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ORIGINAL PAPER

Influence of Corrosion on the Abrasion of Cutter Steels Used in TBM Tunnelling

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Abstract Abrasion on tunnel boring machine (TBM) cutters may be critical in terms of project duration and costs. Several researchers are currently studying the degradation of TBM cutter tools used for excavating hard rock, soft ground and loose soil. So far, the primary focus of this research has been directed towards abrasive wear. Abrasive wear is a very common process in TBM excavation, but with a view to the environment in which the tools are working, corrosion may also exert an influence. This paper presents a selection of techniques that can be used to evaluate the influence of corrosion on abrasion on TBM excavation tools. It also presents the influence of corrosion on abrasive wear for some initial tests, with constant steel and geomaterial and varying properties of the excavation fluids (soil conditioners, anti-abrasion additives and water). The results indicate that the chloride content in the water media greatly influences the amount of wear, providing evidence of the influence of corrosion on the abrasion of the cutting tools. The presence of conditioning additives tailored to specific rock or soil conditions reduces wear. However, when chloride is present in the water, the additives minimise wear rates but fail to suppress corrosion of the cutting tools.

Keywords TBM · Tunnel boring · Abrasion · Cutter steel · Corrosion · Tribocorrosion

1 Introduction

Determining the abrasiveness of soil and hard rock has become a commonly used pre-investigation method during tunnelling projects. Wear and tool life estimates for tunnel boring machines (TBMs) based on simplified methods have been done since the mid-1970s (Bruland 1998a, b). The most common approaches to estimating tool life in connection with hard rock TBMs are the NTNU model (including the Cutter Life Index^{TM}, CLI) and the Cerchar Abrasivity Index (CAI) employed by the Colorado School of Mines prognosis model for TBM performance. The CLI and CAI estimation approaches are both based on tests of steel interaction with a dry rock sample. In the last 5 years, there has been an increased focus on obtaining tool life estimates for TBMs operating in soil and soft rock conditions (Nilsen et al. 2006). Gharahbagh et al. (2011) suggested a method for testing in situ soils involving a wide range of grain sizes (0–12 mm), the introduction of soil conditioning additives and tests on moist soil samples. At NTNU and SINTEF, a similar approach is used (Jakobsen et al. 2013) to study the effect of corrosion on the abrasion of cutting tools used in TBMs, including consideration of the compaction of the soil.

In the present study, tests have been conducted involving abrasion in corrosive media (referred to as tribocorrosion). These tests involved the exposure of a steel sample, representing that used in TBM excavation tools, to abrasion by a

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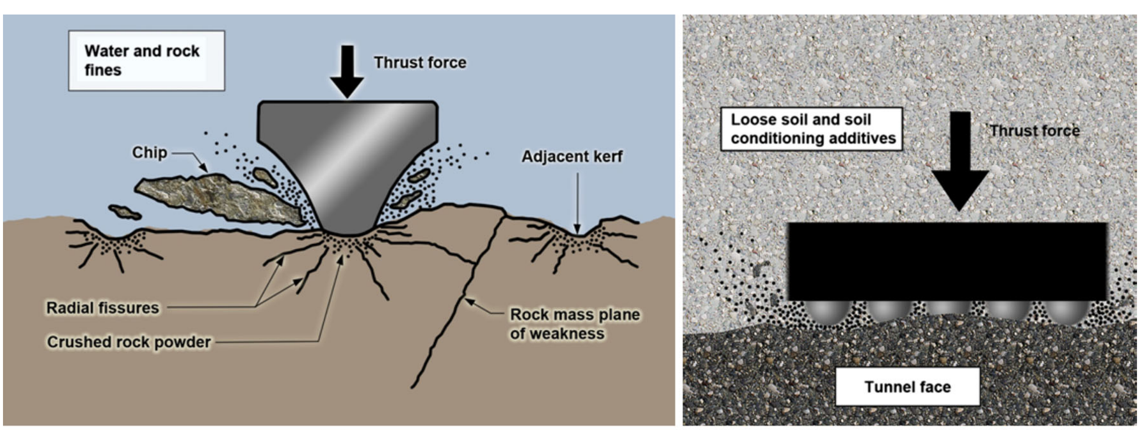
hard rock and a soil. The corrosive effect of soil conditioning and anti-abrasion additives have been evaluated, and have been compared under different liquid media conditions.

1.1 Concept Definitions for Tunnel Boring: Tribology and Tribocorrosion

Tribology was defined in 1966 as the science and technology of interacting surfaces in relative motion (Jost 1966). This is a multi-disciplinary subject combining many different scientific disciplines, including studies of the lubrication, friction and wear of materials. Abrasion is among the four main wear mechanisms recognised in the tribology literature (Rabinowicz 1965; Czichos 1978; Stachowiak and Batchelor 2005). Abrasion is a form of wear caused when solid materials are loaded against particles having equal or greater hardness (Stachowiak and Batchelor 2005). This is commonly experienced in TBM applications. In tribology, two main modes of abrasive wear are defined: two-body abrasion and three-body abrasion. Two-body abrasion occurs when the harder particles or firmly held grits act like a cutting tool against a solid material. Three-body abrasion occurs when the abrasive particles are free to roll and slide over the surfaces of two interacting solid materials. An example of three-body abrasion in a TBM tunnelling context is the excavation of non-cohesive soils such as uniformly graded sands. In theory, hard rock excavation can be regarded as a two-body abrasion process, provided that the flushing and transport of rock chips and fines by the tunnelling system removes any loose particles prior to contact with the excavation tools. Abrasion behaviour in both hard rock and soil TBM tunnelling contexts is complex, and is, as yet, not fully understood. Figure 1a illustrates how the hard rock excavation process works—primarily by means of the interaction of two hard bodies (the cutter disc and the rock), with almost no free particles at the contact. By way of contrast, Fig. 1b shows the interaction of a ripper tool, commonly used in loose friction soils. The term ‘abrasive wear’, commonly used in tunnelling contexts, is not necessarily descriptive of the different wear mechanisms involved in the tribological system which applies to hard rock and soil TBM excavation. These mechanisms depend on system conditions such as speed, the hardness of the interacting materials and environmental factors (corrosive or non-corrosive environments, loads etc.). Identifying wear mechanisms is a way of gathering information about factors such as wear rates and tool failure mechanisms. However, no general approach to predicting wear is, as yet, available, although more than a hundred “laws” relating to wear can be found in the literature (Ludema 1991). For this reason, tests on materials and/or investigations of degradation micromechanisms remain the only ways of improving system efficiency while operating in abrasive environments.

An important topic in tribology is the interaction between mechanical damage and chemical degradation encountered in systems exposed to aqueous or aggressive, high-temperature environments (Stachowiak and Batchelor 2005; Muñoz and Espallargas 2011). In recent years, issues surrounding the effects of mechanical processes on the chemical degradation of materials, and the effects of chemical action on a material’s mechanical response, have developed into interesting topics in tribology. This has led to the expansion of a new research area in the field of tribology called ‘tribocorrosion’. Tribocorrosion uses tribology, corrosion science and engineering approaches to investigate the degradation of materials by this mechanism. Materials properties, surface transformations and electrochemical reactions constitute the primary focus in tribocorrosion studies, in which a combination of mechanical and chemical



(a) (b)

Fig. 1 Simplified tribo-systems involving tunnel boring machine (TBM) tools: **a** hard disc rock cutter (after Bruland 1998a, b) and **b** ripper tool with carbide steel inserts parameter interactions results in unusual responses by the materials involved. In the last 20 years, tribocorrosion research has been shown to be highly relevant in the case of passive metals such as stainless steels. However, the response of active metals, such as the steels used in excavation tools, is a field which demands more detailed investigation (Muñoz and Espallargas 2011).

