Anti-wear and Anti-dust Solutions for Hard Rock TBMs

L. Langmaack[1], B. Grothen[2], P. D. Jakobsen[3]
[1]*BASF Construction Chemicals, Zuerich, Switzerland;* [2]*The Robbins Company, Solon, USA;*
[3]*The Norwegian University of Science and Technology (NTNU),Trondheim, Norway*

1. Introduction

Abrasive wear on cutter tools and high levels of dust are common processes causing problems in hard rock TBM tunneling. Wear and damage on cutter tools are mainly caused by crushed rock powder in the cutter grooves and from falling rock from the tunnel face. Wear rates on cutter tools are also observed to increase when boring without water, most likely because of high temperatures and inability to remove fines in the cutter grooves [1]. To cope with abrasive wear from fines, dust suspension and high temperatures, one approach can be utilization of chemicals. The use of water, water based agents or foam on hard rock tunnel boring machines is not new technology, and dates back to 1973 and earlier. They were or are still used, more or less successfully, in order to reduce the amount of dust and to reduce the dust-related problems.

2. State of the Art Methods

2.1. Wear Reduction

Improved performance of cutters is an area of continued research with substantial improvements made over the past fifty years. Recent research has addressed multiple facets of cutter design with cutter life being an important design objective. Some examples of areas that are evaluated with respect to cutter life are the cutterhead profile, cutter tip profile and cutter metallurgy. The number of cutters changed versus their positions is tracked, with a higher rate of wear being seen at the positions where face cutters transition to gage cutters. This reduction in cutter life in the transition region is due to an increase in both the rate of cutter ring wear and the number of blocked cutters that occur in the region. The area has been shown through the use of strain gauges to have higher loading than face cutters with a comparable spacing. Cutterhead design has evolved over time using tests and experience to refine position and mounting to extend cutter life.

A second area that has been developed to deliver performance while providing a good service life is the cutter profile. The tip width is chosen to give good penetration into the rock while still providing sufficient strength to maintain the integrity of the rings and minimize edge chipping, which is seen on the high cutter loading of modern machines. Cutter metallurgy is also used to combat this issue, with many different steels being used over time. Disc rings were historically made from bearing quality steels. Robbins cutters are made of steel with a proprietary chemistry and hardening process that has been progressively refined to provide higher hardness without the loss of fracture toughness, thereby minimizing chipping.

2.2 Dust Reduction

Dust is an inherent part of tunneling in rock. New regulations in many countries highlight the need to control airborne dust, with specific focus on quartz-containing dust. Dust is currently controlled in two different ways on a TBM. First, it is captured at point of origin to limit excessive airborne particles at the face of the tunnel. Second, water is brought to the face through a rotary union, where it is distributed to equally-spaced spray nozzles on the face of the cutterhead. As

the rock is cut the water spray captures the dust and removes it through the mucking system. Water spray bars may also be installed at dust producing areas, such as conveyor transition points on the backup, and in the muck car loading area. Once the dust becomes airborne it is removed through the use of a dust scrubber. Again this is done primarily in the area of the cutterhead. Large fans pull the dust-laden air through ducting to a dust scrubber located on the back up. Fresh air is brought forward to help replace the air that is removed. The scrubber can be either a wet scrubber, which again uses a water spray to capture and remove the airborne dust, or a dry scrubber that forces the air through a series of filters. In both cases the captured dust is added back to the muck stream and removed from of the tunnel.

