Wear on construction tunnelling machines

Ing. Jan Prajer

Supervisor: Prof. Ing. Jan Suchánek, Csc.

Abstract

In this article we focus on the description of abrasive wear of tunnelling machinery during the work cycle. Next we focus on the description of geological survey and rock abrasion. This technology is called in literature "mechanized tunnelling". Machines used in this technology are called full-profile tunnelling shield (Shield Machine).
During the excavation when shield is boring new tunnel, we can interpolate the model of wear on cutter disks which are part of shield face id. head of the excavation. We can seen on the other integral part of this technology these processes of wear. To ensure of the working machine and other machinery or equipments is used, which are also under wear. This wear is primarily due to the work of the machine or secondary work itself.
The greatest significance of this issue is abrasive wear firstly wear arising between the solid particles which are contained in working space and functional areas. And secondly, the working space abrasion id. abrasion of rocks and soils. It is important to realize, in this case, that these are not the metal particles with an active abrasion wear, but a highly variable rock particles (minerals), soil and other non-metallic materials. These particles are appearing in the working space in which the shields excavate or they appear like added particles into the working space. The working space is changing quickly with large differences in abrasion. It is therefore very important to correctly interpret the results of geological surveys, analyses, and testing and have technical information obtained from the tunnelling machine and other machineries or equipment.

Keywords

Abrasive wear, rock abrasion, abrasion, EPBM, TBM, cutting tools

1. Technology of shield machines (EPBSM)

1.1. Tunnelling machines - History, distribution and characteristics

Tunnelling technology full-profile machines are used worldwide for at least 40 years. In the Czech Republic was first used in the construction of water pipeline between town of Chomutov and Sandwort dam and in the years 1970-1975. It was a shield of 2.7 m from Demag company. Followed by implementation of similar structures such as sewers, water mains and cable tunnels. The construction of underground first shield was used between 1971 and 1978 on the Metro section the Malostranská to Staroměstská both are stations on line A. The machine was supplied from the Soviet union, the machine had a diameter of 5.8 meters and signs TŠčB-2. Furthermore, the more of the Soviet machine was used on other lines Metro excavations until 1990 [1].

Present a detailed divisions of full-profile tunnel boring machines from prof. Thewes [3] within WTCITA / ITES 2007 in the Czech transcription detected in Fig.1.

Machines can be sorted by diameter shield and a small-profile machines from 0.5 m to 5 m diameter shield and large-machinery profile of 6 m diameter shield. The total range of diameters used starting with the aforementioned 0.5 m (sewage system in the U.S.) and the ending has the largest diameter of 19 meters (under construction project in Russia). Another division is according to the geology along the line of the machine excavation. First division for hard rock (Gripper TBM, Hard-rock TBMs), second for followed by unstable rocks with varying strength (EBP Shield APB Shield MixShield) and last one for highly unstable soils (Slurry Shield , MixShield). The last division is the division used by the tail skin or shield on the machine like without a shield, with a single shield or double shield. All of the above divisions are important in designing the cutting tools for the project of construction.

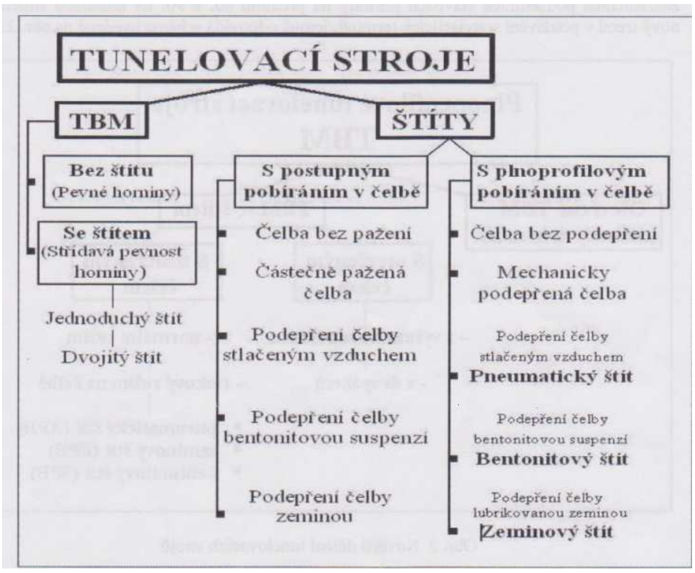

Fig. 1 *Current division of tunnel boring machines*

Most used shield is a shield with full-aspect excavated the face with earth pressure balance system for tz. EPB shield.

