

Development of the Soft Ground Abrasion Tester (SGAT) to predict TBM tool wear, torque and thrust



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ABSTRACT

The Norwegian University of Science and Technology (NTNU), SINTEF Rock Engineering and BASF Construction Chemicals have jointly developed a new test device called the *Soft Ground Abrasion Tester* (SGAT). The ambition and purpose of the design of the test and the applied test procedure is to replicate an *in situ* soil – TBM excavation tool contact, in a small and simplified scale. The current development is attempting to bridge a gap when it comes to estimating soft ground and soil abrasivity, as earlier research on e.g. the NTNU/SINTEF Soil Abrasion Test™ (SAT) shows that it does not catch up all driving factors for soft ground and soil abrasivity directly. The paper summarizes the development of the SGAT apparatus, and shows its capabilities to evaluate, quantify and compare how the soil mineralogy, water content, pressure, compaction, and the use of soil conditioning additives influences the wear rate on the SGAT excavation tool. During testing the required torque and thrust are monitored and logged, making it possible to measure various soil–soil conditioning matrixes requirement for operational parameters.

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1. Introduction

1.1. General

Predicting soft ground TBM tool life is a complex matter. In order to study and quantify *in situ* soft ground abrasivity, The Norwegian University of Science and Technology (NTNU), SINTEF Rock Engineering and BASF Construction Chemicals have developed a test device called the *Soft Ground Abrasion Tester* (SGAT). The intention for developing the apparatus is to provide a reliable test method for determination of *in situ* like soil's abrasivity, as well as various soils and soil conditioners' torque requirement for soft ground TBM applications. The apparatus has the capability of evaluating how soil abrasivity is influenced by water content, air-pressure, compaction or soil density as well as introduction of soil conditioning additives. The developing consortium has been successful and worked in the following manner: NTNU has managed the development based on a BASF design concept. The development has been quality assured by SINTEF. Generally, the SGAT is an open source development and other suppliers, contractors, clients and TBM manufacturers are invited to run tests on the apparatus.

1.2. State of the art on soil abrasion prediction based on hard rock test methods

So far, the research on soil abrasivity and TBM tool life on soft ground tools at NTNU/SINTEF has been limited to the Soil Abrasion Test (SAT™) (Nilsen et al., 2006c, 2007; Jakobsen and Becker, 2012), and the Ball Mill Test for determining the influence of soil conditioning additives and presence of water on hard rock and soil abrasivity (Jakobsen et al., 2009; Jakobsen and Lohne, in press). The initial development of the SAT™ test procedure results from a request from a contractor, which would like to evidence that a specific soil condition was highly abrasive. All these test procedures and approaches originate from NTNU/SINTEF's research on hard rock TBM tunneling performance and tool life estimates, which have been an ongoing research activity for several decades. In 2011, there has also been initiated research on the effect of tribo-corrosiveness of rock and soil in interaction with steel (Grødal et al., 2012). The intention of this present work is to achieve a further understanding of the mechanisms which are degenerating TBM excavation tools.

Similar to the development of the NTNU/SINTEF Soil Abrasion Test (SAT™), the Technical University in Munich introduced the LCPC abrasivemeter (LCPC, 1990) for determining soil abrasivity (Thuro et al., 2007). The LCPC approach has some similarities to the SAT™ procedure available at NTNU/SINTEF, as both test methods use dried soil samples in limited fractions (LCPC 4.0–6.3 mm/

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$SAT^{\text{TM}} < 4.0 \text{ mm}$). The sample used for the LCPC test is however exposed to a steel impeller rotating at 4500 rpm. The high speed rotation of the steel impeller is causing crushing of soil or hard rock fragments, and this interaction causes wear on the steel.

Gwildis et al. (2010) present tool wear data from the Brightwater conveyance tunnel project, which indicate that cutterhead energy consumption together with abrasivity descriptors (e.g. SAT^{TM} , quartz content or Miller Slurry Test) are the driving factors for tool wear. The simplified test approaches such as the SAT^{TM} test and the LCPC abrasivemeter do not have the ability to directly include the soil materials' need for cutterhead energy, as the methods are based on testing the interaction between steel and loose soil particles.

Köhler et al. (2011) present experiences from the tunneling project Lower Inn valley in Austria, and conclude that there are no recognized prediction models for estimating tool wear in shield tunneling in soil. They also consider the possibility to establish correlations between small-scale laboratory index values and real-life TBM wear rates to be unlikely, if not impossible.

1.3. New developed soft ground abrasion test methods

The first approach of developing an apparatus purely intended for soil and soft ground abrasive wear prediction was performed and published by Gharahbagh et al. (2010, 2011, 2013) and Rostami et al. (2012a,b). The Penn state soil abrasion testing system consists of a rotating blade at a fixed position which is in contact with a soil sample. The apparatus has the possibilities of evaluating the influence of various water contents, rotation speeds, higher ambient pressures and various excavation tool hardness. However, the soil sample is not consolidated prior to testing according to the test suggested by Gharahbagh et al. (2010). The soil sample density/consolidation is therefore not a controllable variable. Furthermore, the rotating tool is in a fixed position during testing (not penetrating into fresh soil sample material) and soil conditioners can only be used as an already preconditioned soil sample.

A more recent approach is suggested by Barzegari et al. (2013). The test device consists of rotating steel plates in contact with soil samples or crushed rock. The soil sample can be tested under pressure, and the test device allows utilization of additives.

Due to the assessment of simplified abrasion measurements presented by Köhler et al. (2011), Gwildis et al. (2010) and Jakobsen and Becker (2012), as well as the lacking possibility to run tests on a consolidated sample in the Penn State system, a development of a more advanced prediction method is needed. The development of the new SGAT is an attempt to develop a laboratory approach that after further assessment and work, may work as a pre-investigation tool on tool life for soft ground and soil TBM tunneling.

1.4. Research questions

Jakobsen and Becker (2012) and Jakobsen et al. (2013) evaluated the SAT^{TM} values against observed tool life for some recently completed tunneling projects with bentonite slurry face support. In this evaluation, one of the reasons for empirical outliers were identified as the influence of the soil grading. Single graded soils with high SAT^{TM} values did not cause any reduction in excavation tool life. This effect is, as stated by Gwildis et al. (2010), explained by the relative low amount of energy the TBM needs to apply in order to excavate such soils, and thus relatively low contact pressures between the soft ground tunnel face and the TBM excavation tools.

These previously missing effects of soil and soft ground compaction, together with influence of soil conditioning additives are the main reason for developing the apparatus. If the development

proves to provide valid and reliable predictions of tool life, a secondary effect of the apparatus can be to obtain laboratory data about how soil conditioning additives, compaction, water influence isolated influences tool life, and use these experiences on SAT^{TM} values. The research questions we intend to answer in this paper are:

- To what extent does the soft ground and soil compaction influence the soft ground TBM excavation tool life?
- Is the excavation tool life influenced by the amount of energy the TBM utilizes in order to excavate the soil and soft ground?
- To what extent does the water content influence the soft ground TBM excavation tool life?
- To what extent can the use of soil conditioning additives increase the soft ground TBM excavation tool life and influences other TBM parameters like torque and thrust?