The following methods are of special interest [2]:
- *Water sprays: wetting and airborne capture*

Of the two, wetting of the broken material is far more effective. Adequate wetting is extremely important for dust control. The vast majority of dust particles created during breakage are not released into the air, but stay attached to the surface of the broken material [3]. Wetting this broken material ensures that the dust particles stay attached. As a result, adding more water can usually (but not always) be counted on to reduce dust [4,5,6].
- *Water additives: foam and wetting agents*

For dust control, foam works better than water. It provides dust reductions of 20% to 60% compared to water. Foam also can produce similar results at lower water use. The amount of water needed to make the foam is less than the equivalent water spray. High-expansion foam, when compared to water sprays at a belt transfer point, averaged an additional 30% dust reduction [7]. Foam released from a longwall shearer drum cut the dust an additional 50% compared to conventional water sprays on the drum [8]. Also, the system used one-half the water of the conventional sprays. The drawback of the foam was high cost. Like water, foam works best when it is mechanically mixed with the broken material. A comprehensive review of foam for dust control in mining and minerals processing has been given [9].
Wetting agents receive a disproportionate amount of attention, perhaps because they seem to offer an easy fix to dust problems. Most of the interest has been in coal mining because of the hydrophobic nature of coal. The effectiveness of wetting agents has been the subject of considerable research over the years, without much of a definitive answer on how well they work.

3. The use of Foams and Polymers

BASF has taken a fresh view on the use of foam on hard rock TBMs, believing that its use can be much more effective than the common water sprays and also more (cost) effective than described above. The effectiveness of foam strongly depends on the way the foam is generated and on how it is used – improvements can be made here. Furthermore, a possible incorporation of anti-wear-additives into the foams or the development of foamable polymers represents an interesting dual role for the new additives. The increase of dust catching effectiveness together with their new anti-wear-capacities will reduce the above mentioned high cost draw-back of the use of these additives.

3.1. Laboratory Results and Interpretation on Construction Time and Wear

Imitations of the process of hard rock drilling with TBMs have been tried by several universities and researchers. Two of the most common methodologies for imitation of hard rock TBM tunneling with respect to advance rate, cutter consumption and cost estimates are the NTNU method consisting of the Drilling Rate Index (DRI™) and Cutter Life Index (CLI™), and the Colorado School of Mine's method based on individual cutter forces to determine drilling advance[10]. In addition the Cerchar Abrasivity Index (CAI) is recognized as a quick measure on a rock's abrasivity and expected cutter consumption on TBMs.
The NTNU model is based on empirical relations between rock parameters obtained from laboratory and field, such as DRI™, CLI™, porosity, fracture class, quartz content and TBM parameters [11]. The empirical relations are established with a basis of 30 different tunnels (250 km) with respective TBM production data and wear records on cutter tools. It has been tried to use the NTNU model to check theoretically how the use of anti abrasive agents influence advance rate, cutter consumption and relative tunneling cost.

The DRI™ is based on the rock's brittleness and surface hardness, and the CLI™ is based on the surface hardness and abrasion properties of the rock type. The brittleness value is evaluated in an apparatus which is based on 20 stroking impacts on a known fraction of a rock sample. After the impacts, the percentage of the crushed down rock represents the measured brittleness value. The surface hardness measure is obtained by the Siever's J apparatus, which drills miniature holes in a rock sample. The depth of these holes is the surface hardness measure.
The final rock property needed to be established before calculation of DRI™ and CLI™ is the abrasion. The NTNU model uses an in-house built apparatus consisting of a rotating steel disc applied with crushed rock powder or soil. The soil or rock powder has to pass a cutter ring piece, which causes a measureable weight loss - the result of which is our abrasion value. The abrasion apparatus was used to measure reduction of abrasion by introducing the MEYCO ABR5 anti-abrasion agent on one rock sample from Lötschberg in Switzerland and one rock sample from the AMRII project in India. Results and classification of results are showed in Table 1. The use of additives influences the abrasion test and subsequently the CLI™, whilst brittleness values and surface hardness properties are the same with and without additives.