EPB Shield - Shield the most widely used, 90% of all used shields the EPB shield, earth shield

EPB shield (see Figure 2.) Minted by the squeezing of unstable rocks, without the massive presence of water. Loss of stability of the tunnel face is prevented from creating counter pressure. For shield for soils in cohesive soil enjoy cutting blade (1) to stabilize (support) of the face, unlike other shields, which are dependent on the support that is secondary to the stabilization of suspensions. The shield, in which the cutting head rotates is called the working chamber (2) and the whole tool bit part. Next part of the shield is body shield, which distributes parts on under pressure and part with atmospheric pressure with the pressure bulkhead (3). Soil is eroding the cutting tools on the cutting head, loose soil then falls through the holes in the cutting head into the combustion chamber and is mixed with a mixture of soil, previously commented and additives (chemicals). Uncontrolled penetration of soil into the face shield is prevented so that the power piston (4) is transmitted from the pressure bulkhead (3) of the face. Steady state of the rock mass and the shield is reached when the soil in the working chamber can also compress and therefore be further compaction. Excavated material is discharged from the combustion chamber by screw conveyor (5). Amount of excavated material is controlled by the screw speed and size of the upper discharge of screw conveyor. The screw conveyor transports the muck on conveyor belts which are on tunnel. Tunnels are usually reinforced with prefabricated lining segment ie. Tubbings (7), which are installed under the atmospheric pressure by the erector (6). The injection mixture is continuously injected into the space between the outer diameter of the segments and excavated profile despite the injection holes in the back of the shield and directly or through openings in the segments.

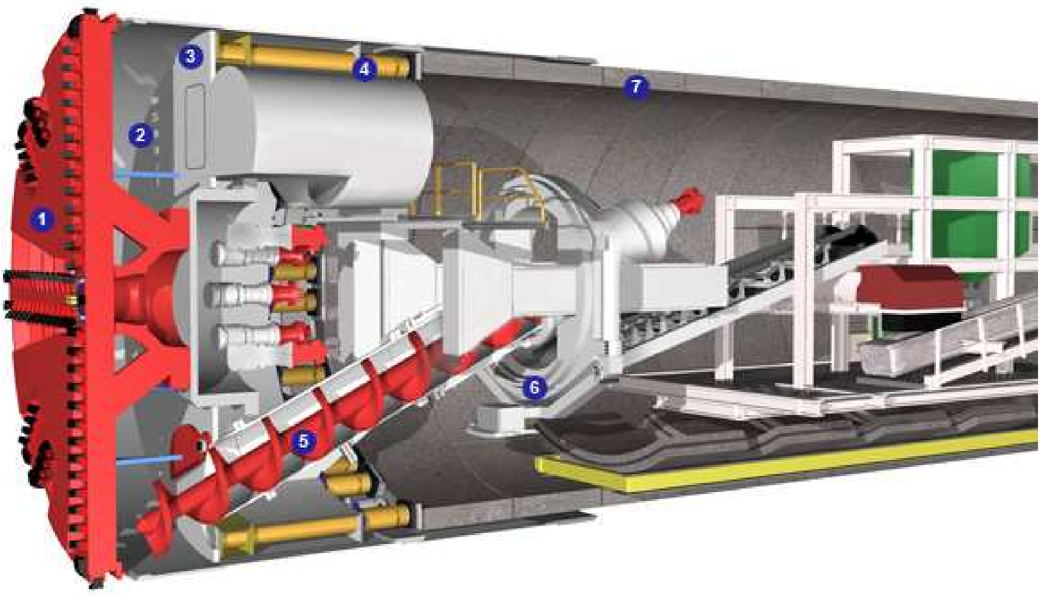

Fig. 2 *EPB Shield*

1.2. Other parts of shield machines technology

Conveyor belt System (CBS) is used to transport the muck to muck store, ie. intermediate stockpile located on the surface on the construction site. The whole system works automatically and is controlled by the pilot who is on the shield machine.