2. The New Soft Ground Abrasion Tester (SGAT)

The SGAT apparatus consists in the actual status of a drive unit (rotation and vertical movement), a shaft attached to an exchangeable cutterhead-like tool consisting of two steel bars of Vickers Hardness 227 equal to 20 HRC, a testing chamber for the soil sample with a lid which is airtight up to 6 bars pressure, and a foam pump, see Fig. 1. During testing, water, bentonite or soil conditioning additives can be added continuously and directly at the cutterhead-like tool, replicating the real TBM operation. The current steel type, which the results in this paper comprise, is a carbon steel with the chemical composition presented in Table 1.

The drilling tool consists of two steel bars attached to a holder. The tool is designed in order to achieve mixing between the soil sample and the possible used soil conditioning additives, and to achieve relatively high contact forces between the lower steel bar (Fig. 2) and the compacted soil sample during the test. The use of two separate steel bars to form the drilling tool does also provide a possibility to distinguish between primary wear, wear on the lower steel bar, and secondary wear recorded on the upper steel bar. The length of the steel bars is 13 cm, which allows large grains ($\leq 20 \text{ mm}$) to pass between the drilling tool and the periphery of the testing chamber. The inside periphery of the test vessel consist of steel. For verification issues, some tests have been run without the lid in order to see whether the soil sample rotates along with the tool, which has not been the case.

The rotation speed is variable between 0 and 100 rpm. The fixed maximum speed of 100 rpm is chosen in order to avoid erosive wear, and to reduce the possibility of high impacts between the steel and soft ground and soil fragments. Running tests on 100 rpm results in a travel speed of approximately 0.7 m/s, which is in the range of a TBM excavation tool, which typically ranges between 0.1 and 1.5 m/s dependent on the tool position.

Several techniques have been tried in order to apply soil conditioning additives, during the development of the SGAT apparatus. Fig. 4 shows the three main approaches, (a) applying the soil conditioning additive on top of the compacted soil sample prior to testing, (b) injecting foam continuously during testing and (c) pre-mix the soil and soil conditioning additive prior to testing. The by far closest to reality technique for applying soil conditioning additives is by injecting through the points shown in Fig. 2, equal to the method shown in Fig. 3b.

2.1. Preliminary test procedure

Generally, all soil samples have been dried for 48 h in a ventilated oven at 30 °C prior to testing. After the drying, grains above 10 mm are removed from the sample. The next step is to add water and properly mix water and soil. Similarly to Rostami et al.

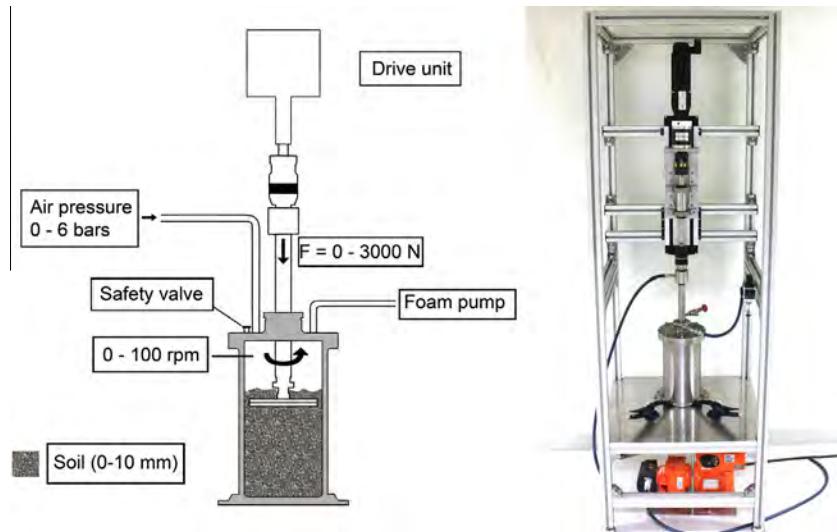


Fig. 1. Outline of the new Soft Ground Abrasion Tester (SGAT) (left) and photo of the test rig (right). The height of the test rig is 210 cm and the width is 75 cm, and the test chamber is 30 cm high and with inner diameter of 15 cm (photo by Simon Alexander Hagen).

Table 1
Chemical composition of the steel type used for the SGAT tool in the initial testing.

C	Si	Mn	Ni	P	S	Cr	Mo
0.43– 0.45	Max 0.4	0.5– 0.8	Max 0.4	Max 0.045	Max 0.045	Max 0.4	Max 0.1

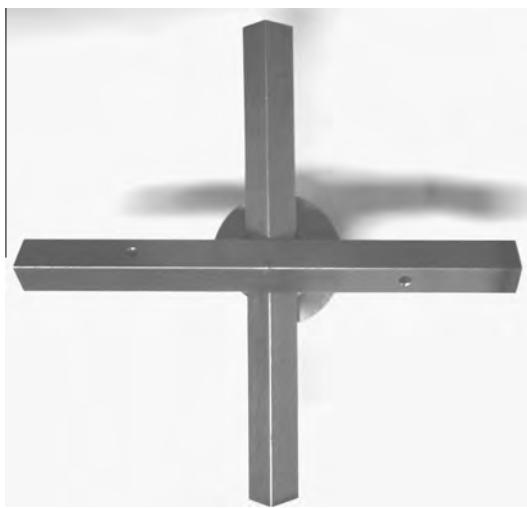


Fig. 2. The SGAT drilling tool. The test pieces have 1 × 1 cm cross-section, and the holes on the lower steel bar is the nozzles for soil conditioning additives.

(2012a,b), the mixing of water and soil were done carefully in order to ensure an uniform distribution of water. In order to avoid crushing of soil grains, thereby introducing more fines in-to the sample, the mixing were done carefully by hand¹. For soil samples with the desired water content, testing have been conducted on the original soil sample without drying.

After finishing the sample preparation, the soil samples were assembled in four layers with different grade of compaction as shown in Table 3. Fixed volumes of soil samples have been applied to the test bucket, causing the sample weight to vary (between 6500 g and 8000 g dependent on the grain density and level of compaction). An evaluation of various compaction levels along the sample has not yet executed. The authors expect an increase of compaction towards the bottom which is backed up by increasing torque and thrust data.

The SGAT test can be run under different operational schemes. In this paper, the rotation speed and vertical penetration has been fixed, causing the torque and thrust to vary. Oppositely, it would be possible to run tests under a fixed torque with varying vertical penetration or varying rpm. The tool penetration is about 15 cm for the results presented in this paper, with a penetration rate of 40 mm/min. The apparatus has the possibility to reduce the penetration rate or even run tests without any penetration, see Table 4.