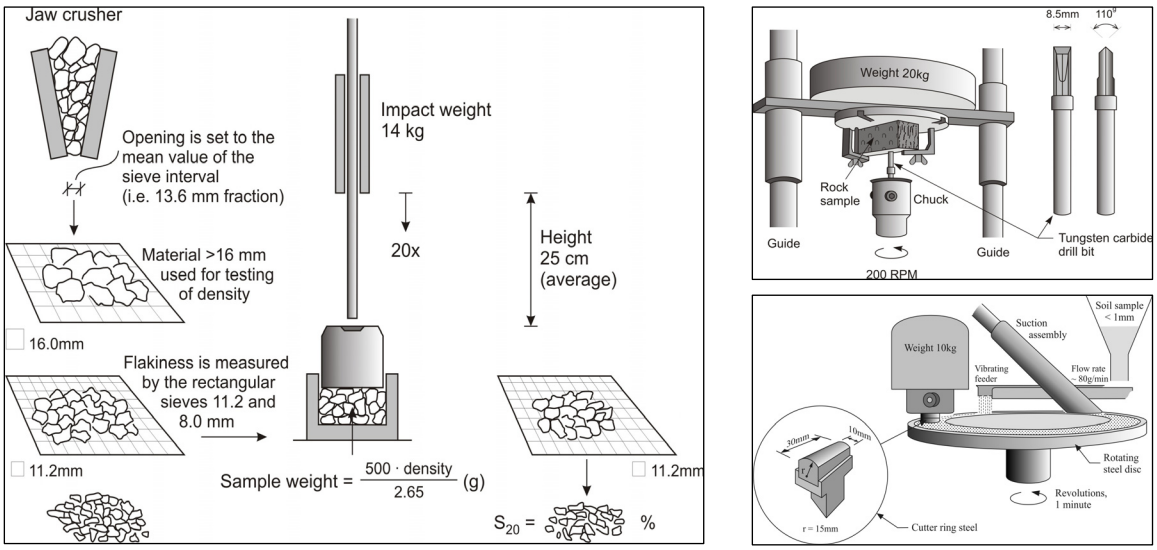

Figure 1. Schematic introduction of brittleness testing (left), Sievers J (top right) and abrasion testing (bottom right).

For further and detailed description of laboratory test procedures and pictures needed for the NTNU model please refer to http://www.drillability.com.

Table 1. Drillabillity indicies and classification for evaluated rock samples.

TEST RESULTS

Sample No.	1	2	3	4
Sample ID	India	India foam	Lötschberg	Lötschberg foam
Brittleness Value (S_{20}, 11.2 - 16.0 mm)	52.5	52.5	57.7	57.7
Flakiness	1.39	1.39	1.31	1.31
Compaction index	0	0	1	1
Density, g/cm^3	2.57	2.57	2.64	2.64
Sievers' J-Value (SJ)	1.7	1.7	2.8	2.8
Abrasion Value Cutter Steel (AVS)	49.0	32.0	25.0	10.0
Quartz content (DTA) weight %	72.0	72.0	NA	NA

CALCULATED INDICES

Drilling Rate Index (DRI)	43	43	52	52
Cutter Life Index (CLI)	3.8	4.5	6.0	8.5

CLASSIFICIATION:

Category	DRI	CLI
Extremely L	≤ 25	<5
Very Low	26 - 32	5.0 - 5.9
Low	**33 - 42**	**6.0 - 7.9**
Medium	**43 - 57**	**8.0 - 14.9**
High	**58 - 69**	**15 - 34**
Very High	70 - 82	35 - 74
Extremely Hi	≥83	≥75

The NTNU advance rate, cost and cutter consumption model have been used in order to go one further level in the evaluation of ABR5. The evaluation has been done with a software called fullprof which is provide quick estimates of the NTNU model [12]. The summary of the estimation

is showed in Figure 2, and the estimation indicates an increase of weekly advance rates and increased cutter life.
The input parameters are drillability indices as presented in Table 1, with rock mass classification I, which is equal to average spacing of 80 cm between fissures and joint system in the rock mass. To excavate the Lötschberg rock it is assumed a hard rock gripper TBM with 51 cutters of 19 inches and average cutter thrust of 260 kN per cutter. For the excavation of India rock it is assumed a hard rock gripper TBM with 67 cutters of 19 inches and 312 kN per cutter in average thrust.