Conveyor Belt is a composite consisting of rubber and textiles. The strip is reinforced and flame resistant according to DIN 22102. Type of belts are EP800 / 4, 5 +3 "K". Tension belt means, tension is controlled in tension towers in Figure 3 or by free weights. For the smoothest possible shield tunnelling work and to shorten the time required for further working cycle is the ability to accumulate belt in storage and used strips to serve as reserve capacity for a certain length of the excavation without every cycle connection conveyor belts.

Fig. 3 *Horizontal and vertical storage belt*

Fig. 4 *Discharge points*

Two-component grouting used to fill the space between the excavation and lining of precast segmental lining (SPO) Tubbings short, the Anglo-Saxon countries, the customary designation for a community of tubbing.
A component is a mixture of cement, bentonite, chemicals (accelerators, retarders) and water. Mixture components and is characterized by very low abrasiveness.
Component B, ie. water glass, liquid sodium silicate (Na2SiO3). The mixture forms a gel that prevents the ingress of water to the segment lining and also distributes the pressure of the disturbed rock mass on the tubbings. Component A is drawn in a 2.5 "pipes up the shield, which is just before the outlet valve is fitted with a mixing component B and all of the rapid reaction between component A and B, reaction time is 10s - 20s, when the time between liquid and solid phase of the mixture. The mixture of Component B is placed abrasion.

2. Abrasion

2.1. Rocks and soil abrasion

Under term "rock abrasion” [4] we understand ability of the rock damaged the working tool by wear, in this case, the cutting discs and knifes positioned on the cutting head tunnelling machine in the process of mutual interaction of the bit and the rock by mechanical disintegration of rocks.Because the tool wear during the excavation is changing the geometric dimensions of cutting tools, it is to increase contact area between the tool and the surface of rocks. Changing these dimensions entails a change in the speed of the tunnelling machine and change the specific energy for rock cutting.The intensity and rate of wear depends on several factors operating simultaneously in the interaction of isolating instruments and rock. The most important factors affecting the wear of cutting tools include [4.7]:

- Geometry of cutting tools
- Type and characteristics of friction areas
- The characteristics of rock (strength, hardness, abrasive quality, silica content)
- The mode of operation isolating instruments (input variables isolating the process)
- Qualities (presence of water, temperature)

Abrasion [6] is a summary of the general physical and mechanical properties of rocks in contact with the disconnecting cutting tool. Because depending on the characteristics of isolating abrasion is necessary to laboratory characterize conditions always choose the instrument with a forward-known physical-mechanical properties. The results of laboratory tests obtained abrasiveness that characterizes disintegrated (testing) rocks or soil.
The interaction process isolating instruments and rock influences the environment in which the actual interaction takes place. The influence of working space is not negligible, and therefore it is necessary to ensure the laboratory is always a stable working space. This eliminates the systematic impact of environment on the overall result.
Abrasion tests used in the present time can be divided into three groups (ISRM) [5,6]:

- Shock test - Los Angeles, sand test, test Burbakovův
- Pressure test - Dorr, ASTM 2-241-51 (D2938, D3967), drilling test, Taber Abraser Model 143, the UCS test
- Wear tests - Devalov test Cerchar test (CAI)

Unconfined compressive strength is a parameter of strength, this parameter characterizes the class of the driving facility of the rocks. Parameter is determined from basic rock samples using the ASTM method. Breaking free of talc is calculated by dividing the maximum failure load of the test sample and the sample surface disturbed.

$$\sigma t_1 = F / A \tag{1}$$

Indirect tensile strength parameter indicates the rock as well as its strength. The test specimen is loaded perpendicular to the axis of the core.

$$\sigma t_2 = (2 * F) / (\pi * L * D) \qquad (2)$$

Cerchar abrasive index (CAI) [8] diagram of the test facility is shown in Figure No. 4 The test shows the wear of sharpened steel pins of known high-strength alloy steel. The pins are used to scratch the surface of freshly broken rock. Statically loaded with 7 kg. The index is determined by the resultant wear steel pins. When you use the same material as the pins on the cutting tool can be used Cerchar abrasive index as a variable determining the wear of cutting tools. CIA values range between 0.5 for soft rocks (eg shale and limestone) and 5.0 for hard rocks (eg quartzite).