1.2 Why Tribocorrosion in TBM Applications?

Verhoef (1997) described a tribological system for the cutter dredging of soft rocks and soils, incorporating components such as the cutting tools, soft rock/soil, rock debris and the surrounding medium, which often consists of seawater. In addition to these components, a TBM may encounter all types of geology, from soft clays, silts, sands etc., to extremely hard rocks and their associated mineralogies and chemistries (Fig. 1). During tunnelling, the combined action of abrasion on the cutters rolling against the rock and the mineralogy/chemistry of the rocks has the potential to generate a tribocorrosion scenario that may become accentuated if humidity, water, oxygen and conditioning additives are involved in the process. In determining the importance of tribocorrosion in TBM applications, it is not possible to investigate corrosion and abrasion separately and simply sum their contributions, because the overall process is influenced by the mutual interaction and influence of abrasion/wear and corrosion, and corrosion will be influenced by abrasion/wear. The synergy of corrosion and abrasion may enhance the material removal rates, and may be a source of additional defects that have the potential to influence the mechanical properties of the excavation tools (Muñoz and Espallargas 2011).

The interaction can be expressed in simple terms using the following Eq. (1), previously proposed in the early 1980s to quantify abrasion–corrosion processes involving mining equipment (Muñoz and Espallargas 2011; Madsen 1994):

$$T = W + C + S \tag{1}$$

where T is the total wear arising from the two contributions, W is the wear in the absence of corrosive media, C is material loss in the absence of mechanical wear (abrasion) and S is the synergistic term. All these parameters can be determined from tests, although the S term must be estimated by isolating it using Eq. 1. The synergistic term can be further split into two contributions using the following equation:

$$S = W_c + C_w \tag{2}$$

where W_c is the change in wear rate due to corrosion (corrosion-accelerated wear) and C_w is the change in corrosion rate due to wear (wear-accelerated corrosion). Normally, the C_w term makes the greater contribution to the tribocorrosion interaction, especially in stainless steels (Muñoz and Espallargas 2011). The approaches used to determine C_w and W_c are rather complex and have some limitations. Other tribocorrosion models are also available that might be considered as a means of quantifying wear-accelerated corrosion in a tribocorrosion system (Muñoz and Espallargas 2011). However, an exact quantification of tribocorrosion is beyond the scope of this paper, and no further discussion of these mechanisms will be presented here.

2 Experimental Set-Up and Materials

The aim of this study is two-fold. Firstly, to demonstrate the importance of the influence of corrosion on the abrasion process in the context of TBM cutter tools. Secondly, to develop a laboratory test protocol which facilitates a rapid and relatively easy way of testing the conditioning additives used in tunnel boring operations. Conditioning additives are designed to prolong cutter tool lifetimes and reduce tunnelling costs (Langmaack et al. 2010).

2.1 Tribocorrosion Tests Applicable to Geological Materials

This study employed two different tribocorrosion test rigs in order to evaluate the abrasion–corrosion performance of cutter steels on exposure to different chemical and

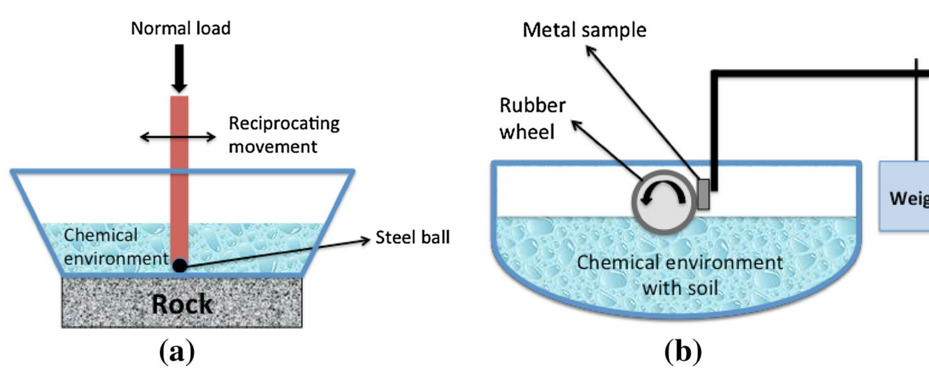


Fig. 2 Tribocorrosion test rigs: **a** reciprocating ball-on-plate and **b** wet rubber wheel

geological media: (1) a reciprocating ball-on-plate (sliding wear) test for hard rock systems and (2) a wet rubber wheel (abrasion–corrosion) test for the soil system. Figure 2 shows sketches of the two rigs. The durations of the ball-on-plate and rubber wheel tests were 1 h and 40 min, respectively. All tests were performed at least twice in order to check their repeatability. A description of the materials tested in the rigs will be given in Sects. 2.2 and 2.3.

2.1.1 The Reciprocating Ball-on-Plate Test

Using this apparatus, tests are performed by sliding a 6-mm-diameter steel ball (made from a steel disc taken from a cutter) back and forth on the rock surface with a stroke length of 10 mm. A normal load of 5 N is applied and the reciprocating frequency is 1 Hz (Fig. 2a). The normal load for the tests was chosen considering a common stress indentation in a cutter disc of a TBM in hard rock of 400 MPa. According to Hertz's theory of contact, and given the geometry proposed in this study, this corresponds to a normal load of 5 N (Stachowiak and Batchelor 2005). During the tests, the rock material was exposed to a variety of ambient media: (a) dry conditions, (b) water obtained from the same site as the rock, (c) distilled water and (d) a foam made using a 3 % solution of conditioning additives in water (see Sects. 2.2 and 2.3 for more details). The friction coefficient between the rock and steel ball was recorded for each test.

2.1.2 The Rubber Wheel Test

To test the influence of the chemical environment on the abrasivity of the soil, a rubber wheel test rig modified for wet environments was employed (Fig. 2b). The tests were performed by applying a force of 220 N between the rubber wheel and the sample. The wheel is then rotated at about 200 rpm, which gives a linear speed of about 2 m/s (i.e. within the range to which a cutter disc will be exposed during boring). The experiments were performed in different chemical media: (a) water obtained from two field sites and (b) foams made using 3 % solutions of two different conditioning additives in water (see Sects. 2.2 and 2.3 for more details). The reference soil used was a highly abrasive sand with very uniform particle size distribution and shape.

2.2 Tests Using Material Obtained From the Field

Samples obtained from field sites were tested using the two tribocorrosion rigs, both tailored to geological materials, and described in the previous section. The cutter tool steel being tested is defined as a hard rock tool steel, type H13 (AISI 2013). The abrasive materials were derived from two samples (a soil and a hard rock sample) obtained from two different geological sites. The soil sample is from a recently completed project in the Middle East (hereinafter referred to as ME) and the hard rock sample is from a recently completed project in Scandinavia (hereinafter referred to as SC). As well as samples obtained in the field, a commercially available cast-in sand was used as a reference soil. Table 1 presents a summary of all the field materials used and the corresponding tests and measurements performed.

In this first group of experiments, tests were conducted under dry and wet conditions using water obtained from the same sites as the soil (ME) and rock (SC). Water samples from these respective projects are expected to exhibit contrasting chemical contents. Chloride content is the major factor influencing tribocorrosion because it determines corrosion rates in metals (including cutter disc steels). The highest corrosion rates in air-saturated water are achieved at a concentration of 3.4 wt.% chloride, which is the same as that in seawater (Winston and Uhlig 2008). Actual tunnelling projects occasionally use soil conditioners or anti-wear additives to prolong cutter tool life. Thus, tests have been performed using two different additive types manufactured by BASF Construction Chemicals; (1) ABR 5—designed for hard rock (BASF, MasterRoc ABR 5 2013) and (2) SLF 41—designed for soft ground/soils (BASF, MasterRoc SLF 41 2013). The concentrations of the conditioning additives used, and their physical state, have been selected to conform to real project situations, i.e.

