Soil abrasiveness for EPB-TBM along Tehran metro tunnel line 7, Iran

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1. Introduction

Full-face shielded tunnel boring machines (TBM) including earth pressure balance (EPB) shields have been used almost exclusively for soft ground tunneling because of the many advantages the offer in comparison to the conventional methods. The total number of EPB-TBMs that were utilized for tunneling between 2005 and 2010 is approximately 350 units worldwide as reported by [1].
These machines encounter a wide range of geological conditions and hazards. One of the most critical adverse conditions is encountering abrasive soils and excessive wear on the cutting tools and the cutterhead as has been reported in many EPB tunneling projects worldwide [2], [3]. Inspection and maintenance of cutting tools below the groundwater table is usually performed under hyperbaric conditions where air pressure is used to provide tunnel face stability. This involves creating a plug at the face, removing the spoils (muck), applying compressed air, and allowing the crew into the cutting chamber via an air lock. This entire process can take days to complete. Consequently, the tool inspection and maintenance in soft ground tunneling is a time consuming, risky, dangerous, and costly [4].
Abrasiveness of soil and rock is a factor with considerable influence on the wear of tools. The wear of excavation tools is an important measurable indicator of rock and soil excavation in tunnelling, in addition to the volume of material excavated (Fig. 1). [5].

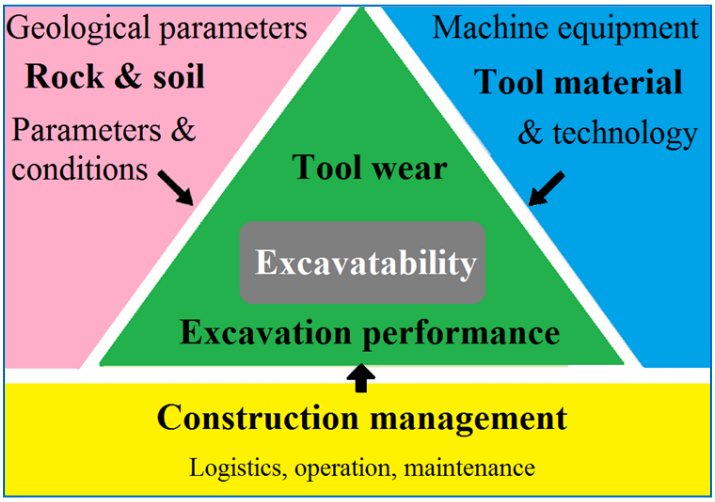


Fig. 1 *Parameters influencing tool wear and excavation performance [5]*

In mechanized tunneling the term wear is classified into two categories, primary wear and secondary wear. Primary wear is an expected type of wear that can occur on several parts of the excavation tools, such as drag bits, disc cutters, scrapers and buckets, etc. Secondary wear, on the other hand, is an unplanned type of wear that affects the cutterhead spokes, cutter saddles, bulkheads and also much conveyance parts such as the screw conveyor. The first type of wear requires replacement at appropriate intervals whereas the second type is not and therefore the parts are not anticipated to be replaced regularly. As such the TBM performance may be affected significantly if sever secondary wear occurs [6].

In this paper, an investigation was undertaken to discern the main cause of the observed wear on EPB-TBM of Tehran Metro Line 7 (North-South lot). The wear potential of soils and rocks are assessed with respect to approach on the matter was introduced by [5] and Cerchar test, respectively.

2. Description of project and Engineering geology

Fig. 2 *Main route of Tehran Metro Line 7*

Fig. 3 *General view of the North-South Lot of Tehran Metro Line 7 EPB-TBM*

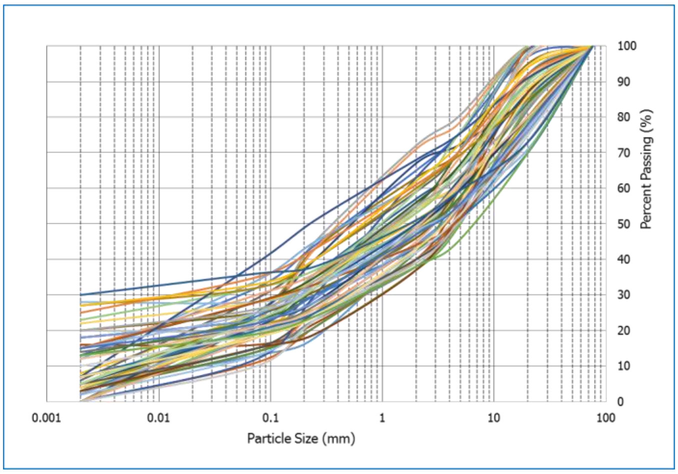


Fig. 4 *Grain size distribution curve, Gravely sand with clay/silt and sandy gravel with clay*

