the spoil holds water in the soil matrix. Sole use of slump testing can be misleading due to aggregate angularity. Addition of HDLS to achieve a fines content between 15% and 20% in silty gravels may effectively improve consistency to a point where the screw conveyor and EPBM could efficiently function. Due to the water portion of the HDLS, a point of diminishing returns will be reached where consistency will no longer exhibit significant change. Testing of alignment soils and conditioning using HDLS is recommended to find the approximate point of optimal effectiveness.

Laboratory Testing on Soils with Low Fines

Testing of soil with low fines at BASF laboratories included two laboratory manufactured soil samples with low fines and a sample from SVRT. The SVRT low fines sample was assembled from two separate layers that appeared to contain the least fines of the layers present in the boring. The sample would be classified as sandy gravel with 4 to 6% fines.

Laboratory testing on BASF samples. To illustrate the conditioning of soils with low fines content, laboratory tests were conducted on a sand sample, and a mixture of gravel and sand. The tests used the following materials and parameters:

- Conditioning foam: Meyco SLF 30 @ C_f of 2.5%, FER 10%, FIR was varied
- HDLS; addition rate of 20% by weight of sample
- Polymer: Meyco SLF P2

The HDLS was made using Marble White 200 pulverized limestone [98% passing the No. 200 (75 μ m) sieve] and water, at a solids content of 73.5%. No stabilizer was added to this HDLS due to the short time between creating the slurry and adding it to the soil.

Sand 0 to 4 mm. This sand contains >17% fines and EPBM tunneling could be done with only foam for conditioning. The addition of foam improved the appearance and consistency of the sand. The sample was more homogeneous. The slump increased as the FIR increased. To decrease the slump, Meyco SLF P2 was added and provided improved soil structuring for better handling. Figure 6 illustrates the change in the soil with the associated soil conditioning.