The edges on the steel bars on the drilling tool are sharp edged, prior to use. In order to avoid replacement of the steel bars after one single use, the tools need to be runned-in for 2 h in an abrasive soil sample prior to the first test.

As a standard test procedure the penetration speed and rotation speed were fixed, while the thrust force and torque varied dependent on the soil properties and possible use of soil conditioning additives. This approach is carried out in order to compare different soil samples' torque requirement, which is thought to be a good indicator of how easy or hard a soil is to excavate mechanically, as well as indicating the influence on the steel wear rate.

2.2. Data collection and software

The rotation and penetration are driven by two separate servo motors with a gear ratio. The control of the motors use standard analog IO (0–10 V) for position, rotation, penetration speed, thrust and torque. These data are together with a dedicated signal for measuring the air pressure inside the SGAT test chamber continuously logged and presented in the control software (Fig. 4). The software is written in LabVIEW 2012 and utilizes NI CompactDAQ as interface for the control of the motors.

¹ For the soil in sample 3, lumps of sedimented clay and silt were mechanically crushed from gravel and stone size to soil <10 mm.

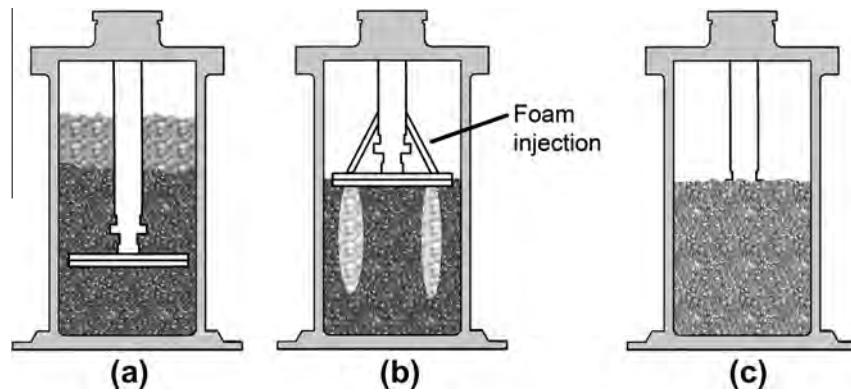


Fig. 3. Overview of possibilities to add soil conditioning additives in the SGAT apparatus. (a) Shows addition of foam on top of the soil sample, (b) shows a continuous addition of foam through nozzles, and (c) shows a premix of foam and the soil sample.

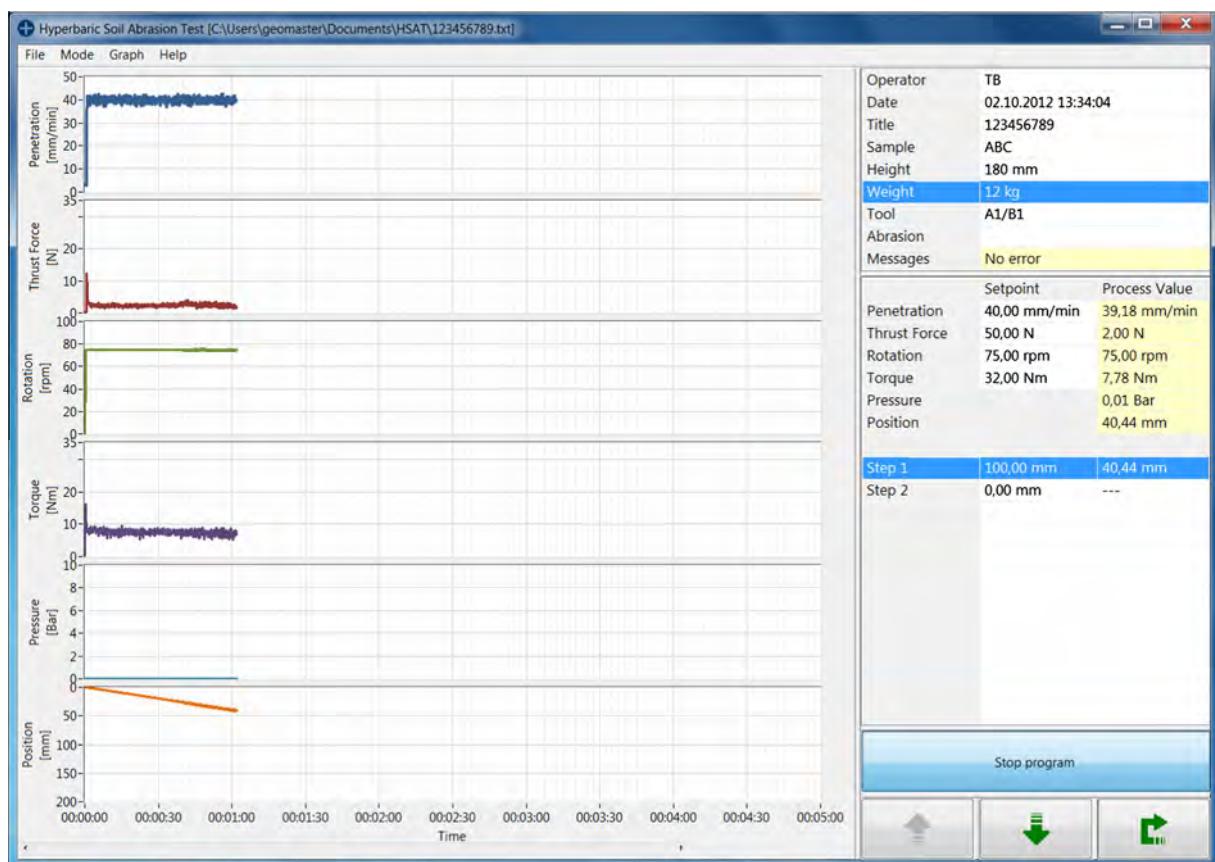


Fig. 4. Screen view of the SGAT operational and data collection software.

Table 2

Mineralogy of the soil sample obtained by X-ray diffraction (XRD), and measured abrasivity with the Soil Abrasion Test™.

	Soil sample 1	Soil sample 2	Soil sample 3
Quartz (%)	44	42	76
Mica (%)	18	<1	16
Plagioclase (%)	15	36	NA
Chlorite (%)	12	6	NA
Kali-feldspar (%)	5	15	NA
Amphibolite (%)	3	NA	NA
Calcite (%)	3	NA	7
Albite	NA	NA	<1
SAT™ value	26 (high)	23.5 (high)	6.5 (low)

Table 3

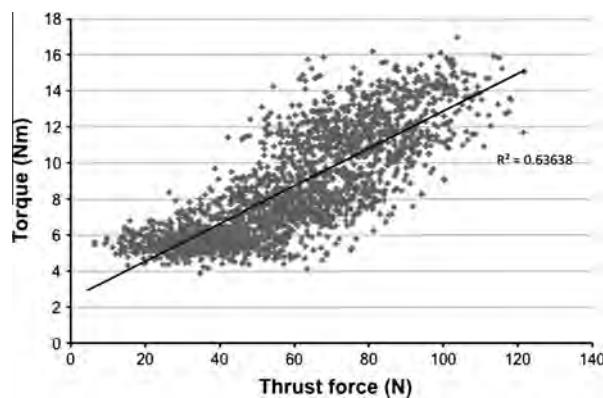
Example of influence of soil compaction and density on wear and torque for Soil sample 1.