Table 1 Summary of test approaches and measurements performed for the materials used in the field tests

Material	Steel	Soil	Rock	Water 1	Water 2	Conditioning additives
Nomenclature	H13	Reference soil	Scandinavian site	Middle East	Scandinavian site	ABR 5 and SLF 41
Abrasiveness (AVS/SAT™)	n/a	Yes	Yes	n/a	n/a	n/a
Hardness	Yes	Yes	Yes	n/a	n/a	n/a
Composition	Yes	Yes	Yes	Yes	Yes	Yes
pH	n/a	n/a	n/a	Yes	Yes	Yes
Tribocorrosion (sliding)	Yes	n/a	Yes	n/a	n/a	n/a
Abrasion–corrosion (rubber wheel)	Yes	Yes	Yes	n/a	n/a	n/a

as foams comprising 3 % concentrations in the liquid media (water or seawater) in question.

The tests performed using field samples have been carried out to set up the baseline for the test protocol under controlled laboratory conditions (see Sect. 2.3).

2.3 Tests Carried Out Under Controlled Laboratory Conditions

Tests under controlled laboratory conditions were designed because of the difficulties in controlling the chemical composition of water samples obtained in the field (ME and SC). For this reason, tests using distilled water and distilled water containing salt (3.4 wt.% NaCl, hereinafter referred to as seawater) were also performed.

Tests were also performed in media containing conditioning additives prepared using distilled water, and seawater, in order to observe the influence of the chloride ion (Cl^-) content on cutter steel wear. The additives and their concentrations were identical to those used in the first series of tests (see Sect. 2.2).

In this second group of tests, the steel tested was a hard rock cutter tool steel (H13), and the geological material selected was a granite from Iddefjord in Norway. The properties of this rock are well established. It exhibits high abrasivity and uniform behaviour under laboratory conditions, which is important for test reproducibility (Bruland 1998a, b).

Table 2 presents a summary of the controlled chemical media used during the tests, the properties of the materials and the measurements carried out.

2.4 Materials Characterisation Tests and Chemical Analysis

In order to characterise the materials used in this study, a variety of experimental techniques were employed. All tests were performed at least twice in order to confirm the repeatability of the results.

2.4.1 Steel

The composition of the steel was measured using an X-ray fluorescence (XRF) technique (Thermo Scientific, Niton XL3t). Microstructural characterisation was performed using a metallographical preparation technique (grinding with SiC paper, polishing with diamond paste to a mirror finish and etching with nital to reveal the grain structure). Hardness was measured using the Micro Vickers Hardness Test (MicroWiZhard, Mitutoyo) and scanning electron microscopy (SEM; Hitachi S-3400) was used to study the microstructure of the steel and topography of the worn materials surfaces after testing.

2.4.2 Soil/Rock

The mineral composition of the soil and rock samples was investigated using an X-ray diffraction (XRD) technique (Bruker D8 ADVANCE). Hardness was estimated using the Vickers Hardness Number Rock (VHNR), as described by Bruland (1998a, b), and the topography of the worn surfaces after testing was examined using SEM (Hitachi S-3400).

2.4.3 Liquid Media

The chloride content of the water obtained from the field sites was measured by titration (a precipitation-based process). The metal content of the solutions used was measured before and after the tribocorrosion tests using inductively coupled plasma mass spectrometry (ICP-MS; Finnigan ELEMENT 2). ICP-MS is a form of mass spectrometry analysis which is capable of detecting both metals and non-metals at very low concentrations (up to one part per trillion). Ions are generated by plasma ionisation, and a mass spectrometer is then used to separate the ions and determine their concentrations.

The pH of all liquid media (water and conditioning additives) was measured using a PHM210 Standard pH Meter manufactured by MeterLab.

Table 2 Summary of materials and measurements carried out during the controlled laboratory tests

Material	Steel	Rock	Distilled water	3.4 wt.% NaCl	Conditioning additives	Conditioning additives + 3.4 % NaCl
Nomenclature	H13	Iddefjord granite	Distilled water	Seawater	ABR 5 and SLF 41	ABR 5 and SLF 41 + seawater
Abrasiveness (AVS)	n/a	Yes	n/a	n/a	n/a	n/a
Hardness	Yes	Yes	n/a	n/a	n/a	n/a
Composition before testing	Yes	Yes	Yes	Yes	Yes	Yes
Composition after testing	n/a	n/a	Yes	Yes	Yes	Yes
pH	n/a	n/a	Yes	Yes	Yes	Yes
Viscosity	n/a	n/a	Yes	Yes	Yes	Yes
Tribocorrosion (sliding)	Yes	Yes	n/a	n/a	n/a	n/a

Finally, the viscosity of the liquids was measured using a Haake III Rheometer. The liquid media were placed in a sample holder and the viscosity measured using a rotational device. In this study, viscosity was measured by applying a constant increase in rotational speed over a period of 180 s. Subsequently, the speed was kept constant at 500 RPS for 15 s, and then gradually reduced for 180 s until the rotation ceased. The viscosity values used in this study are those measured during the period of constant rotational speed. The measured viscosity is referred to as the dynamic viscosity (Pa s) of the fluid, and all measurements were performed at room temperature (25 °C).

3 Test Results and Discussion

3.1 Steel Characterisation

In this study, the cutter steel tested is a reference steel (H13 tool steel) used in hard rock TBM tools. XRF measurements, taken from three different positions on a cutter disc cross-section, indicate an average composition of 90.8 wt.% Fe, 0.6 wt.% C, 4.8 wt.% Cr, 1.3 wt.% Mo, 0.9 wt.% Si, 0.9 wt.% V, 0.3 wt.% Mn, 0.1 wt.% Cu and 0.1 wt.% Ni. Figure 3 shows the microstructure of the steel after metallographical preparation. The steel displays a typical tempered martensite microstructure with some lighter coloured areas of retained austenite. The steel has been die-forged and heat-treated to increase its hardness, measured at approx. 639 VH. A comparison of this value with typical H13 steels (600 VH or 54 Hard Rockwell C) (AISI 2013) leads us to the assumption that the steel was air-cooled from a temperature of about 1,000 °C and then tempered at about 500–550 °C. However, this assumption has not been confirmed by data obtained from the manufacturer.

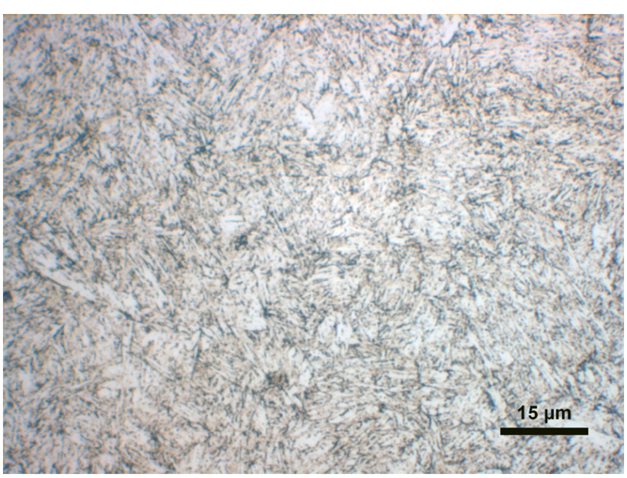


Fig. 3 Microstructure of the cutter disc steel (H13 tool steel) tested in this study

The chromium (Cr) content of the steel may provide some protection against corrosion, but the value stated above is not as high as for stainless steels (>11 wt.%). The steel also contains some molybdenum (Mo), which provides protection against chloride penetration (pitting) and increases its hardenability. The vanadium (V) and nickel (Ni) present will contribute to increasing both the strength and hardness of the steel and its resistance to impact. The carbon (C), silicon (Si) and manganese (Mn) will contribute to hardness, but will reduce ductility. In the light of its heat treatment and the alloying elements present, the H13 steel should possess a good balance between hardness and ductility/toughness. It should also exhibit some degree of protection against corrosion.