Tehran Metro Line 7 is nearly 27 km in length with 25 stations. The Line 7 tunnel is divided into two sections: Lot 1) East– West and Lot 2) North– South (see Fig. 2). The North– South Lot of Tehran Metro Line 7 is under construction. This tunnel is about 14 km length and 9.164 m in diameter and is being excavated by an EPBM (Fig. 3). EPB tunnelling started from N7 station in May 2010 and have continued to 6498 meters of tunnel at a rate of 9-11 m per working day towards North terminal.

The Tehran plain mainly consists of quaternary formations, which are often the result of erosion and re-deposition of former sediments [7]. The ground along the tunnel alignment is formed by alluvial deposits, composed mainly of gravely sand with clay/silt and sandy gravel with clay (Fig. 4). Among the fluvial deposits there are some layers and/or lenses of sandy GRAVEL or gravely SAND (Fig. 5). Another noticeable phenomenon in these deposits is the considerable content of cobbles and boulders in the tunnel face (Fig. 6).

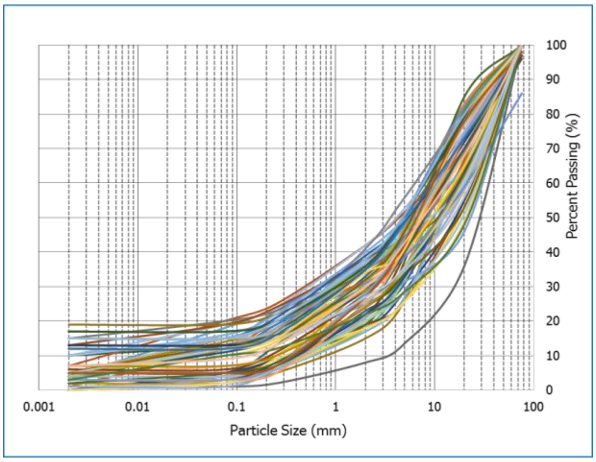


Fig. 5 *Grain size distribution curves, sandy GRAVEL or gravely SAND*

Fig. 6 *Cobbles and boulders collected during the excavation*

3. Wear of EPB-TBM

Disc cutters have proved successful in very dense or well cemented soils (or where mixed faces of rock and soils are expected). Scrapers are preferred for softer ground types, e.g., sands and clays, and rippers are preferred for medium dense lightly cemented silty sands and sandy silts. Ensuring that disc cutters continue turning in the softer ground, particularly when the TBM is required to operate at relatively high earth pressures (>2 bar), is one difficulty to overcome when the cutterhead is dressed with a combination of disc cutters and scraper or chisel cutters [8].
Generally, the effect of abrasive soils on TBMs can be described as wear that is either primary or secondary. Primary wear entails the corrosion of cutting tools such as scrapers, rippers and disc cutters. These tools are designed for ground excavation and are replaced by new ones at appropriate intervals. It is clear that when a TBM is boring in abrasive soils, this cycle of change is shortened. In this study, total number of cutting tools replaced to complete this portion of the tunnel are 1169, including 654 rippers, 357 scrapers and 153 disc cutters. The cutting tools on the cutterhead before and after replacements on the Tehran metro line 7 illustrated in Fig. 7.

Fig. 7 *Cutting tools before replace showing wear (left) and after replace (right)*

After primary wear comes secondary wear. Secondary wear, on the other hand, occurs when soil comes into contact with various components of the machine, particularly when the primary wear on the cutting tools is excessive. Secondary wear can lead to wear of the cutterhead spokes, cutter mounting saddles, main body of the cutterhead and screw conveyor.
This project, secondary wear were also observed on machine. Fig. 8 displays secondary wear on the cutterhead of TBM. Also, Fig. 9 shows the excessive wear on the screw conveyor on Tehran Metro Line 7.