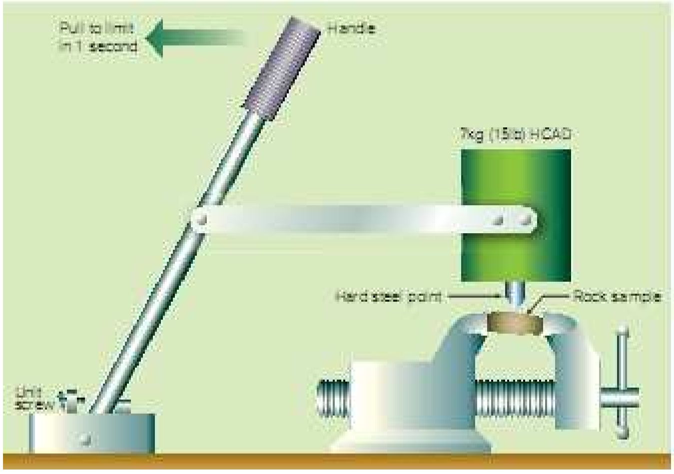

Fig. 4 *Diagram of test equipment CAI*

LCPC test [6], wear rate ABR. The essence of this test is in a rock sample from the grain size 4 mm - 6.3 mm, which is attached to the cylindrical drum and attached to a metal propeller that is rotated at 4500 min-1. The propeller is made of soft steel, which can be easily scratched with a knife. Abrasive rate ABR, which is the output value of the LCPC test, the weight loss corresponds to the propeller at 1000 kg. LCPC test is used mainly for rock samples. There is a relationship between the ABR, CAI.To estimate the rustiness and percussion drilling test was developed by NTNU (AV / AVS). Diagram of test equipment, see Figure 5 Principle of the test sample is rolling material. To test and the sample is made of tungsten carbide, and test the AVS is made of high speed steel. Test principle is to rotate a steel blade, to which it is pouring a mixture of particles of grain size <1mm 80g/min speed. This test helps us to determine particle fragility, BWI index (index of tool wear) and the DRI index (index of drilling speed).For the TBM test was modified and was replaced by BWI index index (CLI tool life index). NTNU model is continuously revised and updated. Currently the data is drawn from the 250 km of tunnels in Norway. In his database of over 3.000 different rock samples from around the world.

