UTILISING EXCAVATED ROCK MATERIAL FROM TUNNEL BORING MACHINES (TBMS) FOR CONCRETE

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UTILISING EXCAVATED ROCK MATERIAL FROM TUNNEL BORING MACHINES (TBMS) FOR CONCRETE

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Abstract

There are more than 2000 completed road, railroad and hydropower tunnels in Norway, with a current annual production of more than 7 million solid cubic metres excavated rock. The road and railroad tunnels are consumers of concrete, which is utilised for rock support, water- and frost protection. A small portion of the excavated rock affiliated with Norwegian tunnelling is used as concrete aggregate, while the major part of the rock is used for landfill. This paper reviews the potential of utilising excavated rock obtained by tunnel boring machines (TBM) as concrete aggregates, including results from recent European TBM projects that have utilised the excavated rock for concrete aggregates. Finally we present test results from excavated rock material from two new (including one ongoing) Norwegian TBM projects. Particle Size Distribution (PSD) of the filler / fines fraction and effect of the fines fraction (< 0.125mm) of the rock material on flow of fresh filler modified cement paste were measured. The reuse in concrete of excavated rock from 8 different recent European TBM projects varied from zero to 100 %. Reviewed PSDs and own PSD measurements show that TBM PSDs vary within wide ranges. Content of fines < 0.1 mm content can be more than 20 % of the total TBM and even higher when the coarsest material is used as feed in production of crushed aggregate. The newest project reviewed, the Norwegian Follo line, is generating the finest material with 50 % < 4 mm indicating the importance of rock quality in addition to TBM-technology for fines generation. The flow results of filler modified paste show that the TBM fines from the two projects with size 0-0.125 microns have very similar effect on fresh cement paste flow properties as a replica limestone filler with similar PSD composed from 3 different filler fractions.

1. INTRODUCTION

Most of the tunnels in Norway are excavated by the conventional drill and blast method. Furthermore, they are mostly less than 1000 m and the excavated rock has mainly been used for landfill, or even dumped in the sea. Around 30 of the tunnels in Norway were excavated by tunnel boring machines (TBMs) [1]. Hydropower tunnels are the main user of TBMs, as the

TBM enables a smooth tunnel cross-section with reduced head-loss in comparison with drill and blast tunneling. Figure 1a) shows a typical TBM cutterhead. Currently the Norwegian Railroad Authorities are utilizing 4 TBMs for a major railroad project from Oslo towards the suburb Ski. Last year the same client achieved the breakthrough of the new Ulriken TBM railroad tunnel project in the city of Bergen. Thus, infrastructure owners in Norway are starting to utilize TBM more commonly for tunneling. One central question is how are the possibilities to utilize excavated rock material locally, for example as aggregate for the tunnel's permanent concrete rock support and linings.

The aims of this paper are 1) to give an overview of the potential of utilising excavated rock material obtained from TBMs for use as concrete aggregates. Knowing the magnitude of the challenge is important to assess the societal impact. 2) Present how various recent TBM projects have utilised the excavated rock for concrete aggregates as input to discuss technical prospects for future reuse of the residues also including fines and not just the coarse parts that are presently used as feed for crushed rock processing plants. 3) Discuss how local aggregates can be exploited more in connection with tunnel projects. The results of the paper are based on a literature review, collection of laboratory data from old, recent and ongoing TBM projects, own laboratory studies of PSD of fines, sand and coarser fractions, as well as laboratory measurements of the effect of filler from TBM debris on flow of fresh filler modified paste. The quality of fines have a proportionally much larger influence than the quality of coarse aggregate on rheology of concrete [2] and therefore we start with the fines in this work. The work is entirely based on the MSc thesis of Torjus Berdal [3]. The key question, which is, whether this reuse can be done within economic benefits is not addressed.

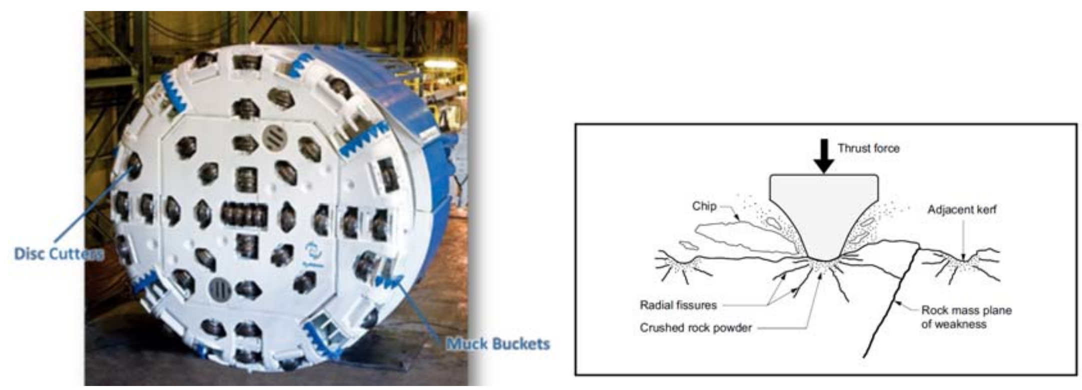

Figure 1: a) TBM cutterhead designed for hard rock excavation. Courtesy of the Robbins company [1] , b) Idealised rock breaking principle under disc cutters after Bruland [1]

2. GENERATION OF DEBRIS, UTILIZATION AND PSD

The rock breaking of hard rock TBMs is done by rotating the cutterhead equipped with disc cutters and applying high axial forces (200 – 315 kN per disc cutter) while the cutterhead is rotating. The axial force enables a crushing zone between the disc cutter and the rock face as well as inducing radial fractures into the rock mass. When the radial fissures range to a natural plane of weakness or a mechanical induced fissure from another disc cutter, chipping occurs, see Figure 1b.