Fig. 8 *Original gap between the shield and cutterhead of EPB-TBM*

Fig. 9 *Excessive wear on the screw conveyor of EPB-TBM*

4. Evaluation of ground abrasiveness

In order to discern the main cause of the wear an investigation was carried out in this study. The growing economic pressure on tunnelling and mining operations has led to an increasing importance of investigation methods for assessing the abrasiveness of rock and soil. Several well acknowledged test and prognosis methods already exist for rock, however there is only very limited knowledge available to describe the abrasiveness of soil and its impact on EPB-TBMs. Three model tests are usually in use for determining the abrasiveness of rock material, consisting of Cerchar test [9], [10] (Fig. 10a), LCPC test [5], [11], [12] (Fig. 10b) and NTNU test [12], [13] (Fig. 11a). In contrast to model tests, geotechnical indices use a different approach for abrasiveness assessment. Some of the geotechnical wear indices most often applied are included Schimazek Index, Vickers Hardness Number of the Rock (VHNR), Equivalent Quartz Content (EQC), and the Rock Abrasiveness Index (RAI) [12], [14]. Although there is already an extensive literature about abrasiveness and wear prediction concerning rock, there is in contrast very little on this subject for soil. Working from experience with the investigation of rock for abrasiveness and wear, tests were undertaken to find out whether the chosen test procedures were also suitable for the testing of soils. Although the Cerchar Abrasiveness test is only practical for single pieces of large components in coarse gravels, cobble and stone and block layers. Therefore, in this study the Cerchar tests were carried out to determine the abrasiveness of cobbles and boulders

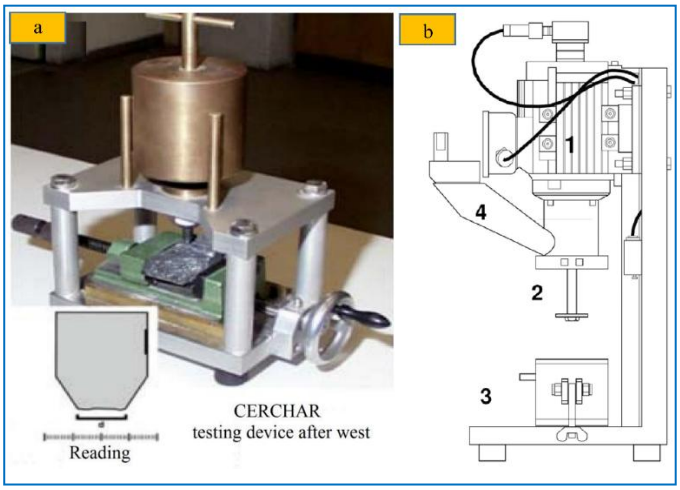


Fig. 10 *(a) Cerchar test and (b) LCPC test*

Although a standard for measuring and defining abrasivity of soft ground has not yet been adopted, several testing methods have been developed and the next step in development seems to be acceptance from the industry and large-scale collection of data from multiple projects to refine the models. One method, developed by a group from Penn State University, Howard University, and The University of Tennessee Knoxville, simulates the wear by rotating a propeller with wear plates in a chamber filled with the material [15]. The weight of the wear plates is measured before and after the test and the reduction is used to define the abrasivity of the material. Actual material from the project can be used without alteration and the propeller speed, pressure inside the chamber, and moisture level can be varied to simulate different boring conditions. Also, additives can be used during the test, with the benefit of further simulating actual conditions and/or testing the efficacy of different additives (Fig. 10b).

In this study, abrasiveness and wear potential of soils along the tunnel alignment are discussed with respect to approach on the matter was introduced by [5] (Fig. 11).

