Abrasiveness of Soft and Sandy Soils with Realistic Densities and Moisture Contents

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Abstract: *Predicting the rate of wear and replacement of cutters may be an important consideration in soft-ground tunnelling by the slurry shield or EPBM techniques. The SAT (Soil Abrasiveness Test) is frequently used to characterize the abrasiveness of sediments and sands. Although naturally granular material is tested, only the size fraction less than 4mm diameter is tested, in a loose dry condition. The measured abrasiveness may not be truly representative of the in-situ conditions, where the material may be denser, coarser, and wetter than the SAT laboratory test material. The SGAT (Soft Ground Abrasion Tester) has recently been built to test naturally occurring sediments in conditions more closely approximating field conditions. Testing protocols for ensuring that SGAT test specimens have densities and moisture contents closely approximating field conditions have been developed, and will be described in the paper. Geotechnical investigation samples from 3 local tunnelling projects, submitted for SAT testing, have now also been tested by the SGAT method. The outcomes of the 2 sets of test results will be discussed.*

Keywords: *Soft-ground tunnelling, Soil abrasiveness, Cutter wear, Geotechnical investigations.*

1. INTRODUCTION

Large and complex tunnel boring machines (TBMs) are increasingly being used in soft-ground conditions, especially in urban environments. It is desirable that the rate of damage or wear to cutting tools and materials handling systems be predicted and quantified when planning and scheduling TBM operations, so that the costs and delays associated with changes and replacements can be accommodated in the management systems. Well-established testing procedures such as the NTNU/SINTEF soil abrasion test (SAT) method [1] and the ABROY (LCPC) abrasimetre [2] [2][2] may semi-quantitatively quantify relative abrasiveness, but do not take into account density, moisture content, cohesion, and the existence of particles larger than 4 mm in the soil matrix [3], so may not necessarily truly represent the abrasiveness under the practical field conditions. To resolve the inconsistency between existing abrasiveness testing procedures and soft ground field situations, Gharahbagh et al. (2011) [4] and Rostami et al. (2012) [5], among others, developed more complex testing methodologies, more closely approximating field conditions. Jakobsen et al. 2013 [6] recently developed their Soft Ground Abrasion Tester (SGAT) to improve the predictability of TBM tool wear.
The ability to predict the wear caused on TBM cutting tools in real saturated granular sediments can improve project delivery for project owners, engineers and contractors by preparing more informed and thorough project tenders, leading to refined schedules and cost estimations for projects. The purpose of this paper is to bridge the knowledge gap between the well-known SAT procedure and the recently developed SGAT approach by applying both testing methods to the same soils in order to compare SGAT results and SAT results.

2. MATERIALS AND METHODS

2.1. Soils and properties

In this research a total of 6 types of soil were used, three of which were commercially available sands, and the other three were naturally occurring soft ground soils. Table 1 presents a description and physical properties of the soil samples. The soil types are demonstrated in Figure 1.

Table 1- Description and physical properties of the soils used in this research

Soil ID	Description	Specific Gravity	Coefficient of Uniformity	Coefficient of Curvature
BTS	Brown Turf Sand (commercially available)	2.62	2.23	0.83
MBS	Muckadilla Turf Sand (commercially available)	2.60	1.50	0.86
WGS	White Granitic Sand (commercially available)	2.69	5.71	1.19
F	Naturally occurring sandy soil (Perth, AU)	2.58	3.76	1.33
M	Naturally occurring soil mixture of clay, silt and & a little sand (Melbourne, AU)	2.62	NA	NA
W	Naturally occurring mixture of clay, silt and sand (Auckland, NZ)	2.64	NA	NA