Density (kg/m ³)	Compaction proc.	Wear (mg)	Avg. torque (Nm)
1544	No compaction	52	8.7
1886	5 Blows/4 layers	82	10.7
1958	10 Blows/4 layers	75	11.2
2058	15 Blows/4 layers	92	13.2
2109	20 Blows/4 layers	92	11.4
2228	30 Blows/4 layers	115	17.0

Table 4

Comparison of the new SGAT test procedure and the Penn state soil abrasion testing system.

	Soft Ground Abrasion Tester (SGAT)	Penn state soil abrasion (SAI) testing system (personal communication Jamal Rostami September 2012)
Tool design	4 Steel spokes	Propeller blade with var. pitch angle. Standard pitch angle is 10°
Tool steel	Standard construction steel. Vickers hardness 227 ≈ HRC 23 has been used so far to limit the testing time	17, 31, 43, 51 and 60 HRC
Rpm	1–100	60–180 (tested so far)
Length of penetration through the soil sample	Up to 200 mm	Fixed position, with 150 mm soil above and below the propellers
Penetration rate	0–200 mm/min	Not applicable
Thrust force	0–3000 N	Not applicable
Torque variation	0–32 Nm	Not known, but torque is measured
Ambient pressure	Atm – 6 bars (4 bars with cont. foam injection)	Atm – 10 bars
Maximum grain size	10 mm (for consistent and comparable results)	Published results include D_{50} ranging from 0.5 to 7 mm (Rostami et al., 2012a,b)
Soil compaction	Manually by proctor hammer prior to testing. Compaction as desired.	Not applicable (compaction under the propeller blade during the test)
Addition of soil conditioners	Continuous addition through the drilling tool	Premix and continuous addition through pre-installed ports

**Fig. 5.** Example of relation between thrust force and required torque for achieving a fixed penetration of 40 mm/min for one soil sample.

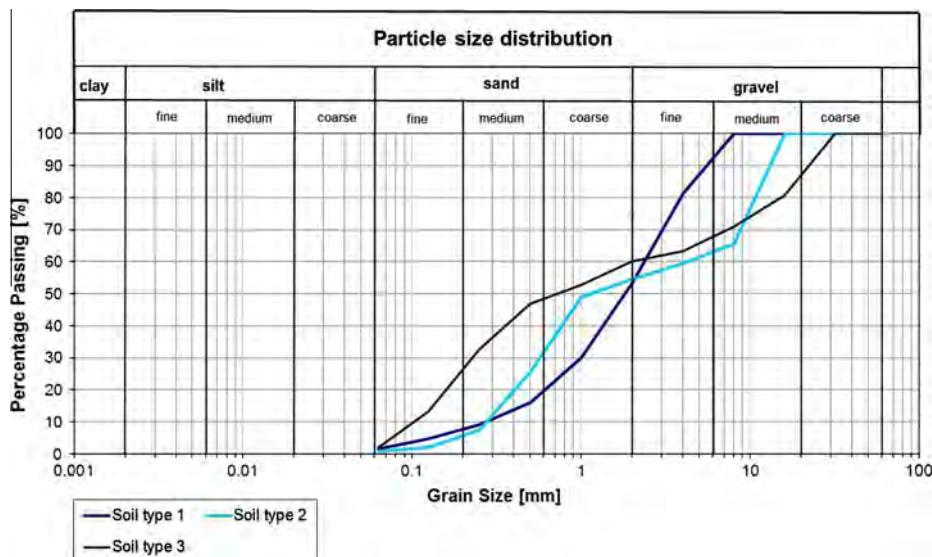
The continuous data collection enables the analyst to find how varying operation parameters influence each other. Fig. 5 shows an example of thrust force and torque correlated in the SGAT software.

3. Initial test results

The initial results are obtained by testing a soil sample with grain size between 0 and 6.4 mm (Fig. 7), a soil from an ongoing European soft ground TBM project and a soil originating from an upcoming soft ground project in Asia. As reference, Soil Abrasion Test™, mineralogy by XRD and grain size distribution analyses have been performed in addition to the SGAT values, see Table 2 for sample mineralogy and SAT™ values.

In the initial testing scheme, some SEM images have been taken, in order to show the degradation mechanisms on the steel's micro-structure. Fig. 8 shows abrasive wear, and Fig. 9 shows tribo-corrosive wear, which is a synergy of abrasive wear and corrosive wear. There has been observed degradation in the micro-structure due to corrosion in short tests (Grødal et al., 2012). The SEM photos showed in Figs. 7 and 8 originates from SGAT tests with a 40 min duration. The corrosive effect has not been possible to detect quantitatively by weight loss, meaning that the SEM photos are the only evidence to show the effect (Grødal et al., 2012).

Observations and explanations on how the soil compaction/density, pressure, and introduction of soil conditioning additives influences the abrasivity and torque measurements are presented in the following.

**Fig. 6.** The grain size distribution of Soil samples 1, 2 and 3.

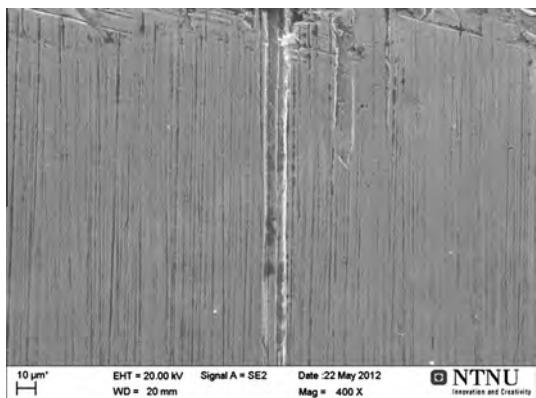


Fig. 7. SEM image showing abrasive wear on the SGAT tool steel after exposure to a dry soil sample. The photo is of the lower steel bar on the SGAT tool (photo Christian Kreyberg Grødal).

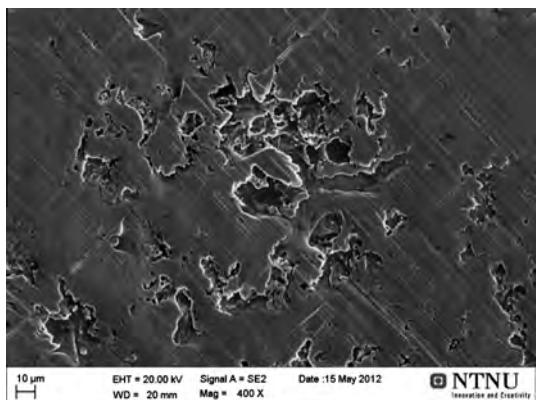


Fig. 8. SEM image showing a combination of abrasive wear and corrosion on the SGAT steel tool after exposure to a soil sample with 8 weight% water. The photo is of the lower steel bar on the SGAT tool (photo Christian Kreyberg Grødal).