3.2 Characterisation of the Geological Samples

The mineral composition of the rock and soil samples as determined by XRD measurements is shown in Table 3. The hardness of the samples estimated using the VHNR technique (Bruland 1998a, b) is also shown in the table. As indicated, these samples are dominated by hard abrasive minerals (quartz and feldspar) and their abrasivity is, thus, expected to be very high (see Sect. 3.3).

3.3 Chemical Analysis and pH of the Liquid Media

The pH of the liquid medium is an important factor influencing the corrosion resistance of steels. In pure or soft waters, very low pH values (<4) lead to rapid corrosion and pitting (due to the dissolution of the iron oxide film). For pH values between 4 and 10, the corrosion rates are constant, but decrease rapidly for pH values above 10, due to the formation of a protective iron hydroxide film (Winston and Uhlig 2008). In hard water, high concentrations of calcium carbonate ($CaCO_3$) will result in the deposition of a surface coating, which protects the steel from oxygen diffusion. The formation of the carbonate layer depends on, among other things, the pH of the water and the concentration of dissolved $CaCO_3$. To determine whether a hard water will provide protection against corrosion, the saturation index (SI) and concentration of $CaCO_3$ in the water must be known. If the SI is positive, the steel will be protected against corrosion (Winston and Uhlig 2008).

In the present study, three different types of water were investigated. Two of these were obtained from the field (SC and ME), while the third was distilled water. The hardness of all water samples was tested by performing a strip test (the use of strips to measure $CaCO_3$ concentrations). In the case of the distilled and SC water samples, the $CaCO_3$ concentration was between 40 and 70 mg/L, which corresponds to soft water. The ME sample exhibited a value of >375 mg/L, which corresponds to a very hard water. The

Table 3 Mineralogy of the geological samples measured using X-ray diffraction (XRD) and the calculated Vickers Hardness Number Rock (VHNR)

Soil/rock name	Quartz (%)	Feldspar		Clinopyroxene (%)	Magnetite (%)	Calcite	Actinolite	Muscovite (%)	Albite (%)	Magnesia (%)	Microline (%)	Mica (%)	VHNR
		Plagioclase (%)	K-feldspar (%)										
Abrasive reference soil	73	–	–	–	–	–	–	2	12	1	12	–	893
Scandinavian site	3	79	4	12	2	–	–	–	–	–	–	–	798
Iddefjord granite	25	32	35	–	–	–	–	–	–	–	–	8	785

SI value for the ME water was calculated from samples with and without conditioning additives. The values obtained were 1.3 and −3.5, respectively, indicating that the surface of the steel is protected against corrosion when exposed to water alone, but not when the conditioning additive is present. For this reason, the measurement of the pH is used in this study as a predictor of the expected degree of steel corrosion.

The pH values of all liquid media used in this study were measured using a pH meter and are presented in Fig. 4. This figure shows the results of two independent pH measurements. Figure 4a shows the pH values of all three water samples (SC and ME from the field, and distilled water). In all cases, the pH is above 7, and they will, thus, be expected to promote a constant rate of steel corrosion. However, some degree of passivation (corrosion protection) should be expected in the case of the ME water, since its pH is close to the minimum value required for passivating iron (Fe) (Winston and Uhlig 2008). Figure 4b shows the pH values of water samples with and without conditioning additives. The figure clearly demonstrates how samples containing additives exhibit lower pH values than those without. The lowest pH values are recorded for the SLF 41 additive in distilled water and for the ABR 5 additive in water containing 3.4 wt.% salt. Both of these samples would be expected to cause higher corrosion rates.

As mentioned previously, chloride (salt) exerts a major influence on the corrosion rates of steel in air-saturated water. Corrosion rates increase at chloride concentrations up to about 3.4 wt.% and then decrease to values below that observed in distilled water when concentrations reach about 26 wt.% (Winston and Uhlig 2008). This phenomenon is due to the solubility of oxygen in water, which decreases with increasing chloride concentration. The initial increase in the corrosion rate is linked to the nature of a protective hydroxide film formed on the surface of the steel. When chloride concentrations are well below 3.4 wt.%, the conditions favour the formation of the film. On reaching concentrations of 3.4 wt.%, the conditions favour the formation of soluble iron chloride ($FeCl_2$), accompanied by the continuous dissolution of iron (Winston and Uhlig 2008). For this reason, the chloride concentration in the water samples investigated has an important influence on the results of this study.

The concentration of chloride in the field-derived water samples was measured by titration with silver nitrate ($AgNO_3$) solution. $AgNO_3$ reacts with NaCl to form a white precipitate of silver chloride (AgCl). By measuring the volume of $AgNO_3$ required to form the first precipitate of AgCl, it is possible to determine the chloride concentration in the water. Chloride concentrations in the SC and ME water samples were 0.02 and 1.43 wt.%, respectively. The lowest chloride concentrations recorded were those for

Fig. 4 pH values of all the liquid media used in this study: **a** field-derived and distilled water samples and **b** water samples with and without conditioning additives. The figure shows the results of two independent tests performed for each set of circumstances