TBM debris, when intended used for concrete aggregates, needs to be handled similarly in quality control as ordinary concrete aggregate. Particle size distribution (PSD) of fines, sand and coarser fractions is hence one of the most important aggregate quality parameters. PSDs were therefore reviewed and measured with dry and wet sieving on various TBM debris materials and with X-ray sedigraph on fines, or filler which is the terminology used in concrete technology. Nine different newer TBM projects (Railway- and Hydropower tunnels) in 5 European countries were reviewed as well as 30 older TBM projects (25 Norwegian, 5 Swiss). Regarding the other continents, no data on TBM-debris were found in Asia, Oceania or America in this study [3]. Table 1 shows an overview of 8 different TBM projects with varying degrees of reuse in concrete from almost zero to 100 %. So in practice the variation in reuse is large.

Table 1: TBM projects with confirmed utilisation of TBM excavated rock in concrete [3]

Project name	**Duration (year)**	**Minimum utilization fraction (mm)**	**Utilization of excavated rock (%)**
Zugwald	N/A-1998	16	16
Gotthard base tunnel	1999-2016	0	23
Lötschberg	1999-2007	0	29.1
Linthal	2010-2015	0	100
Nanth de Drance	2008-2016	0	25
Breheimen	1986-1989	10	N/A
Follo Line	2016-2021	20	10[1]
Koralm KAT2	2013-2023	16	17

A literature review from various sources has compared PSDs from hard rock TBM projects between 1977 and 2018 from Switzerland or Norway. The number of projects and time span of the projects enables high reliability, in terms of varying geology, TBM operation and TBM development. Figure 2 shows an overview of PSDs from the major Norwegian and Swiss TBM projects. Fines contents vary from< 5% to > 20 % and maximum particle size vary from < 10 to > 100 mm so these are clearly very variable materials. In addition, it is important to remember that use of coarse debris particles as feed in rock crushing plants will further increase the amount of fines. Careful selection of process technology for reuse of TBM debris is very important to limit the problem of fines generation and optimize particle shape. Although particle shape was not investigated in this study it needs to be addressed in concrete aggregate production. An interesting observation from figure 2 is that the Follo line, which is a new project, is generating the finest sieve curve (50% < 4 mm). The reason for this could be related to the TBM operation

[1] The utilisation of excavated rock for concrete purposes has stopped at the Follo line due to sulphur content ≈ 0.1 %

(relative low load per disc cutter), the brittleness of the rock mass and/or the TBM cutterhead design. Anyway, this project shows how a modern TBM with carefully distanced cutter discs and a high thrust force for maximum penetration rates is not enough to generate coarser sieve curves. The geology and petrography seem to influence the outcome of TBM debris quality to a large extent.

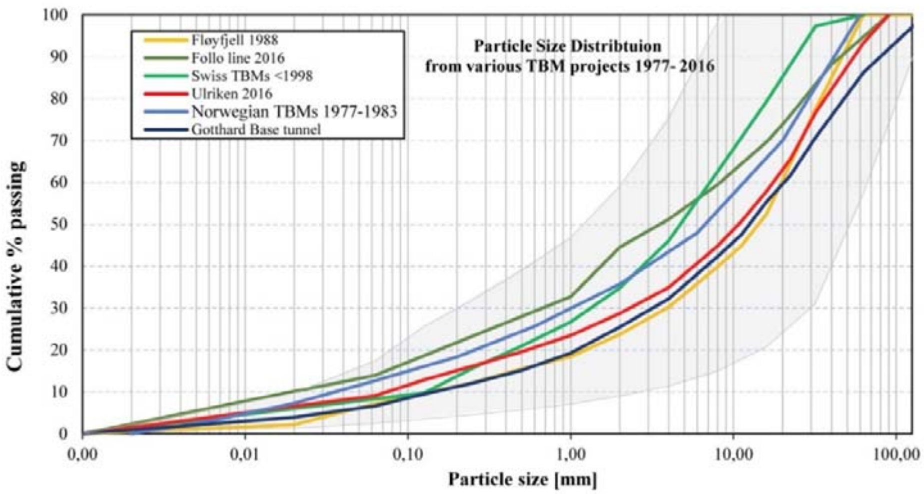

Figure 2: PSD from various hard rock TBM projects showing mean curves. Grey area represents possible variation for a single sieve curve

Observations in optical microscope of debris from Ulriken revealed that fines could adhere to the surfaces of larger (sand) particles to various extents, possibly due to the TBM process itself. This may cause negative effects on concrete properties (bond etc) as well as affect the measured PSDs. Therefore, both wet and dry sieving were done on 1 kg samples. These showed a +2.46% increase on the 0.125 mm sieve and +5.79% increase on the 0.063 mm sieve when wet sieving compared to when dry sieving. This seems to verify the visual observations of fines adhering to the surfaces of larger particles.