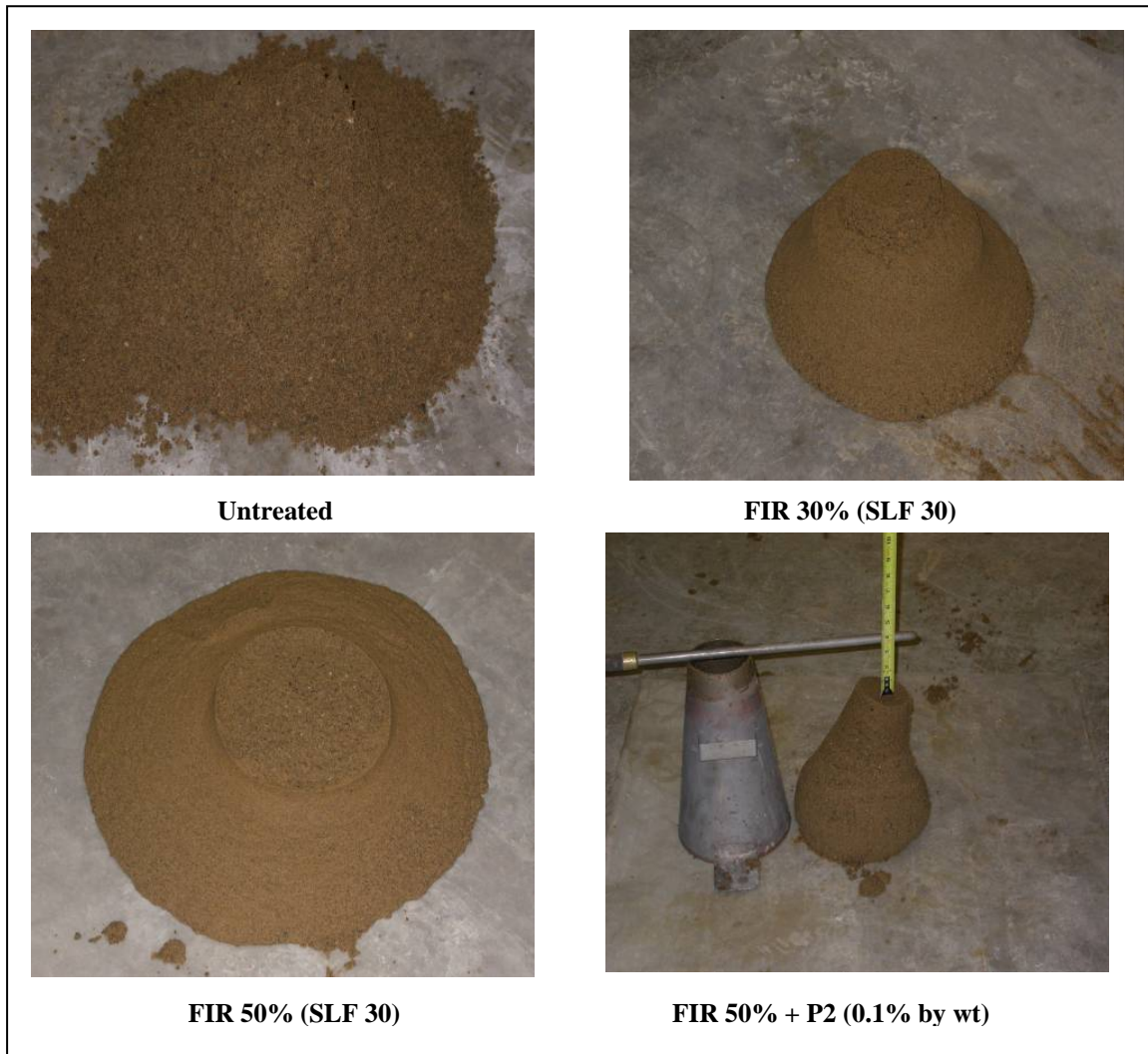


Figure 6 – Photos of foam only soils conditioning on BASF sand sample with low fines

Sand & Gravels 0 to 25 mm. The mixture of sand and gravel has <5% fines and required the addition of HDLS. Figure 7 illustrates the change in the soil with the associated soil conditioning.