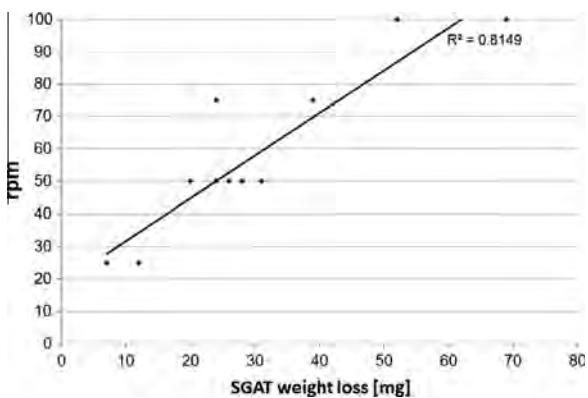


Fig. 9. Recorded influence of rpm on the SGAT weight loss for sample 3.

3.1. Influence of different soil compaction

The influence of compaction on tool life and torque has been measured on Soil sample 1. A proctor hammer has been used to compact the tested soil samples. The varying grade of compaction has been achieved by varying the number of applied blows.

The results summarized in Table 3 are based on a rotation speed of 50 rpm, a varying torque, 200 mm vertical travel length and 40 mm/min penetration rate of the drilling tool and 5 weight% water content in the soil sample.

3.2. Influence of rpm

The influence of rpm on the recorded wear by SGAT has been evaluated on Soil sample 3, see Fig. 9. The testing conditions are fixed at 40 mm/min penetration and 9% water content. The figure also illustrates the variation of test results at identical soil conditions, which seems to increase with increasing rpm.

3.3. Influence of earth pressure mode

In order to simulate the face pressure system at shielded TBMs, the test procedure allows running tests in pressurized mode. The pressurized mode utilizing air which is applied through a valve in the lid of the test chamber. A series of tests have been conducted by adding an over-pressure from atmospheric conditions to 5 bars. The rotation speed of the drilling tool was 50 rpm, with a varying torque, 400 mm total vertical travel length (200 mm downwards and 200 mm upwards) of the drilling tool, and 5-weight% water content in the soil sample. The up and down movement was performed in order to evaluate the pressure's possible influence on direction inside the test chamber.

The weight loss (wear) at different pressures is presented for the lower steel bar (test piece A in Fig. 10) and the upper steel bar (test piece B), as well as the total weight loss in Fig. 10.

The findings in Fig. 10 corresponds well with the Rostami et al. (2012a,b) findings, which conclude that the amount of additional steel wear due to increased ambient pressure is not significant. However, the findings presented in this paper only take into account a few tests on one single, relatively uncompactable soil sample. It is therefore necessary to conduct further testing to conclude, if hyperbaric pressure influences the wear rate.

The example of the face pressurés influence on the tool wear is based on the relatively single-graded soil lacking fines (sample 1 in Fig. 6). The possible effect of the support pressurés influence on the tool wear will be evaluated for a more compactable soil with water content close to the saturation point, at a later stage.

3.4. Influence of moisture and soil conditioning additives

The development of soil abrasivity for various moisture contents, when exposing the SGAT drilling tool to 1000 mm drilling, 50 rpm and 100 mm/min penetration speed, with stepwise drilling (50, 100, 150 and 200 mm) has been evaluated by Jakobsen et al. (2012). The stepwise drilling involves 50 mm drilling down, 50 mm retraction, 100 mm drilling down, 100 mm retraction, etc., until the 200 mm depth is reached and retracted. The stepwise drilling was used in 2012, in order to mix the soil conditioning additives with the soil, prior to the development of continuous conditioning (Jakobsen et al., 2012). For comparison the same development has also been evaluated for 400 mm drilling length, 50 rpm and 40 mm/min penetration speed. Fig. 11 shows the influence and importance of moisture content on the measured weight loss and torque on the SGAT.

The development of abrasiveness for varying water contents (Figs. 11 and 12) corresponds well with Rostami et al. (2012a,b) tests on the Penn state abrasion testing system. The increase of water content has previously showed a general increase of wear by using the Ball Mill Test. (Jakobsen et al., 2009) and (Klemetsrud, 2008). However, the reduction of wear after reaching a specific water content has not been observed previously with the Ball Mill test.

The Norwegian Geotechnical Institute (NGI) performed a study on soil compactability, dependent on different moisture contents in the early 1980s in order to evaluate the tightness of rock fill dams (Damgruppen, 1983). The main conclusions of this study were that

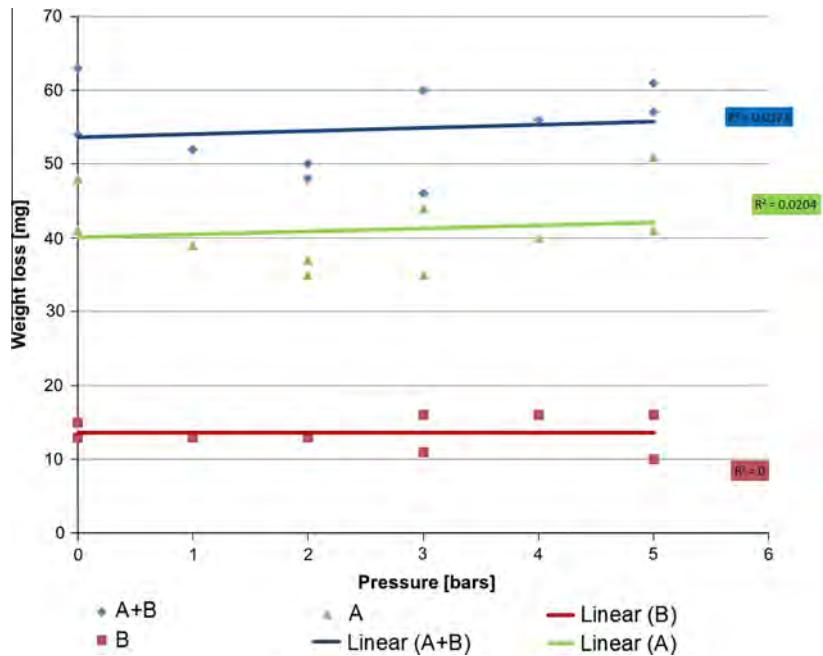


Fig. 10. Example of relation between weight loss (abrasion) and face support pressure (bars) for Soil sample 1.