3. TBM FILLER VS LIMESTONE FILLER – PSD MEASUREMENTS AND CEMENT PASTE

TBM filler from Ulriken TBM project was collected on site in October 2017. The fraction <0.125mm was sieved out. Then the PSD was investigated with X-ray sedimentation using Micromeritics SediGraph III PLUS. With the known PSD of the TBM filler, the same PSD curve was composed with three different fractions of a crushed limestone filler. The reference limestone filler had been produced prior to the TBM material and separated through air classification and divided into coarse (40/250µm), medium (20/60µm) and fine (0/20µm) fractions. Figure 3 (left) shows the PSD of the TBM filler that was replicated with limestone filler with the method presented in [4]. A filler modified cement paste which would resemble that in a B45M40 concrete was designed for the purpose of measuring effect of TBM filler on flow properties in terms of mini-slump flow value and flow resistance [5]. The mini cone had bottom diameter: 89 mm, top diameter: 39 mm, height 70 mm. The cement content in the mix would resemble a cement content of 360 kg/m^3 in a 1 m^3 concrete mix. Table 2 shows composition with mass ratios water/cement = 0.40 and filler/cement = 0.36.

Table 2 Cement paste composition used with TBM filler and limestone filler

Constituents	**Kg**	**Density(kg/m3)**
Norcem CEM II/A-V	2.288	3020
Water	0.915	1000
Superplastizer (0.9%)	0.021	1050
Filler (TBM/Limestone)	0.818	2700

2 litre cement paste mixes were prepared in the lab according to the procedure [6]. The slump-flow measurements were performed on a transparent plexiglass plate and assured no leakages between matrix and cone. In addition FlowCyl values were measured [5**]**. The latter method is similar to the Marsh cone and the resulting flow resistance number λ_Q (0 - 1) correlates well to plastic viscosity whereras slump flow correlates to yield stress [2,6]. Table 3 gives average results of 2 parallel mixes for each of the 5 studied fillers: 4 TBM fillers and 1 reference limestone filler. The results show marginal differences between the mixes. The slightly better workability of the replica limestone filler with similar PSD is in line with previous findings that limestone filler can have a favourable effect on workability compared to other minerals [6]. Figure 3 also shows that the replica lime stone filler has slightly lower content of the very finest particles which also contributes to the slightly higher mini slump flow and lower flow resistance number λ_Q seen in Table 3. The photos in Figure 3 show very stable edges on the slump flow samples.

Table 3: λ_Q and Mini-slump results, each value is average of two parallel mixes

Constituents	**λ_Q**	**Mini-slump(cm)**
Limestone	0.745	27.2
TBM Ulriken 1	0.807	23.4
TBM Ulriken 2	0.808	22.8
TBM Ulriken 3	0.806	21.3
TBM Follo	0.817	21.3

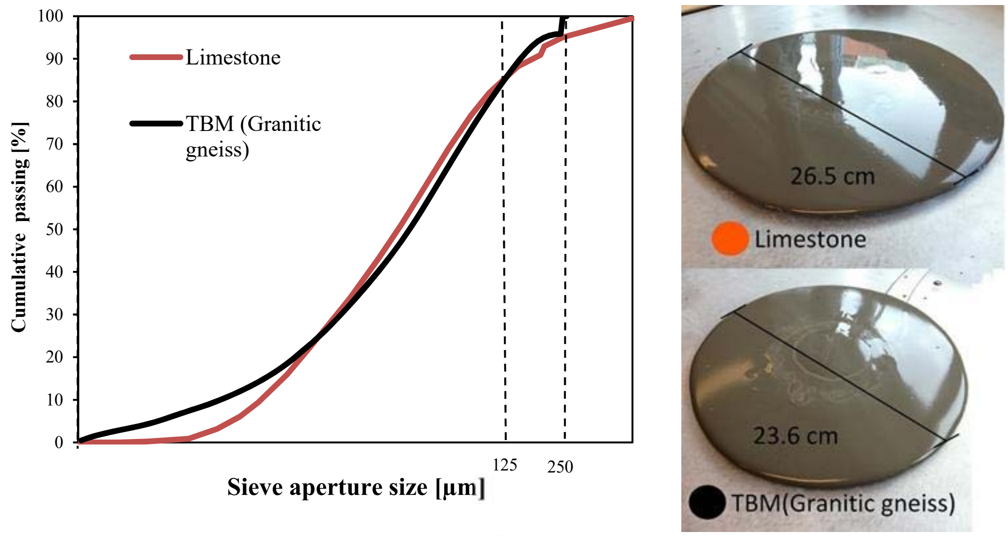

Figure 3: PSD of the filler from TBM debris and replica limestone (left) Mini slump measurements with stable edges (right)

4. REFERENCES

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