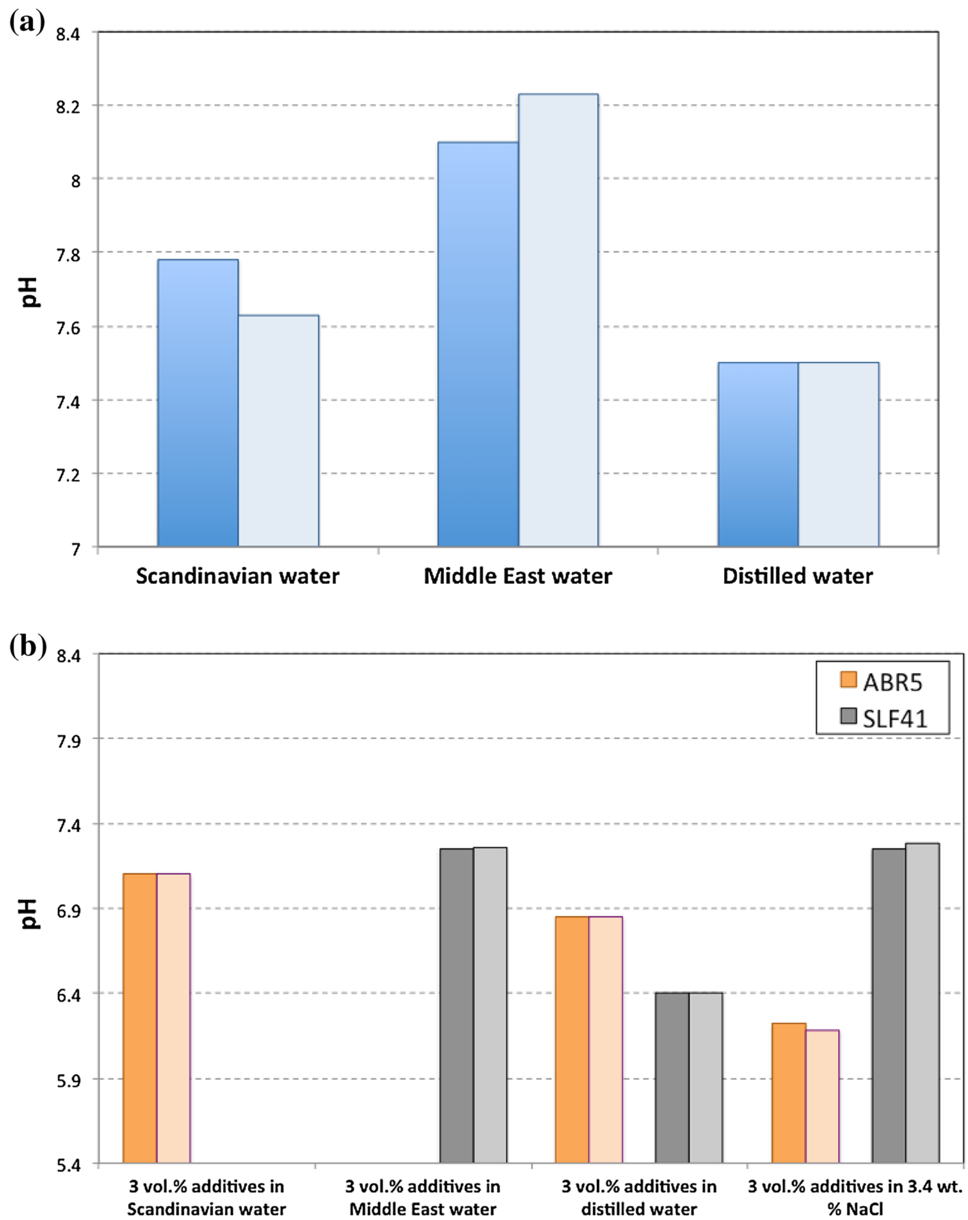


Table 4 Summary of the dynamic viscosity of the conditioning additives and their mixtures with water and seawater

	ABR 5	SLF 41	3 vol. % ABR 5 in distilled water	3 vol. % ABR 5 in 3.4 wt.% NaCl	3 vol. % SLF 41 in distilled water	3 vol. % SLF 41 in 3.4 wt.% NaCl
Dynamic viscosity, Pa s [10^{-3}]	29.14	45.82	1.47	1.49	1.80	1.68

the SC and distilled water samples. As such, these will be expected to result in very low corrosion rates. The highest concentration of chloride was measured in the sample taken from the ME project, and this is expected to result in high corrosion rates, close to those for seawater (Winston and Uhlig 2008). For this reason, the solutions chosen for the laboratory tests were distilled water and artificial seawater.

3.4 Viscosity of the Conditioning Additives and Their Mixtures

Viscosity is an important parameter in lubrication. High viscosities normally promote good lubrication performance and, thus, reduce wear rates. In this study, dynamic viscosity measurements were performed in order to assess whether the viscosity of the conditioning additives and their mixtures may have an influence on the wear observed after tribocorrosion tests. The SLF 41 conditioning additive exhibits a higher dynamic viscosity than ABR 5 (Table 4), which may reflect the greater polymer content. However, when the conditioning additives are mixed with distilled water and artificial seawater, these values decrease dramatically, and the resulting solutions exhibit viscosities only slightly higher than pure water (i.e. 0.8×10^{-3} Pa s at room temperature) (Stachowiak and Batchelor 2005).

3.5 Abrasive Wear of Steel Under Dry and Wet Conditions

3.5.1 Abrasion Ranking Under Dry Conditions (AVS and SAT Tests)

As mentioned in Sect. 3.1, the geological samples used in this study contained hard minerals such as quartz and feldspar. In order to quantify the abrasivity of these materials, Abrasion Value Cutter Steel (AVS) tests were carried out on the SC rock and the Iddefjord granite, and a Soil Abrasion Test™ (SAT) was performed on the reference soil. The results are presented in Fig. 5. The figure demonstrates that the hard rock abrasion values are classified as medium (Scandinavian site) and very high (Iddefjord granite and reference soil) according to the system determined by Dahl et al. (2012).

The main mineral components of the geological materials used in this study are much harder than the steel (see Table 3). For this reason, the wear on the steel will be severe. According to the theory of abrasion, the hardness of the cutter steel should be 1.3 times the hardness of the rock if wear is to be reduced to rational levels (Stachowiak and Batchelor 2005). However, in practice, this would make the steel too brittle to withstand fracturing during tunnel boring projects. Because the rock is harder than the steel, this will cause more wear on the steel, preventing unwanted fracture failure of the tools, and, therefore, assuring the cracking of the rock at high enough pressures.

3.5.2 Abrasion Under Wet Conditions (Rubber Wheel Tests)

As mentioned in Sect. 2.2, rubber wheel tests were performed under wet conditions to simulate abrasion–corrosion situations in soil tunnel boring systems. Two different types of tests were performed: (1) using field-derived water samples (SC and ME) in order to test the effect of chloride concentrations (corrosiveness) and (2) using field-derived water samples containing 3 vol. % of the conditioning additives SLF 41 (designed for soil tunnel boring) and ABR 5 (designed for hard rock tunnel boring) in order to test the effect of the foam. Figure 6 shows the weight losses recorded after the tests were completed. As the figure demonstrates, the effect of chloride concentration on weight loss is quite pronounced. After a 40-min test, the weight loss incurred following tests performed with the ME water sample is twice as high as those carried out with the SC water sample (Fig. 6a).

The results of tests investigating the effect of the conditioning additives on abrasion rate (Fig. 6b, c) show that, for both the SC and ME water samples, the use of the conditioning additives reduces the abrasion rate of the H13 steel. However, the effect is more pronounced in the case of the ME water sample, for which both additives function constructively. In the case of the SC sample, the effect of the additives is less pronounced, although the additive designed for soil conditions does promote a lower abrasion rate.

Figure 7 shows the wear topography of the H13 steel after rubber wheel testing. As expected, following tests performed in SC and ME water in order to check the effect of chloride on the abrasion rate, additional abrasion marks