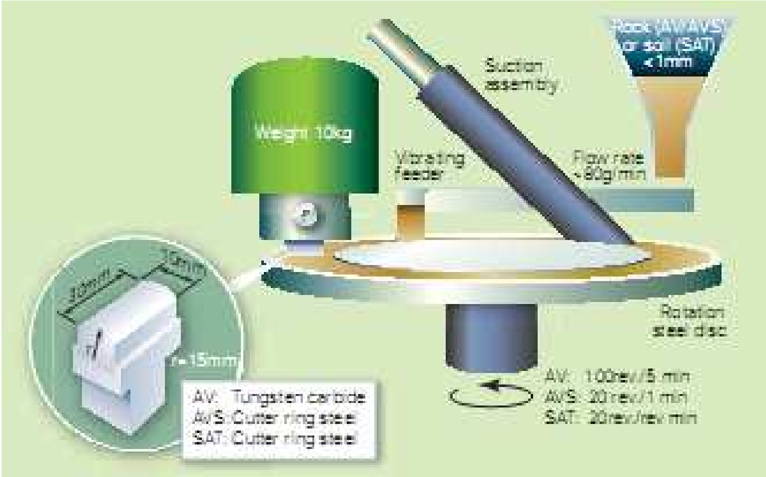

Fig. 5 *Diagram of test equipment NTNU*

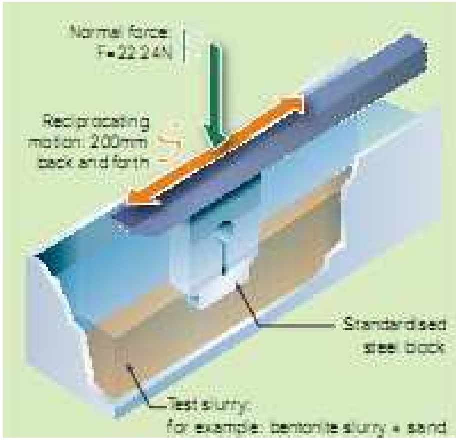

Fig. 6 *Diagram of test equipment Miller test*

Examples of tests that describe the properties of soils and soil are the Vickers hardness (VHN) Mohovsova hardness, abrasive mineral content (AMC), Los Angeles abrasion model of earth, Ball Mill Test (NBMT), the Miller test (ASTM G75-01), see Fig . 6, NTNU SAT, LCPC 2007th Like most appropriate and most meaningful value I choose NTNU SAT test LCPC 2007, compared to the results of these two tests is shown in Figure 7.

	SAT Test (modified AVS)	LCPC Test
Type of material to be tested	Soil	Soil
Grain size range	<4mm	<6.3mm
Material of test piece that is subject of abrasion	Cutter ring steel	Soft steel
Rotation speed within contact surface that is subject of abrasion	20 rpm	4,500 rpm
Type of contact causing abrasion on test piece	Friction at low velocity within contact surface	Friction due to impact & due to high-velocity within contact surface

Fig. 7 *Compare features NTNU SAT test and LCPC 2007*

2.2. Excerpts from the Final Report detailed geotechnical survey for the construction PCRR, 514th construction

***Table 1**: Abrasion of selected rocks and soils*

GT symbol	Code explanatory	Type of rock	Classification		Abrasion	
			NRTM	ÖNORM B2203	F_{Radv}	CAI
A_n	AN	Fills	-	-	-	-
E	E	Loess soils, loess	5a (5b)*	-	-	-
N	F,DF,D	Clayey and loamy sediments od rock debris	5b (5c)	C2	-	-
T	T	Snad, gravel	5c	C2	-	-
S	K_b	Marls, mudstunes	3 až 4	?	0,099	0,980
P	K_k	Sandstones, conglomerates	3 až 4	B1	1,824	1,2-2,5
J	K_p	Clays, mus¨dstones, siltstones	4 až 5a	B1 až B2	-	-
B_e	SI,O_{kv},O_{bz},O_v,O_{lt},O_{lb},O_d,$O_{š,t}$O	Slate, altered basalts	5b až 5c	B3 (C2)	?	?
B_z	SI,O_{kv},O_{bz},O_v,O_{lt},O_{lb},O_d,$O_{š,t}$O	Slate, altered basalts	5a	B2 až B3	0,133	1,0-2,7
B	SI,O_{kv},O_{bz},O_v,O_{lt},O_{lb},O_d,$O_{š,t}$O	Slate	4 až 5a	B2	0,133	1,0-2,7
K	O_{ks}	Siltstone, sandstone	3 až 4	B1	18,435	5,549
Q	${}_qO_ř$,${}_qO_s$	Quartzite, quartz sandstone	3	(A2) B1	5,537	4,3
R	R	Loosened sandstone blocks	5c	?	1,824	1,2-2,5

The findings of silica content and determining abrasion were collected 4 samples of rock. These are samples of rocks, which are important for their future power excavation of large tunnels or on the macroscopic description shows that contain significant amounts of quartz. Determination of abrasion of rocks is important for determining the workability and workability (eg mills). Determination carried out a laboratory accredited by SG – Geotechnice a.s.

Clear abrasion test results are processed in Table 2.

Table 2: Results of abrasion tests

sample (lab. číslo)	kvazihomogenní section	chainage[km]	petrographic typ	Abrasiveness average [mg/m]
80911	B	11.852,3	grained quartz sandstone (KSN1)	4,145
82823	D	12.053,7	claystone (KRD)	0,133
84375	E	12.329,8	grained to medium grained quartz sandstone (KSV1)	16,578
85032	G	12.466,7	strongly calcareous claystone (LIT4)	0,133

PETROGRAFICKÉ ROZBORY

Petrographic ANALYSIS

For the purpose of ascertaining the level of silica, 4 samples were collected for petrographic analysis of rocks. Petrographic analysis carried out by staff of the SG - and Geotechnics Ing. Lodges and Mr. Charles. Renata Sasínová. Summarized results of the petrographic analysis are elaborated in Table 3.