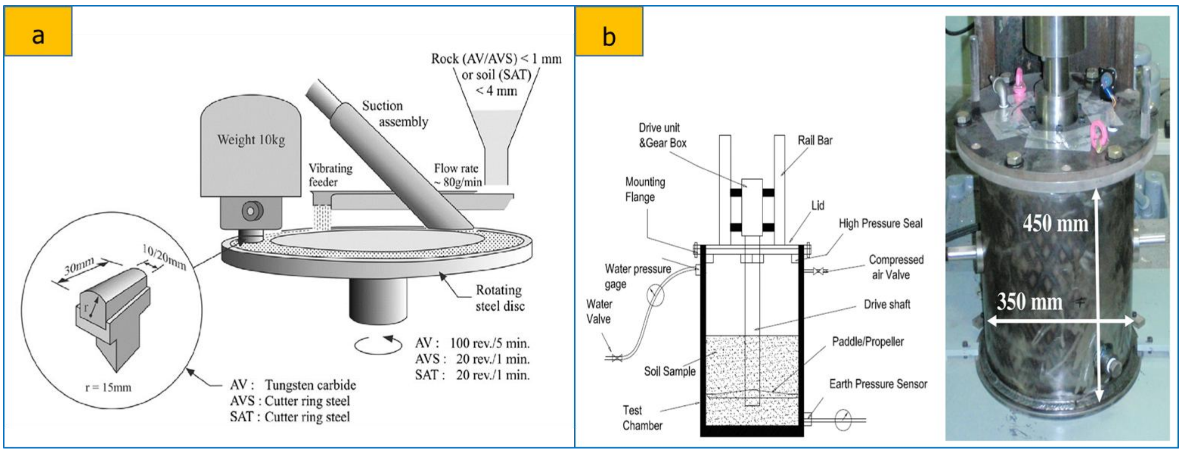


Fig. 10 *(a) NTNU test and (b) Soil Abrasion Testing Device*

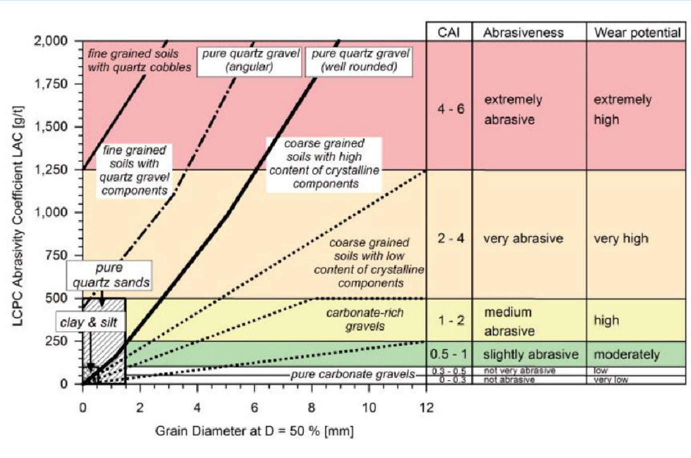


Fig. 11 *Abrasiveness classification diagram for different soil types*

4.1 Abrasiveness of cobbles and boulders

In general, boulders and cobbles are defined as solid objects larger than 300 mm and lower than 300, respectively, which is defined significantly stronger than the surrounding ground. Boulders and cobbles are typically a part of rock blocks of various origins and sometimes carried to the site by stream works, or natural falls from the mountain sides, or frequently transported by glaciers, and often they including the man-made solid materials, too. Boulders and cobbles are commonly found in river beds, glacial tills, and at the bottom of slopes. In order to determine the abrasiveness of cobbles and boulders, the Cerchar tests were carried out on samples collected from the tunnel route. The Cerchar Abrasiveness Index (CAI) represents one of the most common testing procedures for the laboratory research of rock abrasiveness worldwide. Test procedure was done in accordance with the standards of the ASTM D7625-10 [16] and AFNOR: NF P94-430-1 [17]. The Cerchar Abrasiveness Index (CAI) results are given in Fig. 12. As it shows, cobbles and boulders samples were classified as extremely abrasive rock.