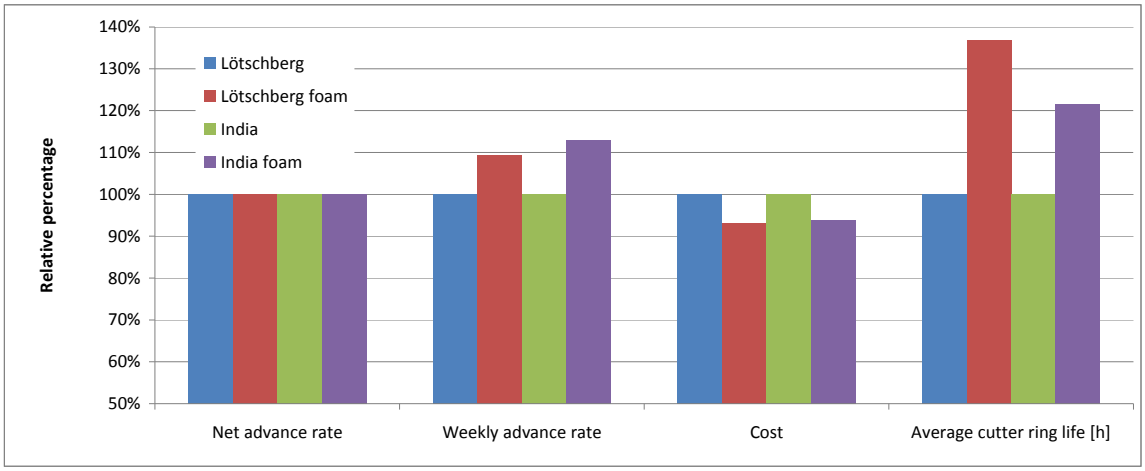

Figure 2. Relative comparison of estimated advance rate, cost and cutter ring life.

3.2. Site Example No1: Guadarrama High Speed Rail Tunnel, Spain

The Guadarrama tunnels belong to the new high speed railway link between Madrid and Oviedo. For this project the Guadarrama mountains between Madrid and Valladolid had to be crossed with a 28.400m twin tube hard rock tunnel. Totally 4 TBMs – 2 Herrenknecht and 2 Wirth – were used and finished boring in June 2005.
characteristics Wirth TBM:
diameter: 9,46m; total installed power: 5.600 kW; cutterhead torque: 27.000 kNm
characteristics Herrenknecht TBM:
diameter: 9,51m; total installed power: 5.500 kW; cutterhead torque: 20.000 kNm

3.2.1. Project description

The geology along the alignment showed 85% metamorphic and igneous rock, 10% weathered rock conditions as well as various fault zones. The 620m long Umbria fault with nearly loose ground conditions represents the longest of its kind, several others last for 10-20m only – leading to a double shield TBM concept.
Nevertheless, the intact granite sections showed UCS values of up to 280 MPa, in addition containing quartz contents of up to 80%. This resulted in measured Cerchar Abrasivity Index values between 5 and 6, classified as extremely abrasive to quartzitic.
In light of these predictions, the JV decided to consider the possibility of using anti-wear-additives and to evaluate their benefits on-site. In order to use these anti-wear-additives efficiently, the TBM needs to be adapted to their use.

3.2.2. Necessary adoption of the TBM

The MEYCO ABR 5 anti-wear-additive must be supplied to the cutter head as foam. In consequence, it requires some modifications of the TBM and additional installation:
- Foam System
A foam system is necessary in order to foam up the anti-wear-agent. Similar to the foam systems used on Earth Pressure Balance (EPB) TBMs, the following components are mandatory to be

installed: water (supplied by water booster pump), dosing pump (for the correct dilution of the anti-abrasion-agent into the water), compressed air, foam guns (which create the foam out of compressed air and the foaming solution) and a regulation system for each foam gun.
Unlike the fully computerised versions on the EPB TBMs, the system installed on the hard rock TBM was manually operated due to lower investment costs and quite steady output values.