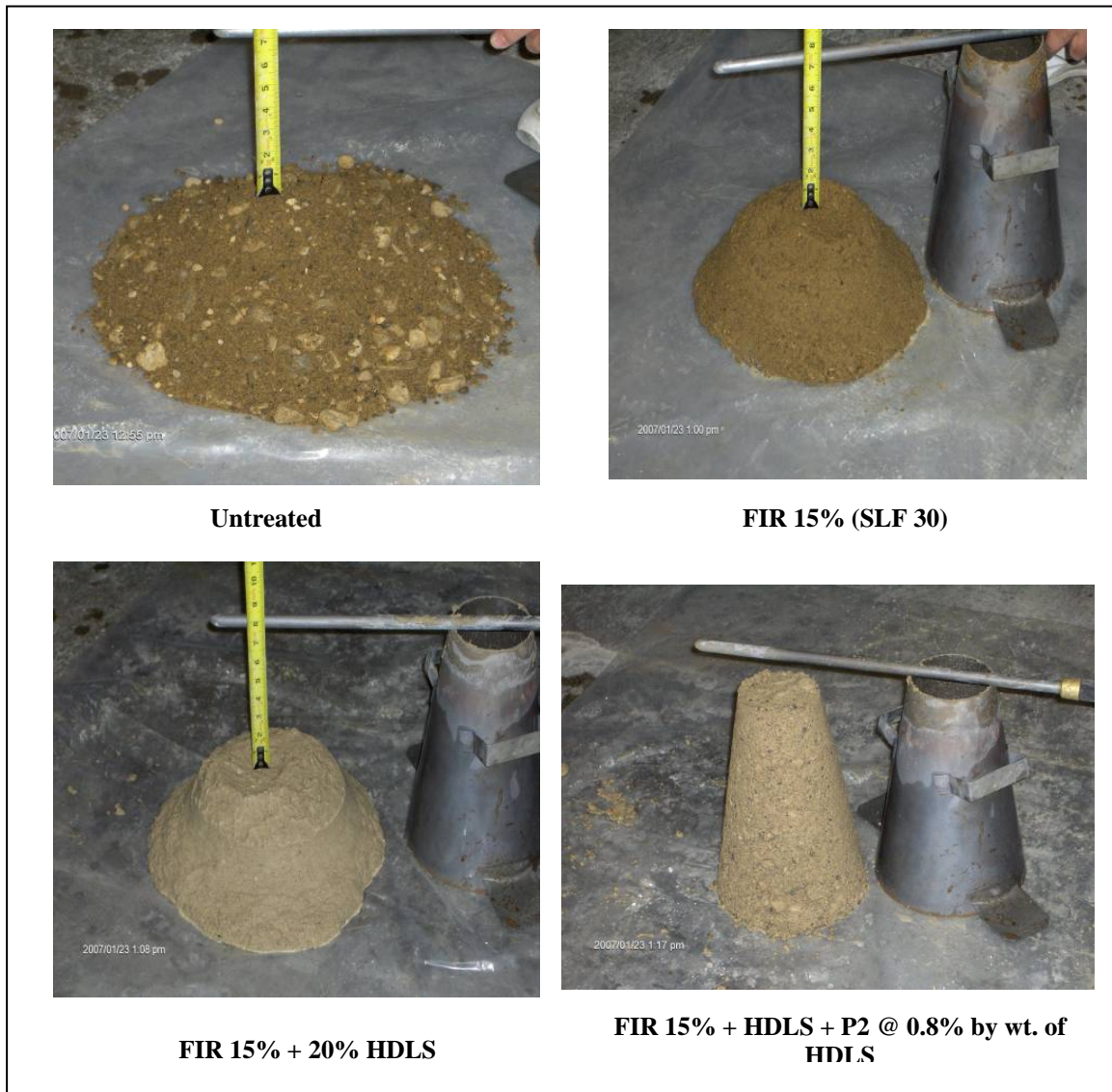


Figure 7 – Photos of soils conditioning on BASF mixture of sand and gravel with low fines

The addition of foam to the sand and gravel mixture improves the consistency of the materials but it remained porous. The addition of the HDLS improved the consistency and appearance of the mixture and produced excellent rheological properties. The addition of the polymer modified the rheology of the mixture by decreasing the slump, thus improving the soil structuring for EPBM excavation.

This laboratory testing was performed and reported as part of a study for the NDBT project where the EPBM was designed to incorporate the addition of fines to the face using HDLS. Although fully equipped, the need to incorporate the HDLS never occurred.

To further illustrate the ability of added fines to improve a coarse soil, Langmaack (2000) cites laboratory tests on a porous soil from Boulevard Peripherique Nord de Lyon (BPNL). The addition of a clayey silt and polymer to the sample decreased the permeability of the soil.

Laboratory testing on SVRT low fines soil. The SVRT low fines sample, with an initial sample moisture content of 13% and a degree of saturation of 100% prior to soil conditioning treatment, was mixed using a Kol Mixall mixer. The sample possessed a 7.5 inch slump. No significant separation of water from soil solids was observed during this slump test. Figure 8 illustrates the sequence of testing.