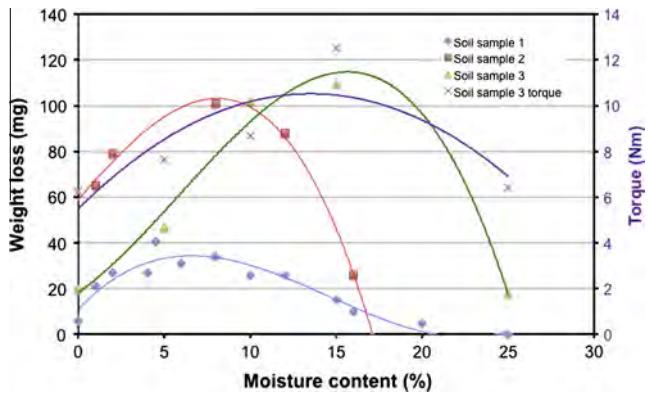


Fig. 11. Example of soil abrasivity development for various moisture contents with the same compaction procedure (5 blows with the proctor hammer in 4 layers). The graph also presents the development of torque for Soil sample 3 with different moisture contents.

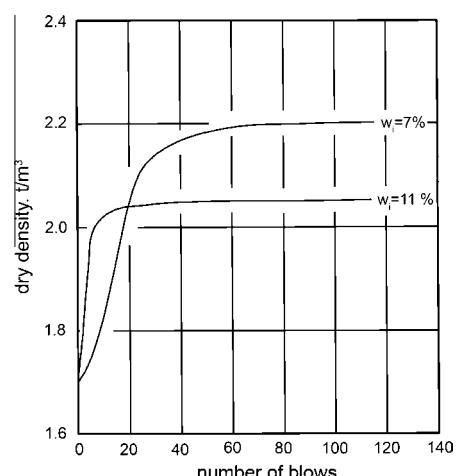


Fig. 13. Influence of the compression work on soil density. Relatively low water content gives a higher density. For higher water contents pores will be easier to close with less compression work (Damgruppen, 1983).

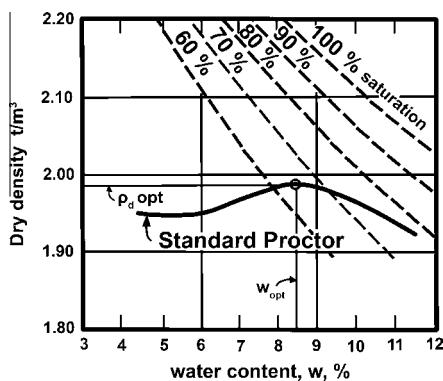


Fig. 12. Compaction curves from a natural moraine (Damgruppen, 1983).

The dry density obtained by compaction is highly influenced on the water content in the soil sample. Single grains have a high strength if the soil is relatively dry. This makes it impossible to fill voids be-

tween the hard lumps. Thus, the dry density is relatively low. If the water content is increased, the soil gets more plastic and during the compaction the voids will be closed, resulting in a higher density (Damgruppen, 1983). This finding can explain the influence of water content on soil density, and thus the soil's potential to cause abrasive wear on an excavation tool. See Fig. 12 for density development related to water content and saturation, and Fig. 13 for the influence of compaction work on soil density.

An evaluation of the possible benefits by adding soil conditioning additives was carried out. The additives were added as (a) foam on top at the soil sample or (b) as a continuous foam injection through small foam injection nozzles 2 cm behind the drilling tool. Initially a pre-mix of soil conditioning additives and soil had been tried, but the results from this approach were discarded as the sample rheology deviated from the reality in front of a TBM.

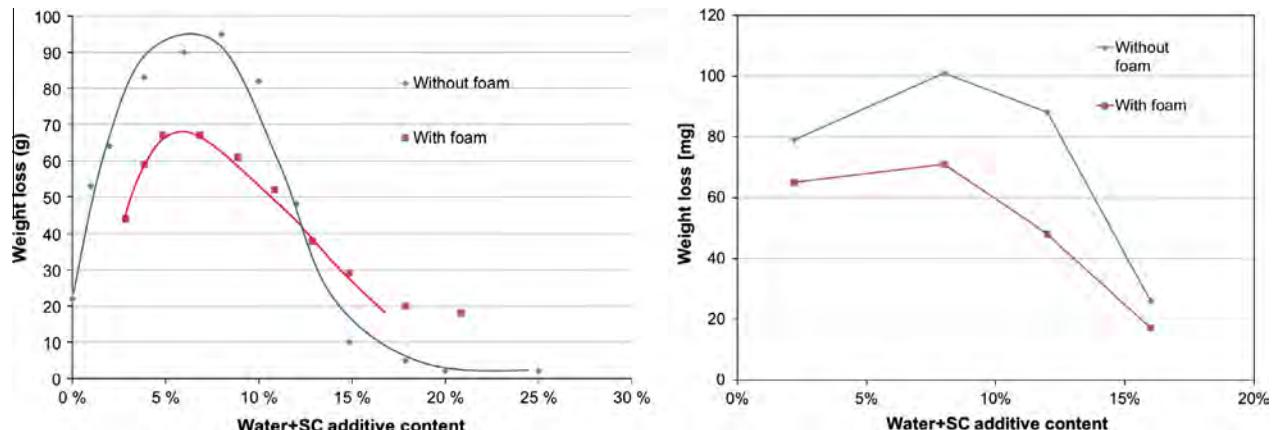


Fig. 14. Soil abrasivity development for conditioned soils. Left figure shows a soil from a natural deposit close to Trondheim, and Right shows results on a soil sample originating from a tunneling project in Europe (Jakobsen et al., 2012).

3.4.1. Tests with foam addition on the top of the sample (testing condition a)

The results presented in Fig. 14 shows that adding foam on the top of the soil sample reduces the weight loss of the drilling tool, as well as the torque. It was however discovered that the foam did not properly mix with the bottom part of the soil sample. This might indicate a too high Foam Injection Rate (FIR) in the upper part of the soil sample and a non-existing conditioning of the lower part of the soil sample. The densities of the two soils presented in Fig. 13 are approximately 2100 and 1900 kg/m³, and the results do not have torque measurements. The tests were done in atmospheric pressure conditions with foam expansion ratio (FER) of 10 and foam injection ratio (FIR) of 30%. The results shown in Fig. 14 are obtained on moistened soil sample prior to testing.

The results obtained by foam addition on the top of the sample seem to indicate benefits of soil condition, in terms of reduced wear and torque. However, the upper part of the soil sample is likely to be over-conditioned, while the lower part remains under-conditioned to unconditioned. Quantification of varying grades of soil conditioning, subsequently the test is not done. However, in all the conducted tests, it appears that the top of the soil sample (10 cm) is over-conditioned and the lower part of the soil sample is gradually exposed to less soil conditioning additives. This effect will again not correctly indicate the effects and benefits of soil conditioning agents.