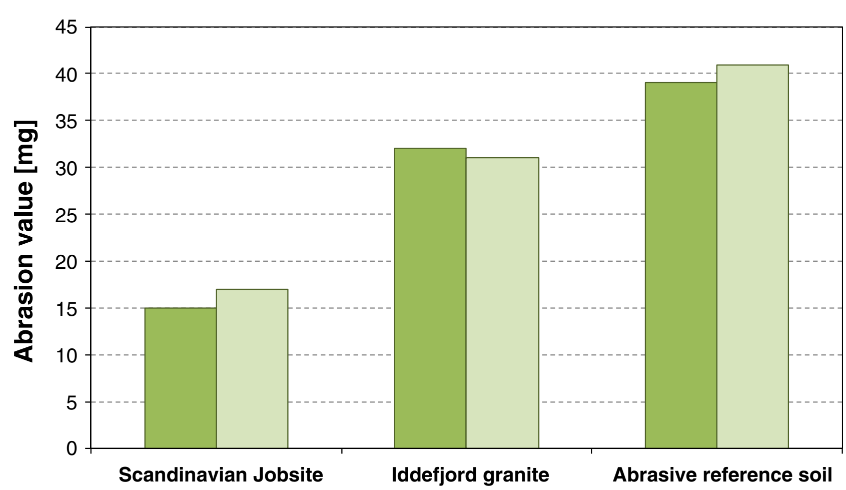


Fig. 5 Abrasiveness ranking for the geological materials used in this study

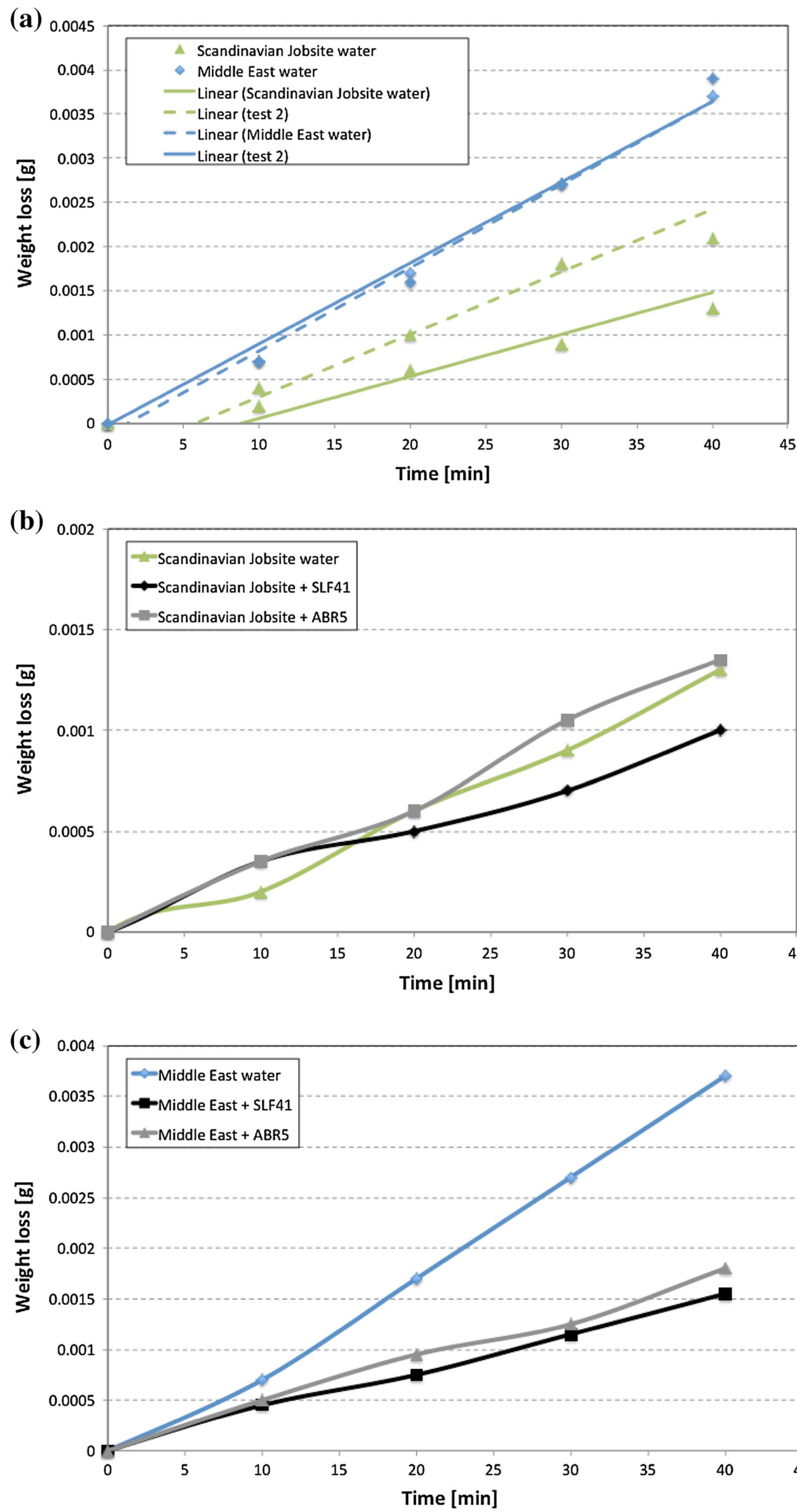


Fig. 6 Weight loss increase with time for the H13 steel tested using a reference sand for: **a** the SC and ME water samples, **b** ME sample with and without conditioning additives and **c** SC water with and without conditioning additives. In **a**, the results of two tests performed under the same test conditions are shown in order to establish repeatability. In **b** and **c**, only one set of test results is shown for each scenario because the results of **a** demonstrated that repeatability was good

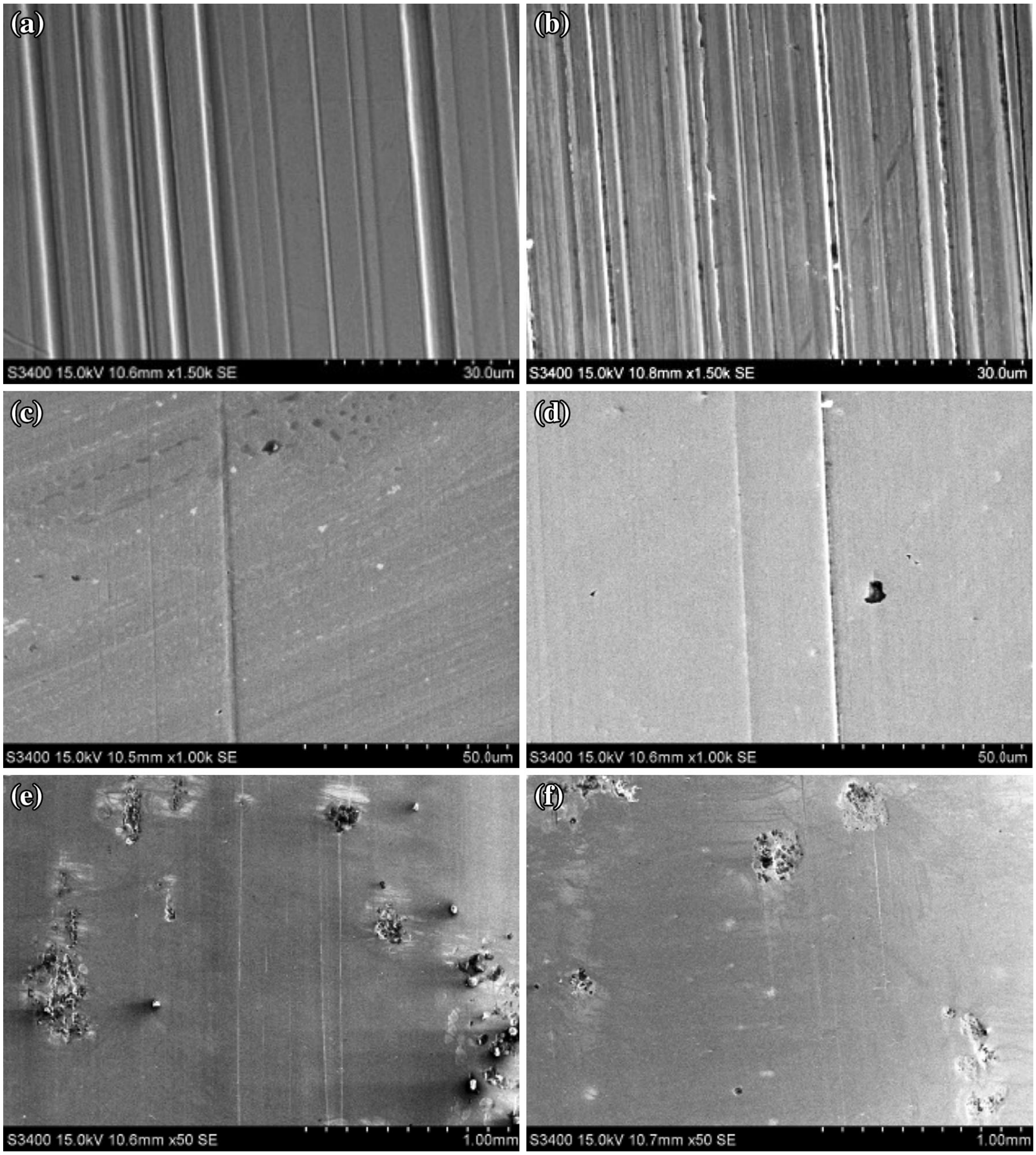


Fig. 7 H13 steel wear topography after rubber wheel testing: **a** Scandinavian site water (0.02 wt.% chloride), **b** Middle East water (1.4 wt.% chloride), **c** SC water containing SLF 41, **d** SC water containing ABR 5, **e** ME water containing SLF 41 and **f** ME water containing ABR 5

and some corrosion (pitting) are observed following the test performed using ME water (Fig. 7b). This concurs with the higher abrasion rates recorded in Fig. 6. We can, thus, conclude that chloride concentration has a negative effect on the abrasion rate of the steel and that premature failure of the steel should be expected under these conditions (higher abrasion rates due to the tribocorrosion effect). The presence of conditioning additives in both cases causes the wear rate to decrease, although the medium containing SLF 41 performs best. This should be anticipated because this additive is tailored to soil conditions. The decrease in the abrasion rate in the presence of additives may be due to the greater viscosity of the liquids (Table 4). The lower abrasion rates are confirmed on examination of the SEM images (Fig. 7c–f), where almost no abrasion marks are found. However, pitting is observed on the surface of the steel after testing in ME water mixed with conditioning additives (Fig. 7e, f). This confirms that the additives succeed in decreasing wear (for which they were designed), although the media in question are clearly not optimal in