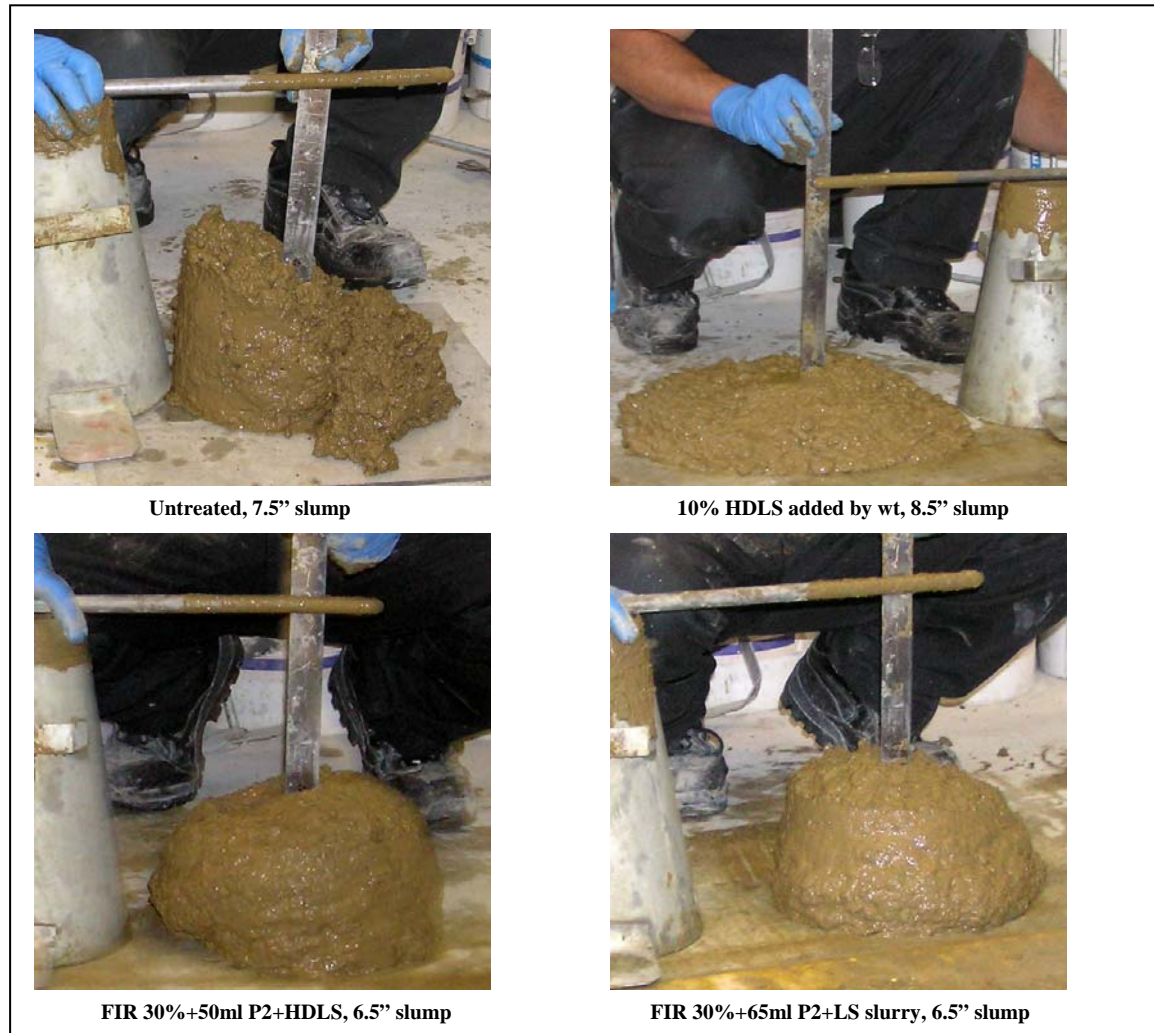


Figure 8 – Photos of soils conditioning on SVRT sample with low fines

The addition of the HDLS at 10% of the initial sample weight created a color change that was immediately apparent, as well as a visual change in the consistency of the soil mix, which began to behave more uniformly as soil slurry. The addition of the water in the limestone slurry had affected the slump of the base soil material, but the uniformity of the mix may also have contributed to the increase in slump.