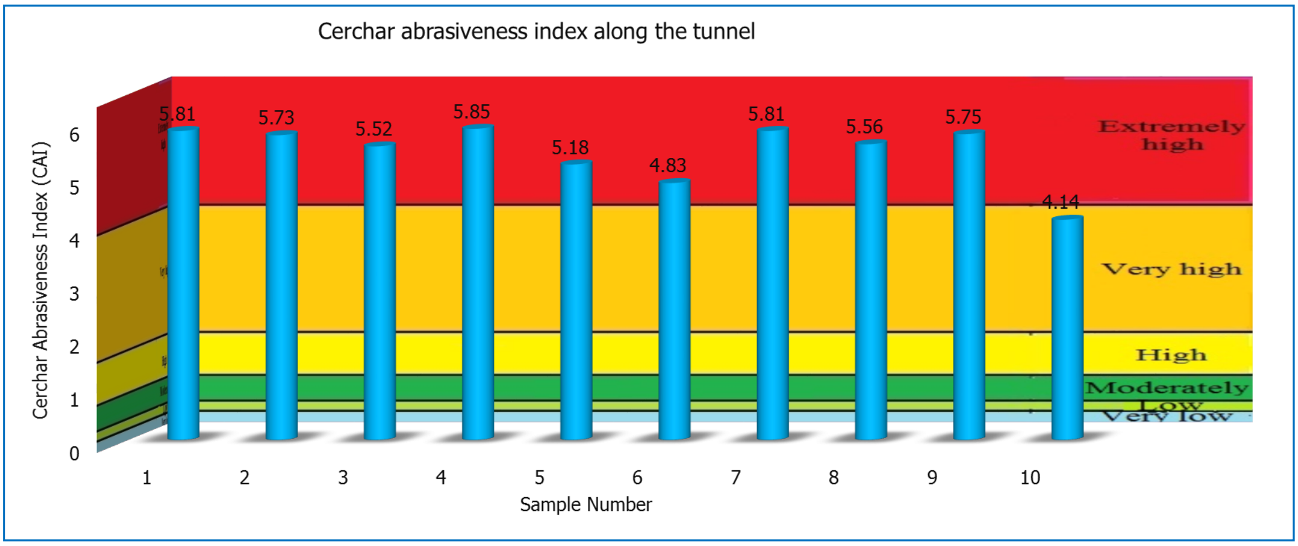


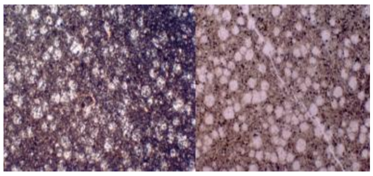
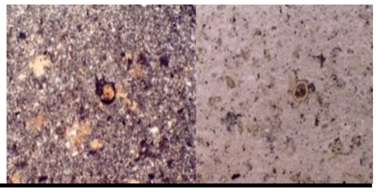
Fig. 12 *Results of The Cerchar tests (CAI) on cobble and boulder samples*

4.2 Abrasiveness of soils

Abrasiveness and wear potential of soils along the tunnel alignment were assessed based on the approach introduced by [5]. In this method, the effective properties of the soils, which are quite significant in practice (e.g. mineral content, grading distribution and roundness of the grains), are reproduced by the LCPC test in the laboratory and are then entered into a diagram. The diagram shows average grain size of a 50% mass fraction versus the LCPC Abrasivity Coefficient LAC (Fig. 11). The absolute grain size is, therefore, reflected in the sharpness of the grain size mixture prepared for the LCPC test. This leads to classification diagram (Fig. 11) which has different fields for various types of soils [5], [11]. In this study, for use of this classification diagram, firstly mineral contents were determined by micro-petrographic examination on the some particles of soils. According to the micro-petrographic examination results of the selected samples, given in

Table 1 with proper photos taken in ordinary and polarized lights, these particles are mostly made of rocks with genetic groups of acid volcanic, intermediate intrusive and pyroclastic materials. The mineral composition, texture, and rock name of the examined particles are also listed in Table 1.

Table 1 *Micro-petrographic examination results of the particles of soil*

Mineral Composition	Texture	Rock Name	Photo
In all probability, Feldspars with free Silica, Opacite minerals, as Iron Oxides.	Cryptocrystalline/ Amygdaloidal	Rhyolitic Tuff	
Mostly Feldspars with less free Silica, as Quartz, Alteration Products, as Calcite and Chlorite, Opacite minerals.	Aphanitic (Tuffaceous)	Rhyolitic Tuff	

Therefore, based on the micro-petrographic examination results, the proper field in the diagram (Figs. 11 and 13) is "coarse grained soil with high content of crystalline components". Then, the tests results of particle size analysis were used to determine the average grain size of a 50 % mass fraction. Then these indices were plotted on the Fig. 13 (on the field of "coarse grained soil with high content of crystalline components") to find the associated classification of abrasiveness and wear potential of soils. As shown in Fig. 13a, the samples were classified as low to extremely high wear potential.
The wear potential of the soil is presented graphically on pie chart of Fig. 13b. As shown Fig. 13b, the 88% of all samples at tunnel route were have wear potential between high to extremely high (high=36%, very high=51% and extremely high=1%).