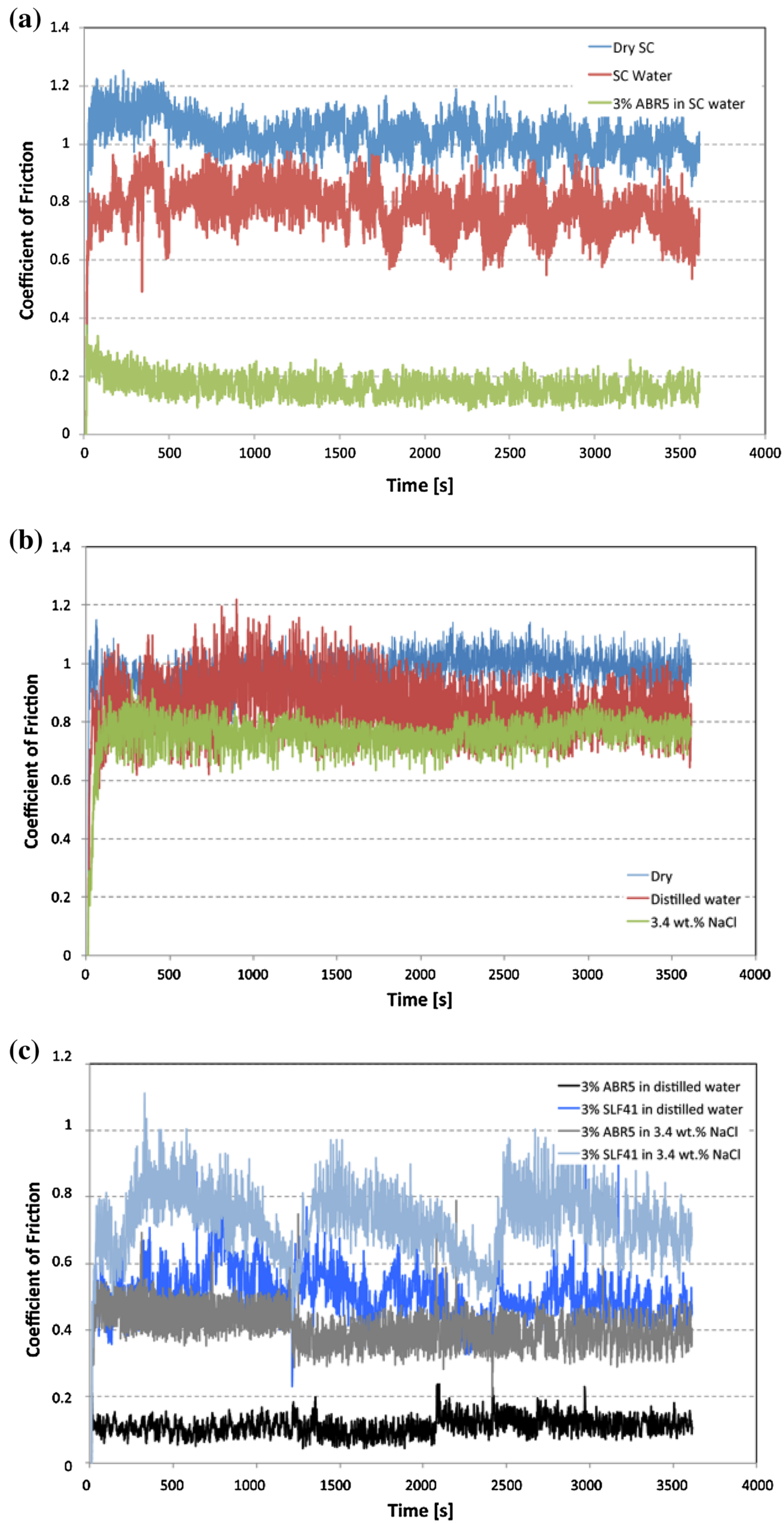


Fig. 8 Coefficient of friction vs. time after ball-on-plate tests performed under: **a** field test conditions, **b** laboratory-controlled conditions in distilled water and 3.4 wt.% NaCl (seawater), and **c** laboratory-controlled conditions using conditioning additives mixed with distilled water and 3.4 wt.% NaCl (seawater). Only one curve per test is shown because repeatability tests proved to be positive