Table 3*: Results of petrographic analysis*

vzorek (lab. číslo)	kvazihomogenní úsek	staničení [km]	petrografický typ	obsah křemene [%]
80911	B	11.852,3	jemnozrnný křemenný pískovec (KSN1)	90 - 95
82823	D	12.053,7	jílovec (KRD)	sporadicky
84375	E	12.329,8	jemnozrnný až středně zrnitý křemenný pískovec (KSV1)	85 - 95
85032	G	12.466,7	silně vápnitý grafitoidní jílovec (LIT4)	bez křemene

From the foregoing, it is necessary to select and then build a system of experiments, which would also confirm and extend knowledge of the geology, which will most affect the wear of cutting tools on the tray.

From the foregoing the need to develop special tests and experiments, so that they can be made relevant model of abrasive wear, ie functional cooperation between the pairs. The best seems to me or use. modification of existing tests for rocks than creating new methods. A clear example is the NTNU and its modifications for the SAT.

2.3. Abrasive wear resistence of surface

Abrasive wear is characterized by separation and moving the particulate material in the creasing and cutting sharp-edged particles. These particles may be free or bound in some way and that between the two functional surfaces in relative motion. Abrasive wear processes are more complex and requires an analysis based on all parameters such as course load, the hardness of the deformed structure, the specific energy (SE), coefficient of wear, abrasive wear, etc. Classification is according to Anglo-Saxon literature on the gouging abrasion (grooving abrasion) , high-abrasion (HV) and low-abrasion (low). Another division is the two-point abrasion (shot - worn surface) and three-point abrasion (shot between two surfaces). The literature shows that the difference between two-and three-point abrasion is the complexity of the preparation and evaluation tests, the two-point abrasion is easier, but not completely accurate and meaningful [9].

In Suchanek [2] says that the wear of friction pairs with the contact between the abrasive surface is much more complicated case than the wear caused by abrasive particles tightly bound. There is how to wear both contact surfaces and the intense violations of abrasive particles and therefore have an important role of physical-mechanical and structural characteristics of worn surfaces and abrasive characteristics of strength, size and shape abrazivnách particles, their concentration between the friction surfaces. Is also important relationship between the size of abrasive particles and the distance of the surface. Other factors are the load, the temperature of friction surfaces, relative velocity between the rubbing surfaces and abrasive particles, the presence of grease or other chemicals and roughness of friction surfaces [2].

There are 3 cases of abrasive wear on functional surfaces of friction pair due to the presence of hard particles [2.9]:

a) Abrasive particles that pass through the space between the contact intact (functional) and the surfaces of the load causes the wear surfaces. The distance between the contact surfaces is given by the initial size of the abrasive particles. The intensity of wear increases linearly with increasing load. This case is real only when a high concentration of abrasive particles with high strength and small external loads.

b) abrasive particles are abused at a certain depth of penetration into the contact (functional) surface. Violation of particles is to limit the size of the DDR, which is due to the dynamic equilibrium of external loads and local pressures borne particles. The distance between the contact surfaces is given DDR. The linear dependence of wear on the load becomes slightly decreasing dependence. This case is typical for medium pressure and low concentrations of abrasive particles having a little strength. It is often the case, and a few pairs of plain loaded roller pairs (secondary wear), see Figure 8.

c) The abrasive particles are abused until they reach a size value δ '+ Δ' (surface imperfections, the size and thickness of lubricating layer) and then pass through the contact area. The distance between the contact surfaces is given by the lubricating film thickness depending on the conditions of hydrodynamic and elastic-hydrodynamic lubrication. The depth of penetration of abrasive particle size and abrasion strength characteristics is given abrasive and does not depend on external load. In this case, are characterized by high rolling contact pressures at the slip (disc cutter).