- Foam nozzles
The foam has to be injected through special designed foam nozzles on the TBM cutterhead. The existing water sprinkler nozzles as standard equipment on the cutterhead will destroy the foam and must be replaced. In the case of the 9,5m diameter Guadarrama TBM, the above indicated 5 injection points on the cutterhead have been chosen to be changed into foam injection points in order to ensure a homogeneous and even foam distribution on the cutterhead.

- Rotary coupling (rotary swivel)
The normally installed water splitter box cannot be used for the anti-wear-additives. Only the installation of a rotary coupling ensures specific outputs per foam injection point representing a key factor for the successful use of the anti-wear-additives.

Generally, existing hard rock machines can be upgraded to the use of modern anti-dust and anti-wear-additives. Nevertheless it is strongly recommended to study especially the installation of the rotary coupling during the TBM design stage, reducing considerably the later upgrading costs without increasing the total TBM costs significantly.

3.2.3. Site test results

Altogether, some 600 tons of MEYCO ABR 5 anti-wear and anti-dust-agent were used on the Guadarrama High Speed Railway Project in Spain.
The following benefits associated with their use were reported:
- Cutter wear reduction
A wear reduction of > 15 % was achieved, resulting in 25 – 30 hours per month less down time due to less cutter changes. This downtime was then used for additional excavation. Disappearance of blocked cutters using MEYCO ABR 5.
- Clean cutter tools
The rock dust with is created during the boring process, can agglomerate on the disks as shown above when using water. This implicates a time consuming cleaning process before these disks can be changed, there may be the risk of clogging the disk window and last but not least the grinding paste formed by the stone dust & water increases wear. At Guadarrama the use of MEYCO ABR 5 prevented the stone dust from creating this paste and the tools remained clean (see figure 3).

Figure 3. dust agglomeration difference: left side water use, right side MEYCO ABR 5.

- Temperature reduction
The use of MEYCO ABR 5 resulted in a significant temperature decrease from 90 – 150°C to around 70°C, resulting in shorter down time due to less cooling and waiting time.

- Improved muck transfer and a dust free working environment (see Figure 4).

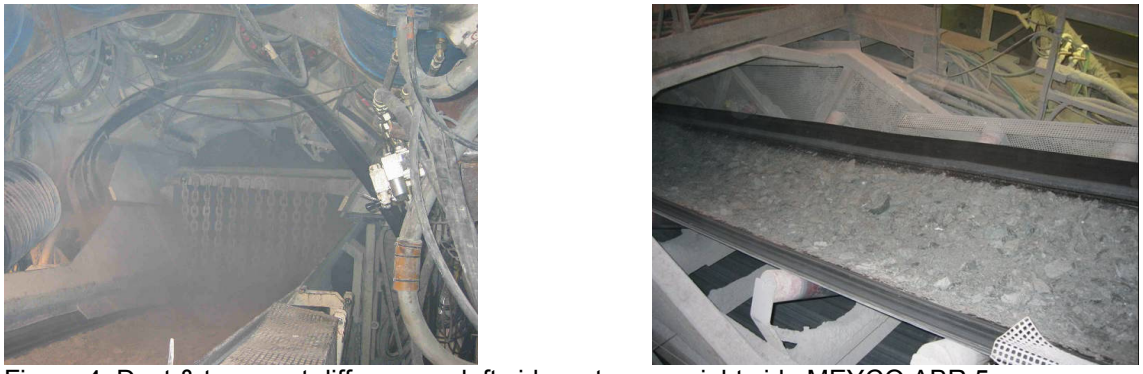

Figure 4. Dust & transport differences: left side water use, right side MEYCO ABR 5.

- Reduction of water usage and less water reclamation
When using MEYCO ABR 5, the amount of injected water was reduced from originally 310 litres/m^3 excavated rock down to 50-100 l/m^3.