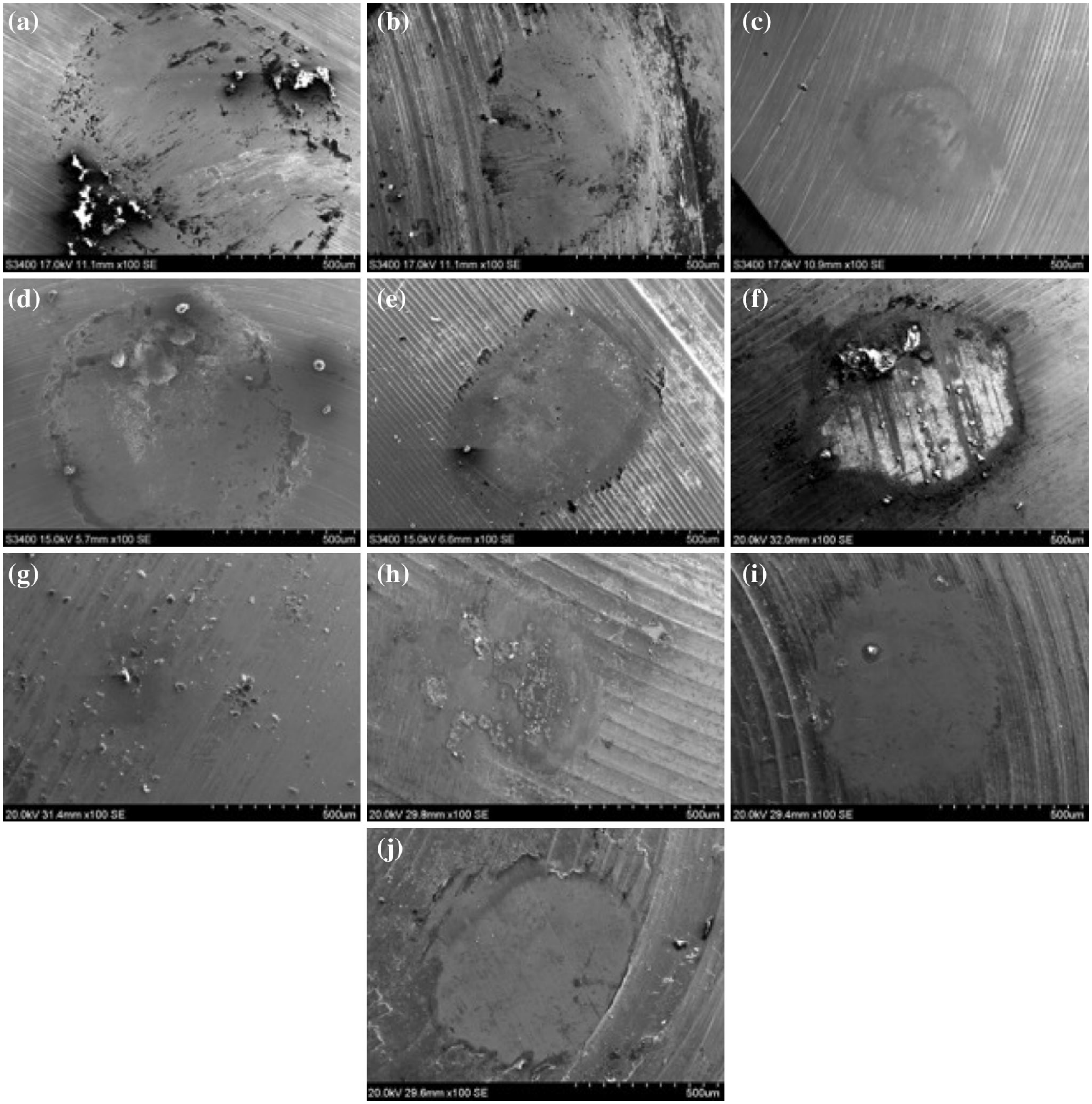


Fig. 9 Wear topography of steel balls after the completion of sliding tests: **a** dry test using Scandinavian site rock, **b** wet test using Scandinavian site rock and water, **c** wet test using Scandinavian site rock and 3 vol. % ABR 5 in Scandinavian site water, **d** dry test using the Iddefjord granite, **e** wet test using the Iddefjord granite and distilled water, **f** wet test using the Iddefjord granite and seawater, **g** wet test using the Iddefjord granite and 3 vol. % ABR 5 in distilled water, **h** wet test using the Iddefjord granite and 3 vol. % ABR 5 in seawater, **i** wet test using the Iddefjord granite and 3 vol. % SLF 41 in distilled water, **j** wet test using the Iddefjord granite and 3 vol. % SLF 41 in seawater

terms of corrosion protection. In addition, the SLF 41 additive seems to result in more pitting due to its lower pH. However, the differences between the SLF 41 and ABR 5 additives in terms of pitting are not as great as might be expected.

3.5.3 Sliding Tribocorrosion (Reciprocating Ball-on-Plate Tests)

Figure 8 shows the variation in the coefficient of friction (CoF) during rubbing tested under the field and laboratory-controlled conditions employed in this study. The CoFs are very high for both the dry tests and those performed using only water (field and distilled) and seawater. In some cases, the CoF values exceed 1. Such values are typical of systems suffering from severe wear and should be expected when poor lubricants such as water are used (Stachowiak and Batchelor 2005). The wear topography of the steel balls after testing is shown in Fig. 9a, b, d, e. Large wear marks and wear debris are observed. This demonstrates the closeness of the rock–steel ball interaction which results in abrasive wear. It is interesting to note the pitting marks and corrosion products on the steel ball resulting from the corrosive effects of seawater (Fig. 9f).

A drastic decrease in friction is observed when using water samples containing the ABR 5 additive (Fig. 8a, c). CoF values less than 0.2 are achieved, which can be regarded as almost lying within the hydrodynamic lubrication regime (full separation of the interacting surfaces resulting in low wear and friction) (Stachowiak and Batchelor 2005). This may be due to the lubricant action of the foam which, in contrast to water, appears to act as an efficient lubricant. The viscosity of the lubricant plays an important role here because it helps to separate the ball from the rock surface and, thus, reduce friction. Indeed, the dynamic viscosity of media involving conditioning additives mixed with water and seawater was larger than that for water alone (Table 4). Such low friction values should be expected. However, it is interesting to note that high friction values are recorded when sliding tests are performed using the conditioning additive SLF 41, which is actually not designed for hard rock tunnelling operations. In this case, values are closer to those obtained in tests performed using water or seawater only. An increase in friction is also observed when the ABR 5 additive is mixed with seawater. These results show that the corrosive properties of the liquid media play a very important role in the friction process, since higher levels of corrosion were observed on the surface of the steel after tests using seawater and SLF 41 (water and seawater) and ABR 5 (seawater), as shown in Fig. 9.

3.5.4 Tribocorrosion of the Cutter Disc Steel Used in TBM Tunnelling

As already discussed and demonstrated in previous sections, the presence of seawater and additive type exert a major influence on the corrosion of cutter steel. In order to quantify steel corrosion in different environments, ICP tests were carried out on the liquid media after testing. These tests measure the quantity of metal ions released to the media during testing and indicate the degree of wear–corrosion interaction.

Table 5 Metal ion content of the liquid media after rubber wheel tests

	Fe (μg/mL)	Cr (μg/mL)	Ni (μg/mL)	Cu (μg/mL)
Reference soil: SC water	0.029	–	0.003	0.003
Reference soil: ME water	0.160	0.003	0.013	0.006
SC water + SLF 41	0.710	0.011	0.008	0.027
SC water + ABR 5	0.492	0.003	0.004	0.019
ME water + SLF 41	1.594	0.011	0.020	0.093
ME water + ABR 5	8.169	0.341	0.214	0.374

Table 6 Metal ion content of the liquid media after ball-on-plate tests

	Fe (μg/mL)	Cr (μg/mL)	Ni (μg/mL)	Cu (μg/mL)
100 % SC water	0.002	–	0.003	0.005
3 % ABR 5: SC water	1.230	0.047	0.072	0.037
100 % distilled water	0.067	0.003	0.013	0.006
3.4 wt.% NaCl	0.792	0.043	0.013	0.011
3 % ABR 5: distilled water	1.787	0.089	0.035	0.173
3 % SLF 41: distilled water	2.493	0.101	0.050	0.278
3 % ABR 5: 3.4 wt.% NaCl	0.511	0.028	0.019	0.235
3 % SLF 41: 3.4 wt.% NaCl	2.820	0.131	0.091	0.573

For the rubber wheel testing, the use of ME water increased the wear rates and pitting marks were observed on the wear topography (see Sect. 3.5.2). The ICP tests confirm these observations in that a greater quantity of metal ions was recorded in the liquid medium after tests using ME water, both with and without conditioning additives (Tables 5, 6). A metal ion concentration increase was observed in following tests using the ABR 5 additive, as might be expected in view of the pitting corrosion observed on the steel following tests using this medium (Fig. 7).

Similar results are obtained following the ball-on-plate tests. The highest levels of metal ion release are observed when additives are used. However, the additives seem to work more constructively in the presence of seawater, especially in the case of ABR 5, where tests reveal both less wear and lower levels of metal ion release.

4 Conclusions

In the present study, the influence of corrosion on abrasive wear on tunnel boring machine (TBM) cutter tool steel during interaction with excavation fluids (soil conditioners, anti-abrasion additives and water) has been evaluated using a variety of laboratory tests. The results clearly show the influence of corrosion on the abrasion rates under both soft ground (soil) and hard rock conditions. However, the validity of the results obtained has yet to be evaluated under operational conditions (actual TBM projects). This issue will be evaluated as more field data, in the form of worn TBM tools, become available. However, the following conclusions can be drawn on the basis of the laboratory tests:

1. The use of conditioning additives results in lower abrasion rates in H13 steel when tested in two different water media (low and high chloride content).
2. In the case of hard rock tests, wear was less pronounced in the presence of additives, demonstrating the positive effect of additives in the abrasion process.
3. Steel corrosion was observed in the presence of seawater and additives. This was measured using chemical analysis of the liquid media and by means of a microstructural analysis of the steel.
4. This work demonstrates the potential of using this approach in the study of TBM tools exposed to degradation mechanisms, wear and corrosion. It should also be possible to test other types of tunnel excavation tools, such as the drill bits used in drill and blast tunnelling operations.
5. In future tunnelling projects, it is important to improve the modelling of steel degradation mechanisms in order to fully understand on-site degradation phenomena. The good performance of soil conditioners and anti-abrasion additives in the laboratory must be validated by on-site data.

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