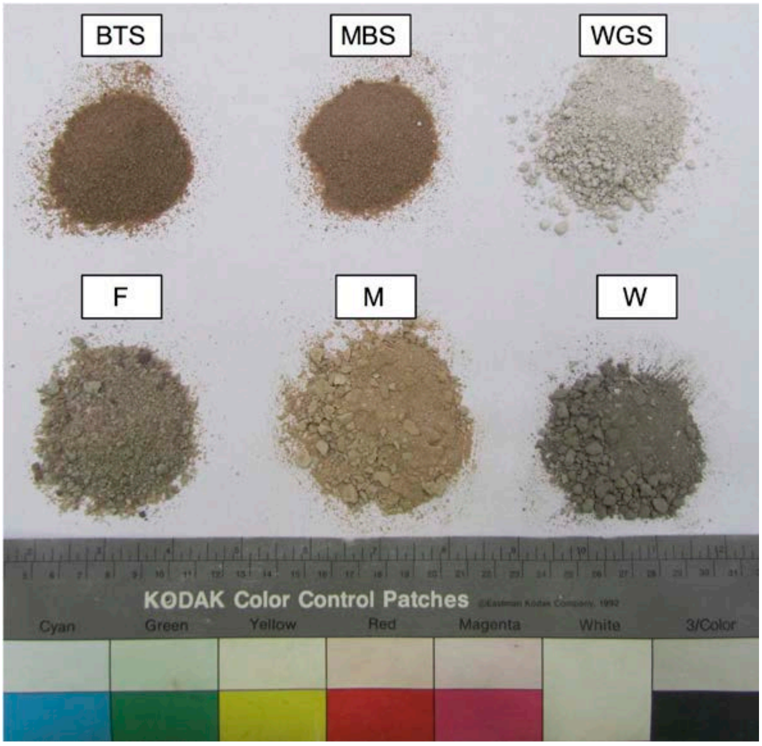

Figure 1 – Soil types used in this research.

Figure 2 shows the particle size distribution (PSD) of the soils used in this research. Among the naturally occurring soils, type F has low fine content (clay and silt) and mainly consists of sand particles. Soils M mainly consists of clay and silt.

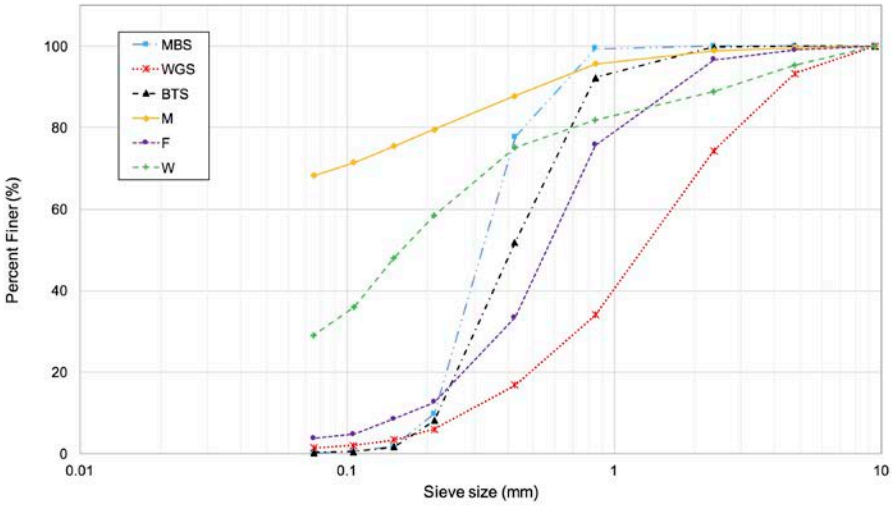

Figure 2 – PSD of soils used in this research.