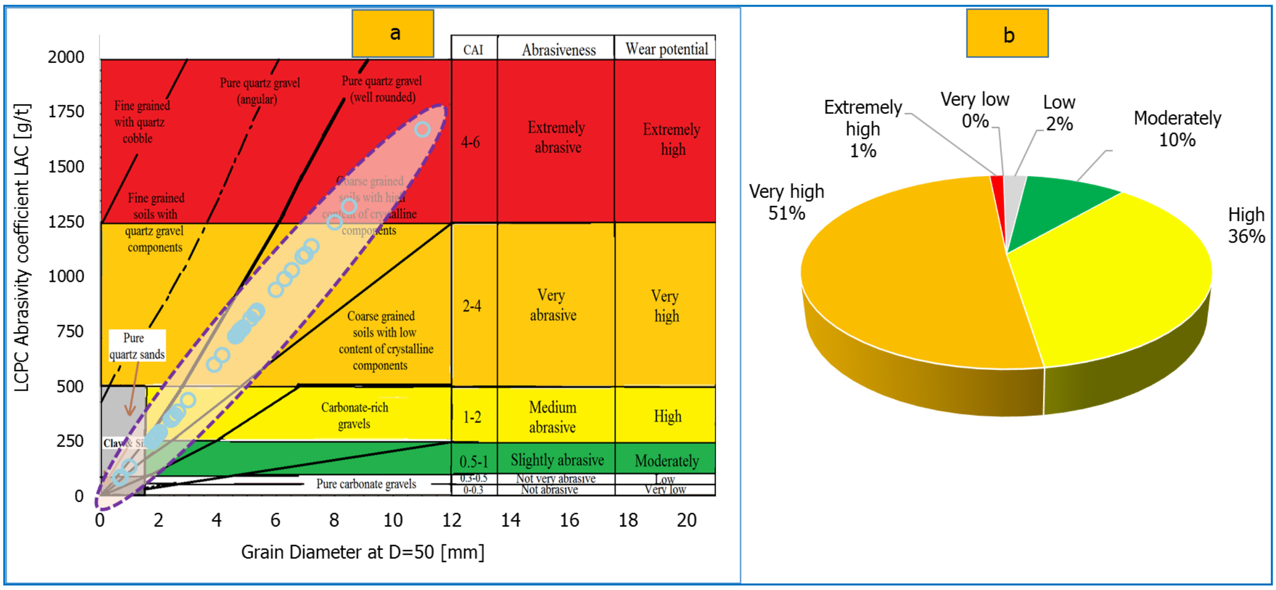


Fig. 13 *(a) Abrasiveness classifications for different soil units (after Thuro and Käsling, [5]) and (b) Distribution of wear potential*

5. Conclusion

The study of wear and its impact on machine performance and wear of the cutting tools and other machine components is very important and is increasingly becoming a major contractual issue in soft ground tunneling projects. The impact of hazards have adverse costs and big delays for a project. Therefore, they should be investigated during the design stage of mechanized tunneling job in order to gain a better understanding of cost and better design of the machines. Otherwise, unpredicted effects will result in disputes and claims between the various parties involved. There are some expectable methods for predicting rock abrasion, but there is no comprehensive method for soil and soft ground. The Penn State Soil Abrasion Testing device as well as the developed Soil Abrasion Index can be used as a standard for measuring soil abrasivity in the design and construction phases of the soft ground tunnels.

The 6498 m of the Tehran Metro tunnel has been excavated. In this length of tunnel the primary and secondary wear were observed on the TBM components. Hence, an investigation was undertaken to discern the main cause of the wear and the results show that abrasive geological conditions is the major factor. Generally, the alignment geology has a very high potential for abrasion, but the potential is extremely high in this project because of the presence of cobbles and boulders. Furthermore, site investigation showed that soil conditioning parameters such as FIR (Foam Injection Ratio), FER (Foam Expansion Ratio) and Cf (Concentration of surfactant) had not been chosen correctly, so TBM was affected by both primary and secondary wear. TBM cutterhead was repaired by the welding of hard-facing Hardox plates. At present, the TBM has completed its course under regular inspections and using better foam conditioning treatment plus anti-abrasion polymer.

According to this study, suggestions that could be mentioned for soft ground shields like EPB are:

- The abrasiveness of ground conditions along a tunnel alignment play a dominant role in many of the major decisions that must be taken in planning, designing, manufacturing and excavation of an EPB-TBM tunneling;
- Good geological predictions and identification of wear potential along the tunnel is really necessary and client must specify for TBM design and manufacturing;
- Application of proper TBM operational parameters;
- Use of soil conditioning by anti-abrasion foams;
- Optimizing soil conditioning parameters lead to tool wear reduction; and
- Regular inspection of cutting tools, spokes, saddles and the cutterhead body during downtime when passing through abrasive ground especially.

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