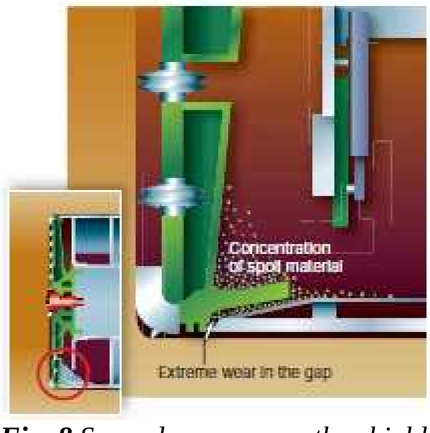

Fig. 8 *Secondary wear on the shield*

With all the above-mentioned cases of abrasive wear meet the technology of mechanized stamping boring shields (SM). For us, it is interesting but the last case, which appears to shield the cutting tools. As an example I wear the head shield, see Figure 9 This wear is monitored by the project. Project monitoring is not yet at a stage where it is possible to identify or examine the degree of wear processes alone wear them to operate the shield.

Fig. 9 *The consequences of poor design of cutting head, the effects of abrasive wear*

3. Conclusion

It is important to create the best possible systems to describe the wear in working conditions and its influence on the occurrence of abrasive wear on the mechanized shields. These conditions include abrasion of rocks and protection of the cutter head shield against wear. The detailed analysis shows us how it is possible to create a theoretical model of wear. It is possible to provide additional wear protection on the cutting tools so as to ensure the smooth operation of tunneling machine.Based on the findings of the study and all the necessary properties of rock and soil samples taken from the geological survey, we get closer to the real working conditions which will be on the excavation face. In an ideal situation and on base informations, we will to be able to simulate real working conditions during the excavation. It is necessary to define the characteristics of cutting tools, their behavior in interaction with the anticipated working condition.The description of the work condition involves finding the real motion of solid particles in muck, the contact pressure metal-soil, humidity, ambient pressure and used additives. With knowledge of the above, we can design a cutting tool which will be better and will be more resistant to forced labor and conditions imposed on them. It is said that after creating and testing a model including the above, the model will be combined with the already existing models from the ongoing project. Based on interpolation of both models it is possible to predict tool wear for different work conditions.

List of symbols

σt_1	*unconfined compressive strength*	*[Mpa]*
F	*maximum force in violation*	*[N]*
A	*section of core sample*	*[m^2]*
σt_2	*indirect tensile strength*	*[Mpa]*
F	*The maximum force*	*[N]*
D	*diameter core sample*	*[m]*
L	*Core sample length*	*[m]*
SM	*Shield Machine*	
TBM	*Tunnel boring machine*	
EPB	*Earth pressure balance*	
CAI	*Cerchar abrasivity index*	
CBS	*Conveyour belt system*	

Bibliography

1. BARTÁK, J.; BUCEK, M. Podzemní stavby. Praha : Editační středisko ČVUT, 1983. 425 s.

2. SUCHÁNEK, Jan; KUKLÍK, Vladimír; ZDRAVECKÁ, Eva. Abrazivní opotřebení materiálů. Praha : [s.n.], 2007. 161 s. ISBN 978-80-01-03659-4.

3. Choozing mechanized tunnelling technoloques. Tunel et ouvraghes souterrain. Hors-serie No.1. 2005, 1, s. 137-163.

4. KREPELKA, František, et al. Určovanie abrazivity hornín pre razenie tunelov plnoprofilovými raziacimi strojmi. Acta Montanictica Slovaca. 2000, 5, 3, s. 225-227.

5. Tackling a new soil : abrasivity index. North American Tunneling Journal. 2010, 4, s. 16-18.

6. NILSEN, B. Abrasivity of soils in TBM tunnelling. Abrasivity & Wear. 2006, March, s. 36-38.

7. BARTÁK, J. Příspěvek k problematice plnoprofilových tunelovacích strojů. In Příspěvek k problematice plnoprofilových tunelovacích strojů. 2009. Praha : [s.n.], 2009. s. 6.

8. STANDFORD, Julian ; HAGAN, Paul. The impact od stzlus metallurgz on the Cerchar abrasivitz index value. In . . USA : UNSW, 2008. s. 7.

9. RÁPAVÝ, Michal. Tribologické vlastnosti funkčních vrstev. Praha : SNTL, 2009. 83 s.