2.2. Testing program

The soil abrasion tests (SAT) were carried out using the modified method of NTNU/SINTEF for soils, in which particles < 4 mm were used [1].
The SGAT testing protocol in this study is a modification of the procedure explained in Jacobsen et al. (2013) [6]. Oven-drying at high temperatures may alter some mechanical properties of clayey sedimentary soils, therefore, the soil samples were dried for 48 hours in an oven set to 30 °C. Rather than testing the oven-dried samples (as is the case in SAT), volumes of water sufficient to achieve moisture contents of 2 to 20% were added to individual samples and left in sealed plastic bags to cure overnight. For each SGAT test run approximately 6-8 kg of soil is required and samples wetted to different moisture contents need to be compacted in the SGAT mould (150 mm diameter). For consistency, all samples were densified using 30 drops of the standard Proctor hammer [7]. Samples were compacted in four layers each finishing approximately 40 mm thick (160 mm total). After compaction, the mass and the approximate volume is measured by the height of the soil column in the test mould, allowing the approximate density to be calculated.
Figure 3 shows the SAT apparatus, and SGAT machine as well as their accessories. The Bamford Rock Testing Services (BRTS) impeller is an exact replica of the tool described by Jakobsen et al. 2013 [6], with two HRC 20 steel bars,10 mm by 10mm cross section, 130mm long each, welded together in a cross shape. Prior to their first use, the SGAT drilling tools are run in an abrasive soil or sand sample for 2 hours, to blunt their sharp edges. The tool is not sharpened after each test; rather it is replaced when it is perceptibly worn. This is when the worn length reaches half of the length of each of the four vanes.

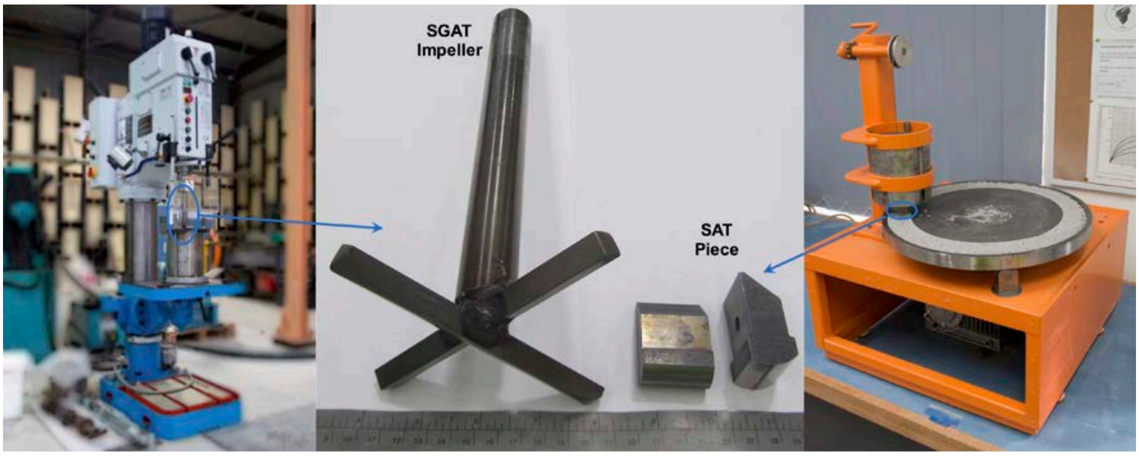

Figure 3. SGAT machine (left), SGAT impeller and SAT piece (middle), and SAT apparatus (right)

Jakobsen et al. (2013) [6] state that the standard test will produce about 150 mm of tool penetration at a penetration rate of 40 mm/min, and a rotation speed of 75 rpm. This implies a "standard" test time of 3.75 minutes, during which the impeller will rotate 281.25 times. The drilling machine used in the BRTS lab has a standard constant penetration rate of 29 mm/min, and a constant rotation speed of 72 rpm. The target depth of 150mm may not be achieved if the amount of sample sent by a client is less than the requested 8 kg (as is unfortunately sometimes the case), so the actual penetration depth able to be achieved before bottoming is recorded. The mass of the SGAT drilling tool is recorded before and after each test run. Abrasiveness is measured as a function of the mass loss suffered by the standard impeller during one test run. Then the two correction factors are applied- correction for the duration of the test run (T), and correction for the depth of penetration (P). T and P are obtained using Equations, 1 and 2, respectively.

$$T = \frac{150\ \text{mm}}{\text{Actual depth of penetration(mm)}} = \frac{281.25}{72 \times \text{Test duration}} \quad (1)$$

$$P = \frac{150\ \text{mm}}{\text{Actual depth of penetration(mm)}} \quad (2)$$

The SGAT value is obtained by multiplying T and P correction factors by the weight loss of the SGAT impeller in milligrams (mg).