Key assumptions made for the following roughly-estimated benefit calculation:
- TBM speed of around 50mm/minute
- monthly advance rate of 500m
- fixed TBM costs around 2000 €/h

With 70.000 € MEYCO ABR 5 monthly product costs it was possible to reduce the wear & maintenance in this case of more than 15%, which can be back-calculated to a reduction of maintenance and material costs higher than 50.000€.

Anti-abrasion-agents are still useful because the reduction of maintenance has not only a direct cost influence but realises also considerable time savings. The 15% of reduced downtime can directly be translated into 80-90m of extra excavation per month – turning the above calculation with an initial loss of 10-20.000€ into final savings of some 40.000€ per month.
In addition, the above quick benefit calculation does not even take into account important benefits such as a nearly dust free environment, more convenient and quicker changing of discs (due to lower temperature and clean discs), drastic reduction of sprinkling water and reduced energy consumption due to less exhausting.
Knowing that these effects do have a significant cost influence in many projects, BASF and Robbins decided to have a deeper and broader look into these parameters by launching a copious on-site test program at the Indian AMR II project.

3.3 Site Example No. 2: AMR II Water Transfer Tunnels, India

3.3.1 Project Description

The Alimineti Madhava Reddy (AMR) Project is a water project located near the city of Hyderabad in Andhra Pradesh, India and is part of a much larger water transportation scheme. The region is one of the most arid in India with only 925 mm of annual rainfall. Local water supplies to 500 area villages are contaminated with fluoride levels that far exceed guidelines. This is being addressed by a system of canals and tunnels, which contains over 100 km of canals and one of the longest TBM driven tunnels ever constructed in India.
There are two main projects emanating from a common reservoir to supply water to four districts in Andhra Pradesh, one of which is the AMR project. The main tunnel will be constructed using two Robbins 10 meter diameter double shielded machines boring from opposite ends. The main tunnel is 43.5 km long and will connect the Srisailam Reservoir to a balancing reservoir on the Dindi River for transfer during the monsoon months. A second 7.3 km long tunnel will then distribute the water to a network of canals to the plains of the Nalgonda District, where it will be used to irrigate farmland and provide potable water to 516 villages.
The geology is generally very stable, as this section of the country is part of the South Indian Peninsular Shield made up of two primary rock types: quartzites and granite. The machines will

excavate in both rock types with the quartzite zones having compressive strength up to 450 MPa, and layered with shale for about 60% of the tunnel length. The granite is expected to have a range of 160 to 190 MPa (23-28 ksi) and makes up the remainder of the tunnel. The quartzite sections are of particular concern with respect to cutter cost due to significant abrasiveness and high strength. The quartzite section can also be very blocky in nature, which can increase cutter wear due to the damage caused by impact loading. The Robbins DS325-317 machine will start at the outlet of the tunnel and bore up to meet the DS325-318 machine, which will start at the reservoir at the opposite end. Both machines were delivered in 2007 and the -317 began boring in November of 2007. While the second TBM parts had been delivered, problems encountered in obtaining access to land necessary for commencing excavation of the inlet portal delayed the start of assembly of the -318 machine until June of 2009.
In early October, the assembled machine, located in the assembly portal, was flooded and covered by 10 m of water. Currently efforts are underway to repair the damage so that boring can commence (see Figure 5).