3.4.2. Continuous foam injection (test condition b)

In order to achieve a proper continuous foam injection and hence an evenly conditioned soil sample, a total of three different

tool designs have been evaluated. So far, the most successful tool design is shown in Fig. 2. Prior to the design showed in Fig. 2, ejection of soil conditioning additives was tried from pipes 1 and 4 cm behind the lower steel bar. The results achieved by running tests with continuous soil conditioning are shown in Figs. 15 and 16.

Fig. 15 repeats the indication of the strong relation between moisture content and wear, and shows the high influence of soil conditioning additives injection rate. In the example showed in Fig. 16, the wear is reduced down to less than 20% of the initial value dependent on the moisture content. The torque and thrust were reduced by more than 30% for the fixed penetration rate of 40 mm/min, on Soil sample 3 with 15% water.

Several techniques have been evaluated for the continuous addition of soil conditioning additives into the soil. The first attempt was based on foam injection through two holes at the SGAT drill-shaft about 5 cm above the drilling tool. The second version used foam injection through the upper drilling tool (part B), whereas the final and currently used version (Fig. 4b) uses a foam nozzle at the level of the lower drilling tool (part A) which is in contact with the compacted soil – directly corresponding with the foam injection at the TBM cutterhead. Only this modification, by being able to apply the additives exactly at the contact zone between the drilling tool and the compacted (virgin) soil, allows SGAT test results to be directly translated to effects in EPB TBM tunneling.

In Fig. 15 the strong influence on wear by the soil's water content can be observed together with the influence of continuous foam injection. Further testing in this manner needs to be carried

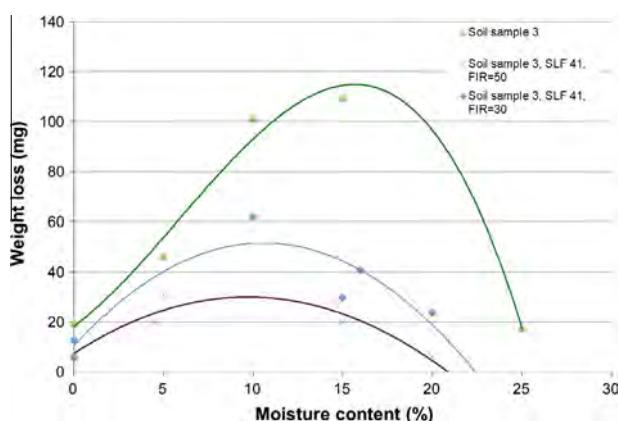


Fig. 15. Example of soil abrasivity development for Soil sample 3 for different moisture contents, and the influence of the foam injection ratio (FIR).

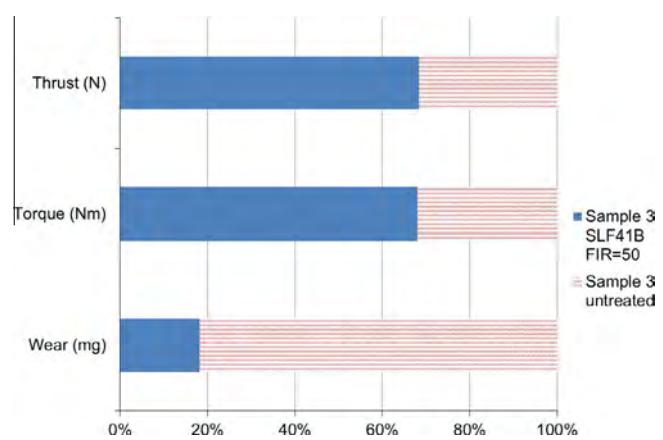


Fig. 16. Example of the influence of proper soil conditioning for Soil sample 3. The wear is reduced to approximately 1/5, and the torque and thrust to approximately 2/3 of the untreated soil.

out, in order to find "good" and "bad" soil conditioning for various soft ground samples.

3.4.3. Premix of soil and soil conditioning additive (test condition c)

In order to evaluate the possibility of premixing soil samples with soil conditioning additives some trial tests have been conducted with FER 10 and FIR of 50%. The tests were conducted with rotation speed of 50 rpm and with a total of 400 mm vertical movement of the drilling tool (200 mm downwards and 200 mm retraction upwards). A small concrete mixer was used to make the premix of soil and soil conditioning additives.

The results obtained by testing a premix of soil and soil conditioning additives do not show the reality between soft ground excavation tools and the conditioned soil, as the recorded weight loss and torque are very low, and in the same range as what is expected for dry testing. For Soil sample 1 the weight loss ranged from 5 to 7 mg and the torque from 6 to 7 Nm in premixed soil and soil conditioning additives. Therefore, the reduced torque and wear is not relevant for TBM tool life research or other phenomena taking place at the cutterhead level. However, these results can only be relevant for estimating the conditions in the EPB TBM working chamber behind the TBM cutterhead.

In order to evaluate the influence of soil conditioning additives correctly, their introduction technique is of high importance. The only way to obtain comparable results to the TBM cutterhead situation is using a continuous injection of soil conditioners at the cutterhead tool which is penetrating into a consolidated ground.

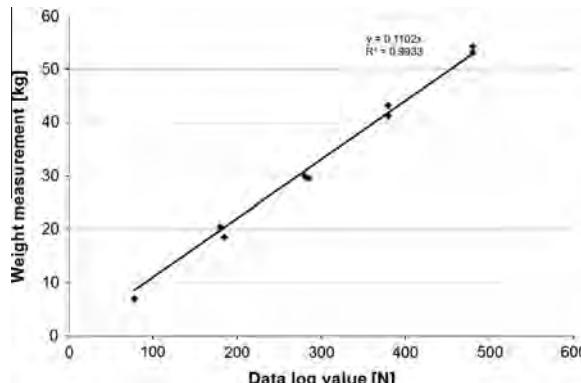
4. Discussion

4.1. General

The ambition and purpose of the design of the test and the applied test procedure is to replicate an in situ soil – TBM tool contact, in a small and simplified scale. The drilling tool was designed in a way which is causing a relative small area of initial contact between the tool and the soil.

The main differences between the SGAT and the existing Penn state soil abrasion testing system are the design of the drilling tool, the rotation speed and penetration of the tool and the possibilities to introduce soil conditioning additives (e.g. foam or bentonite) during the test. The new Soft Ground Abrasion Tester (SGAT) does in addition allow testing of soil samples with a defined compaction. Table 3 shows the similarities and differences between the SGAT and Penn state soil abrasion testing system.

The SGAT apparatus has the possibility of drilling through soil and soft ground samples, hence close to real TBM conditions in soft ground.



The limitation of the presented SGAT test procedure as compared to the real life TBM boring process consists mainly in the limit of the soils grain size. The current tool allows 10 mm large grains to be included in the soil sample. Thus, grains above 10 mm need to be removed from the soil sample material prior to testing with the current drilling tool design. The limitation will not be substantial, as the test is designed to test soft ground conditions. However, in soils containing large amount of gravels and stones, the current test may not be equally suitable.

Our analysis finds the test to be torque sensitive of the position of the drilling tool, indicating an increasing soil compaction towards the bottom. This effect is most likely induced by the layered Proctor hammer compaction procedure.