3. RESULTS AND ANALYSIS

Figure 4 compares the weight worn off the SAT piece (SAT value) and that worn off the SGAT impeller (SGAT value). Comparing the absolute masses proportionately worn off an approximately 190 g SAT workpiece with that of an approximately 2000 g SGAT impeller is not considered relevant here. The initial results appear to suggest that the soils containing a greater sand fraction (BTS, MBS, WGS, and F) show less weight loss than the sand-poor soils (M and W) in the *(wet)* SGAT test, (i.e. lower abrasiveness), whereas the sand-rich soils show greater weight loss than the sand-poor soils in the *(dry)* SAT test, (i.e. higher abrasiveness).

At first sight this seems counter-intuitive, as it might be expected that coarser-grained samples would be more abrasive than finer-grained samples, whether tested wet or dry. It is certainly something that will attract further research, in SGAT testing of finer-grained naturally-occurring soils, from the "M" and "W" project sites.

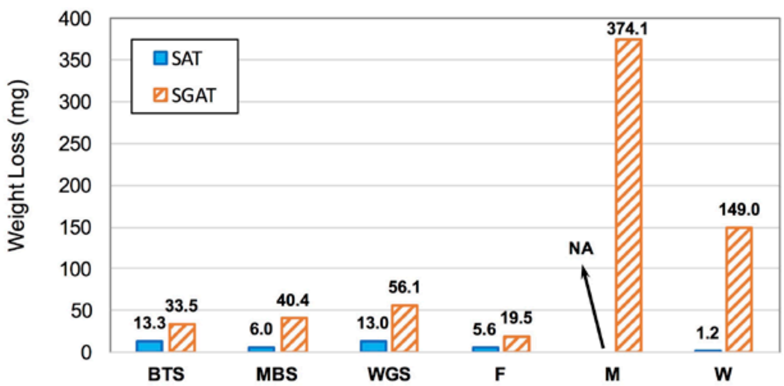

Figure 4 – Comparison of the SAT and SGAT results

Figure 5 compares the compaction curves and SGAT value – moisture content plots of the soils. SGAT value – moisture content curves resemble the well-known compaction curves, in which abrasiveness initially increases by increasing the moisture content and from a certain point decreases by further increasing the moisture content. The abrasiveness in the field situation could be characterized by a point along the line of best fit through the SGAT value – moisture content curve.