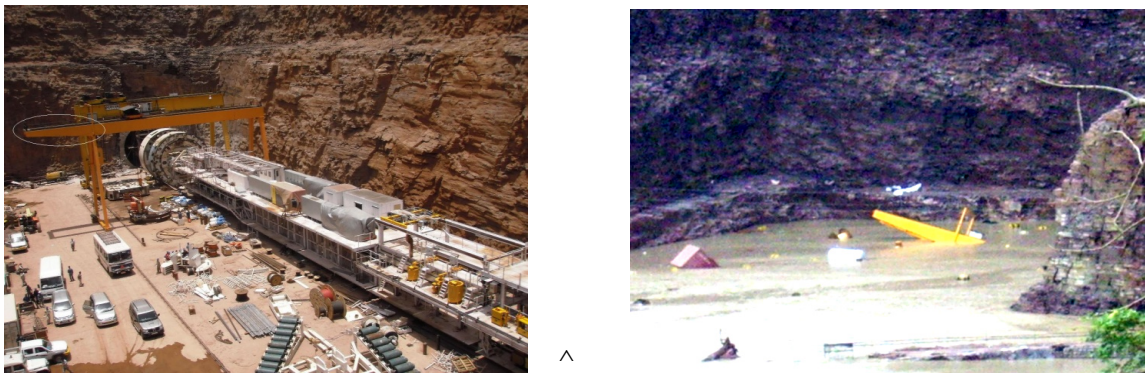

Figure 5. AMR II Inlet portal before flood (left) and after flood (right).

3.3.2 Necessary Mechanical Changes

The delay in the ability to gain site access to the portal provided the opportunity for required modifications to be made prior to machine assembly, and new systems to be added during the assembly process. The most notable change to the machine was the addition of foam nozzles to the cutter head. Water spray nozzles cannot be used with the foam, as they damage the foam and their locations cannot be modified for use with foam, as the water alone is used as a bench mark. Engineers decided that four new locations would be provided on the cutterhead. The modification required ø200 mm holes through 100 mm of structural plate and hard plating. Mounting plates were then welded into place for the nozzle assemblies. Further modifications to the structure were required to allow for the routing of additional plumbing and the addition of a manifold. The new design provides dedicated passages for each foam location and the existing water spray system through a new five passable rotary union.

3.3.3 Necessary Foam Installation

Similar to the Guadarrama foam installation, also here a manually controlled foam system will be used. Nevertheless, a couple of new features are installed to increase the effectiveness and user friendliness:
- data measurement: the foam system is equipped with magnetic flow meters for water, anti-wear agent and compressed air. This ensures correct data logging without any need of calibration.
- Data display: in order to ensure an easy survey, the flow of water, anti-wear-agent and compressed air is displayed at the dosing unit. The specific flow values for each foam gun are displayed at the generator itself.
- Remote control: the foam system can be switched ON and OFF via remote control from the drivers cabin. If switched on again, the foam system climbs automatically back to the latest installed output quantities. Furthermore, the remote control indicates the function (or non-function) of all main dosing components in order to detect defects as early as possible.

- Foam guns: in order to increase the foam quality of the anti-wear agents, a special foam core design has been developed. The foam quality has got a high influence on the efficiency of the anti-wear agents and their lifetime. This is especially difficult for low expansion ratios.

3.3.4 Additional Data Recording

The -317 machine was provided with a data collection system that captures machine data. This includes date and time of day, cutterhead rotation speed, cutterhead power, start / stop time (i.e. propel pressure greater than X), boring stroke position, penetration rate, thrust pressure and gripper pressure, most of which is applicable in evaluating cutter performance. In addition to existing monitored parameters, additional sensors were added for the testing. To evaluate changes in water use, analog flow meters were provided with the foam generation unit, as well as flow meters to monitor compressed air usage. Additional flow meters were added to the TBM water system to monitor water flow to the cutterhead spray system. The flow meters used in combination with the added dust monitor, are then used to evaluate the effectiveness of the foam product in reducing airbone dust and possibly reducing water usage at the face. The final set of sensors added to the machine is the Robbins Cutter Instrumentation System, which supplies real time vibration data, cutter rpm, and cutter temperature. From this it is possible to infer the rock face condition and how it is affecting cutter operation, as well as the state of cutter wear, without entering the cutterhead to inspect the cutters. The cutters will also be closely measured manually during excavation.

4. Summary and Outlook

Laboratory research as well as site data illustrate the possibility to reduce the three main problems on hard rock TBMs: abrasion, temperature and dust.
This can be realized already today by traditional measurements like water sprinkling, metallurgic improvements and exhausting – but there is a chance of significant improvements by using modern foams and polymers.
In order to prove the promising laboratory data, further on-site evaluations are necessary and will be given in the near future by detailed monitoring of the above described AMR II project in India.

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