The soil was then treated by adding a 30% FIR and 50ml of P2 polymer to bind the water and reduce the slump. However, after approximately four minutes of mixing, the soil mixture was found to have a 6.5 inch slump. Additional polymer was added (considered to be excessive), but the slump did not decrease. It was then noticed the polymer being used had an expired shelf life, drastically reducing the effectiveness. The soil consistency at this point was very uniform, homogeneous, and slightly to moderately cohesive.

A side test was performed that consisted of a clear polycarbonate tube (5.25 inch ID) placed vertically and seated over a No. 8 sieve. A portion of the soil mix used in the soil conditioning tests was poured into the tube to a height of 8.5 inches above the base of the tube. Then, 15 inches of water head was surcharged above the plug of soil to test for permeability and soil seal against the container. Upon completion of all testing (2.5 hours later), no measurable leakage through the low fines sample plug and No. 8 Sieve had occurred.

Laboratory Testing Conclusions. It is clear from the testing on the SVRT sample that the same effect could not be produced as the NDBT samples. Since the polymer used was beyond the shelf-life, being biodegradable, there was a considerable effect on the potency/efficacy of the polymer. Tracking of and adhering to age limits is important when using these polymers.

Addition of the first 10% by weight of HDLS (to supplement the soil's fine content) appears to be important in gaining consistency. HDLS and foam added together are not sufficient because they result in too much slump. Polymer needs to be added with the foam to control the slump of the spoil plus fines mixture. Before testing, determine the ideal and maximum material slump for the proposed conveyor system. In addition, determine the percentage of free water in the muck that the conveyor can handle before problems occur.

All tests at the BASF lab were performed at atmospheric pressure with mixers that may be more effective in mixing the soil more thoroughly than would take place in the EPBM excavation chamber. Dosage rates determined during these tests are considered to be a general guideline and may need to be adjusted in the field under actual tunneling conditions.

CONCLUSIONS

The soil conditioning laboratory testing allowed insight into how different additives could modify soil behavior to improve the performance of EPBM mining. Using soil conditioners expands the applicability of EPBMs into the realm of soils formerly considered to require a slurry machine and steps towards the goal of a universal machine that can handle a broad range of conditions. The tests resulted in several important conclusions.

For soils with low fines:

- Addition of the polymer appears to have significant benefits if the fines content is below 20%, as it binds free water in the soil
- If the fines content is below 10%, the use of a polymer and a HDLS appears to improve soil behavior
- Addition of the high density HDLS appears to have significant benefits at a 10% by weight application for improved consistency, cohesion and lower permeability
- The slump test may be used to test the effectiveness of soil conditioning, but careful attention should be paid to the amount of free water that drains from the spoil
- The addition of polymer appears to bind the additional water introduced into the mix in the slurry (preventing adverse slump effects)
- The stated shelf life of chemical additives is important to treatment efficacy. Additives to be used in additional soil conditioning tests must have a manufacture date that puts the proposed test usage within the applicable shelf life of the additive.

For soils that are potentially clogging:

- The Adhesion Limit test does not have enough empirical data to support its use in estimating soil clogging in an EPBM
- Addition of water prior to addition of an anti-clay agent or foam substantially increased efficacy of additives
- Addition of an anti-clay agent and a foam additive resulted in significant reductions in adhesion and required torque, while creating a uniform consistency
- The higher the FIR of the foam additive, the more likely the pressure change at the screw conveyor will induce effervescing of the material and could promote soil bypassing through a stationary conveyor that may be undesirable during mining operations
- Unlikely that the EPBM excavation chamber can provide similar mixing effort as the mixing unit used in the laboratory
- A FIR somewhere between 15 and 30 percent seems to be the most effective to establish a good mix in the EPBM chamber
- Atterberg limits and NMC are proposed on the pre-treated sample to assess the anticipated clogging potentials
- Design excavation chamber layout to maximize mixing effort applied to spoil

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