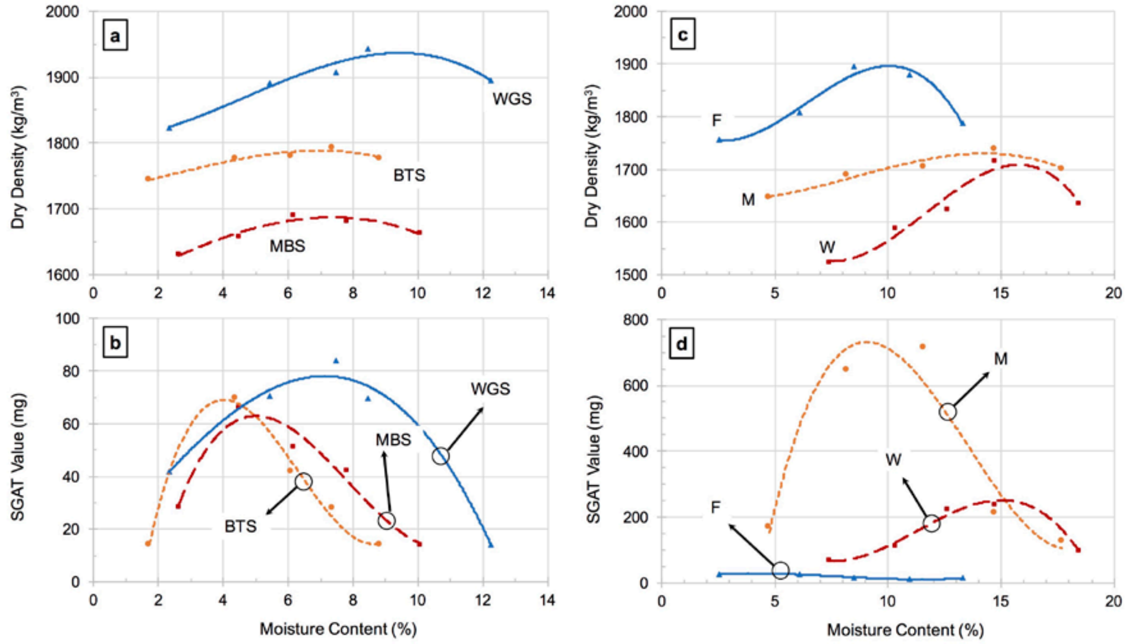

Figure 5 – Plots of (a) and (b) compaction curves and SGAT value vs moisture content for commercial sands, and (c) and (d) compaction curves, and SGAT value vs moisture content for naturally occurring soils

Figure 6 shows the log-normal distribution plot generated using the 30 SGAT values obtained in this research. Five classes of abrasiveness were established- “Very Low”, “Low”, “Medium”, “High”, and “Very High”. The boundaries between the classes correspond approximately to the 20th, 40th, 60th, and 80th percentiles on the log-normal distribution.

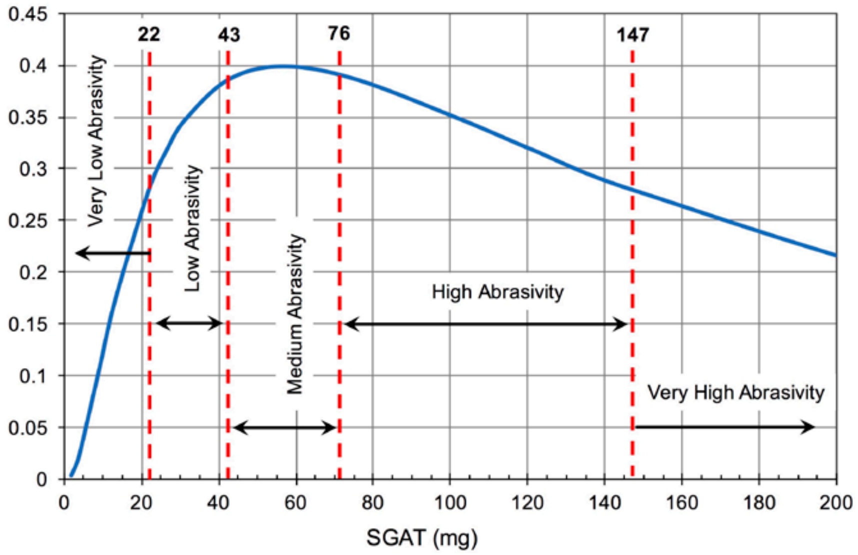

Figure 6 – Log-normal distribution plot to define classification limits based on SGAT data

Table 2 compares the abrasiveness classification of the soils based on SGAT results using Figure 6, and the SAT results using NTNU/SINTEF classification [8]. In the NTNU/SINTEF classification, SAT<7 is classified as “Low”, 7<SAT<22 is classified as “Medium”, and SAT>22 is classified as “High”. Obviously, while SAT proposes a unique classification for each soil, measured at unique moisture content (zero) and density (loose) conditions, classifications based on SGAT can range from "Very Low" to "Very High", depending on the density and moisture content of the soil. For instance, in the case of WGS, while a "Medium" classification was shown by the SAT results, a range of "Very Low" to "High" abrasiveness was shown for the WGS for different states of the sample.