Equally, we find a clear relation between the measured tool wear and the required torque, as well as increasing tool wear by increasing rpm. As the torque increases, the contact forces between the steel tool and soil increases, causing a higher potential for degradation of the steel. The torque has also proven to show grain size variations in the soil sample quite well. A limitation in the torque measurement is an uneven compaction through the soil sample. The lowest part of the sample probably has a higher compaction than the upper part, due to the layered compaction procedure.

4.2. Test relevance and repeatability

The SGAT apparatus still lacks of a detailed test procedure intended for commercial use. The test procedure presented in this paper is preliminary, and might be changed as more data are measured and compared to real torque, thrust and tool life data from TBMs. The test apparatus is designed to evaluate several variables influence on abrasive wear and torque. Thus, the test procedure should be decided prior to testing of a new batch of sample material, based on what the test results should show or not.

In order to quantify the reliability a total of 10 tests on Soil sample 1 with 10% water content, 50 rpm and 40 mm/min penetration were carried out. The standard deviation of these tests were 6.3, which is acceptable taking into account the sources of errors present in testing of geo material with possible varying distribution of water content and compaction.

For assessing the validity of the automatic torque and thrust recording, manually measurements with a scale and torque wrench have been carried out. The findings in Fig. 17 show that there are not any inconsistency between the collected thrust and torque values in the SGAT apparatus.

A few relations between SAT™ values and SGAT values are shown in Fig. 18. The measured Soil Abrasion Test™ (SAT) values do not range in accordance with measured wear on the Soft Ground Abrasion Tester (SGAT), Soil sample 3 has the lowest SAT

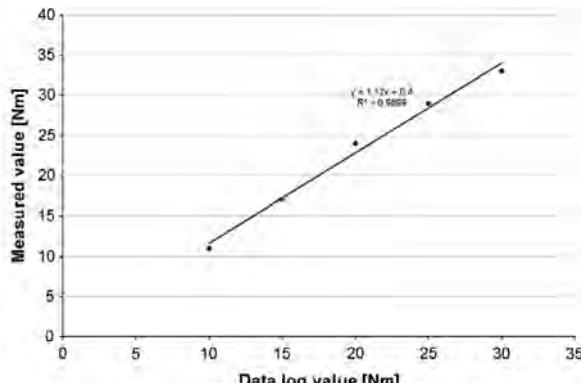


Fig. 17. Relation between data log values and measured values for torque and thrust on the SGAT apparatus.

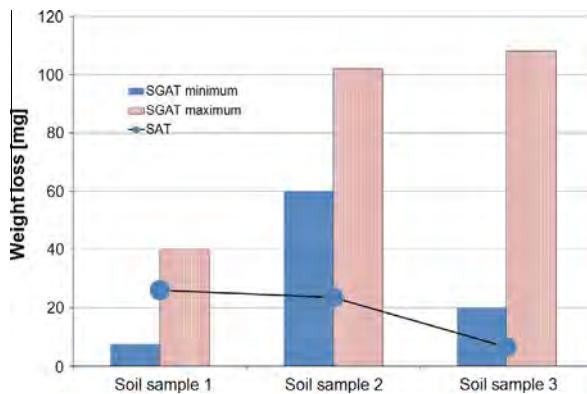


Fig. 18. Relations between SAT™ values and weight loss measured on the SGAT apparatus.

value and the highest measured SGAT wear. The main reasons for this are most likely related to the influence of compaction and soil humidity, which are not taken into account by the SAT™, as well as mineralogy of Soil sample 3, consisting of fines consisting of low-abrasive minerals mica and calcite, with coarser particles consisting of quartz. It is believed that the fines creates a cohesive paste holding the coarser abrasives, causing the high weight loss. The SGAT findings has also shown that a calculation of a more reliable wear index could be achieved by combining the measured SAT™ values with factors for in situ soft ground properties, like humidity and compaction.

4.3. Suggestions for further work

The initial testing of the SGAT apparatus and method comprises only three soil samples. In order to gain more experience and knowledge on how various soil types (clay, silt, sand and gravel) behave when they are exposed to various compaction grades, use of soil conditioning additives and pressure, there is a need for further testing.

For pressurized testing conditions, the tests presented in this paper are conducted on 5% water content. This is relatively far from reality as most pressurized TBM performances are below the ground water table. Further testing on more soil types and with water content close to the saturation point is therefore needed.

The apparatus enables a unique testing procedure being very close to the excavation conditions at a real TBM. The test results obtained with the SGAT apparatus is, however, so far not correlated or validated against any real TBM excavation. This needs to be done in order to evaluate the scaling effect between the SGAT apparatus and a real EPB TBM. Such a study will also comprise an evaluation of the necessity and relevance of distinguishing between primary and secondary wear on SGAT test pieces.

In order to evaluate the relation between SAT™ and SGAT values, more testing is needed. The authors are currently working on a SAT™ based estimate on tool life, where the SAT™ values are adjusted with other relevant geotechnical values.

In this current paper, the soil rheology is missing. Generally it should be evaluated in connection with pre-investigation and evaluations of soil conditioning additives. For the further research on the SGAT apparatus, we will therefore initiate to run flow table mortar testing according to EN 413-2 and EN 459-2 in order to check the conditioned soils rheology for EPB TBM applicability.

5. Conclusions

The set-up and design of the apparatus has the capability to evaluate how soft ground abrasivity is influenced by water content,

pressure, compaction and soil density. In addition, the important influence of different types of soil conditioning additives can be evaluated.

The initial results presented and discussed in this paper are very promising for evaluating various geotechnical parameters' influence on soft ground abrasivity. The TBM operation's influence on tool wear can also be evaluated by adjusting the apparatus rpm, penetration rate, thrust and soil conditioning parameters (Foam Expansion Rate (FER) and Foam Injection Rate (FIR)).

5.1. Main findings

- Wear on steel excavating soft ground in the new SGAT apparatus is clearly influenced by
 - The nature of the soil (e.g. mineralogy, quartz content, abrasiveness, grain size distribution, compaction).
 - The moisture of the soil influences the wear (weight loss) as high as 500%.
 - Type and method of soil conditioning (soil conditioning type, FER, FIR) can reduce the wear rate down to 20% of the unconditioned sample.
- The pressure added to the test chamber did not show any significant influence on the measured soft ground abrasivity for the soil material with 5% moisture content used in this initial research.
- There is a clear correlation between the measured wear and the recorded torque, as well as rpm by the SGAT apparatus.
- The correct use of soil conditioning additives, apart from the above mentioned wear reduction, has clear effects on
 - Reduction of torque by approximately 40% in some cases.
 - Reduction of necessary SGAT penetration thrust by approximately 40% in some cases.
- Furthermore, the differences between "good or bad" soil conditioning can now be quantified, and results from the SGAT apparatus can be used to evaluate and to improve the effect of soil conditioning additives.

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