Table 2. Abrasiveness classification of soils based on SGAT and SAT results

Soil ID	Moisture content (%)	Abrasivity (SGAT)	Abrasivity (SAT)
BTS	1.7	Very Low	Medium
	4.4	Medium	
	6.1	Low	
	7.4	Low	
	8.8	Very Low	
MBS	2.6	Low	Low
	4.5	Medium	
	6.1	Medium	
	7.8	Low	
	10.0	Very Low	
WGS	2.3	Low	Medium
	5.4	Medium	
	7.5	High	
	8.5	Medium	
	12.2	Very Low	
F	2.5	Low	Low
	6.1	Low	
	8.5	Very Low	
	10.9	Very Low	
	13.3	Very Low	
M	4.8	Very High	NA
	8.2	Very High	
	11.6	Very High	
	14.7	Very High	
	17.7	High	
W	7.4	Medium	Low
	10.3	High	
	12.6	Very High	
	14.7	Very High	
	18.4	High	

4. DISCUSSION & CONCLUSION

The SGAT (Soft Ground Abrasion Tester) is being developed as a useful tool to improve the accuracy of characterizing ground conditions for soft-ground machine tunnelling. The widely accepted SAT (Soil Abrasion Test) should continue to be used for broad classification purposes. The ability of the SGAT to more accurately and quantitatively measure the abrasiveness of sedimentary deposits and soils, in conditions closely simulating the conditions of density and moisture content in which they will be excavated by a TBM, makes it potentially a far superior tool.

The unfortunate logistical fact that it may be difficult to obtain many samples, each of at least 10 kilograms mass, for testing from exploratory borings during the investigation phase of a tunnelling project, provided the rationale for the test work on a range of commercially readily available sands: after characterizing the PSD and the soil mineralogy of the small submitted samples, it may be possible by mixing calculated proportions of the several "commercial" sands to construct analogue materials in masses large enough for significant testing at many densities and moisture contents, to bracket the full range of expected variability in-situ.

Planned work at BRTS will enable the injection of different conditioning agents into the test chamber, to quantify the reductions in abrasiveness that may be achieved by appropriate soil conditioning. The consequent changes in torque thrust and power will also show how optimum TBM operating parameters for a particular soil might result from the appropriate soil conditioning agents.

5. ACKNOWLEDGMENTS

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6. REFERENCES

1. Nilsen, B., et al., *Abrasivity of soils in TBM tunnelling.* Tunnels & Tunnelling International, 2006.
2. LCPC, *LCPC Abrasivemeter Standard.* 1990, Normalisation Francaise p. 18-579.
3. Jakobsen, P. and J. Lohne, *Challenges of methods and approaches for estimating soil abrasivity in soft ground TBM tunnelling.* Wear, 2013. **308**(1): p. 166-173.
4. Gharahbagh, E.A., J. Rostami, and A. Palomino, *New soil abrasion testing method for soft ground tunneling applications.* Tunnelling and Underground Space Technology, 2011. **26**(5): p. 604-613.
5. Rostami, J., et al., *Development of soil abrasivity testing for soft ground tunneling using shield machines.* Tunnelling and Underground Space Technology, 2012. **28**: p. 245-256.
6. Jakobsen, P.D., et al., *Development of the Soft Ground Abrasion Tester (SGAT) to predict TBM tool wear, torque and thrust.* Tunnelling and underground space technology, 2013. **38**: p. 398-408.
7. AS1289.5.1.1, *Methods of testing soils for engineering purposes Soil compaction and density tests - Determination of the dry density/moisture content relation of a soil using standard compactive effort*. 2003, Standards Australia: NSW, Australia.
8. Jakobsen, P.D., A. Bruland, and F. Dahl, *Review and assessment of the NTNU/SINTEF Soil Abrasion Test (SAT™) for determination of abrasiveness of soil and soft ground.* Tunnelling and underground space technology, 2013. **37**: p. 107-114.