AGGREGATES FOR HIGH QUALITY CONCRETE AND SHOTCRETE MADE OUT OF EXCAVATED ROCK MATERIAL – EXPERIENCES GAINED ON THE ALPTRANSIT TUNNEL PROJECTS

C. Thalmann; B-I-G Bureau of Engineering Geology, P.B. 240, CH – 3084 Wabern, Switzerland, cedric.thalmann@b-i-g.ch

C. Schindler; Schwerzestrasse, CH – 8618 Oetwil am See, Switzerland

M. Kruse; Ernst Basler & Partner AG, Zollikerstrasse 65, CH – 8702 Zollikon, Switzerland

ABSTRACT: The processing of suitable tunnel muck for concrete aggregate and other chip products has economic advantages in addition to improving ecological balance. The AlpTransit project with two new railway lines (Gotthard and Lötschberg) involves about 100 km of tunnels through Switzerland. A considerable part of these underground constructions are being excavated by tunnel boring machines (TBM), so that an important volume of mineral resources will potentially be available.

Recommendations are given how to investigate the excavated rock material by quick laboratory tests in view of the use as aggregates. The qualification tests are based on the petrography and the stone hardness and can be applied on excavated stone material from TBM or drill and blast. For the test procedures a so called 'Breakability' test, as well as Point-Load-Index and Los-Angeles-Index are applied.

Innovative crushing plants with integrated friction mill (type Hurricane), powerful thickener installations and mica separation with the flotation technique guarantee a good quality of the aggregates.

The obtained concrete results proved that it is possible to make high quality concrete and shotcrete for tunnelling - and other - construction purposes out of suitable and upgraded aggregates from TBM excavated rock materials. Important aspects for the concrete quality are also high resistance against alkali aggregate reaction and sulphate attack.

INTRODUCTION

Tunnel muck is still, in many cases, classified as a nuisance material and was dealt with in the same fashion as domestic garbage or construction debris. The preparation of muck as a gravel substitute was regarded as economically uninteresting because of the alluvial gravel deposits, which were still readily available and cheaper some years ago. Even though an increasing number of tunnel boring machines (TBMs) were employed, the preparation of the cut material for more sophisticated purposes was hardly conceivable until the eighties; because of the types and patterns of TBM cutters (with bits) used at the time, the rock granulations that were produced were considerably finer grained than is the case today.

Material control concepts for current and future projects increasingly take as wide a view of further processing of the excavated materials as possible into consideration. The advantages of further processing are: self-provision of the tunnel projects with their own aggregate products; fewer transport trips for disposing of the muck, fewer for fetching alluvial sand and gravel; sale of the surplus muck and aggregates to third parties; reducing the overall costs.

AlpTransit Project

With the construction of the AlpTransit project in Switzerland with two new railway lines including about 100 km of tunnels, around 42 million t of excavated materials have to be controlled (Figure 1). This quantity corresponds to the annual requirement of gravel products for Switzerland. Of this total, around 24 million t are accounted for by the Gotthard between Erstfeld and Biasca. Some 18 million t will be produced by the Lötschberg Tunnel. The AlpTransit project foresees, as far as possible, the supply of bulk materials and concrete aggregates to the construction lots by preparing the muck on the spot.

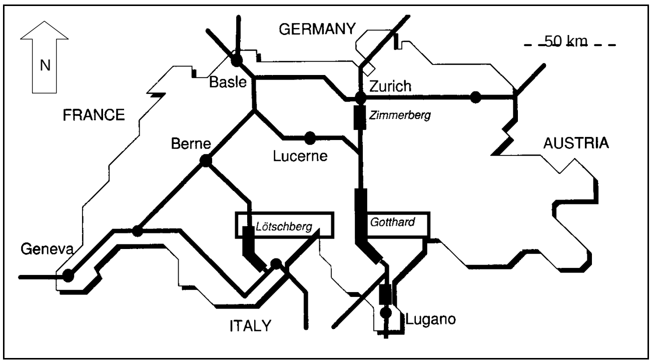


Figure 1. AlpTransit Project with the Gotthard and Lötschberg railway lines and main twin tunnels (Gotthard tunnel 57 km; Lötschberg tunnel 42 km).

Around 30% of the muck obtained from the Gotthard Base Tunnel (24 million t) could be used accordingly. 5 million t of this total have been allocated for re-use as concrete aggregates. A further 30% have been earmarked as construction materials for third parties. Poor quality muck serves to recultivate existing gravel pits and rock quarries. The materials are divided into the following 3 main classes: concrete aggregate or gravel sand substitute, bulk material, technically unsuitable material. Around 15% of the material produced during the Lötschberg project, is scheduled to be used as concrete aggregates.

AlpTransit follows three main objectives in muck treatment: maximum re-utilisation of the excavated tunnel muck, optimal economic efficiency of the complete muck treatment and minimal environmental pollution.

INFLUENCE OF THE EXCAVATION METHOD ON THE MUCK

The current pronouncedly further developed heading methods are, apart from conventional drill and blast, mechanical driving using tunnel boring machines (TBMs) and roadheaders. The excavation rock material resulting from mechanical heading is fine grained (Figure 2).

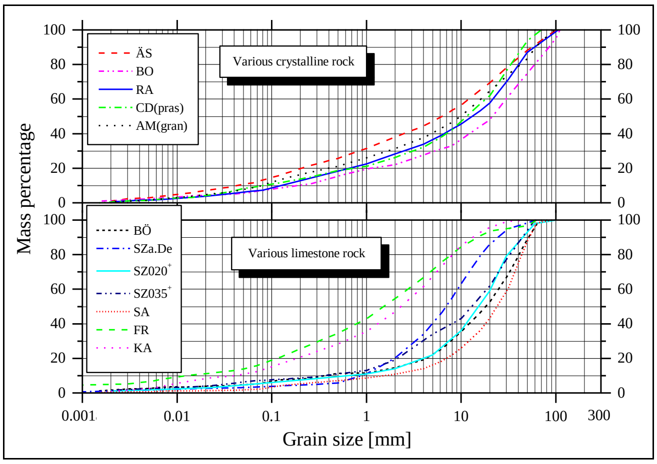


Figure 2. Grading curves for different TBM excavation rock materials (muck). Legend (location of sampling): ÄS: Äspö (S); BO: Bozen (I); RA: Randa; CD: Cleuson-Dixence; AM: Amsteg; BÖ: Bözberg; SZ: Senceboz; SA: Sachseln; FR: Frutigen; KA: Kandersteg.

The material quantities from TBM drives, compared with other types of tunnelling, are shown in Table 1.

Compared with round gravel and crushed aggregates for concrete purposes, the TBM rock material is distinguished by its typical platy-spiky grain form.

Table 1. Muck produced in mass percentages by various tunnelling methods.

Type of tunnelling method	Cutting disc spacing [mm]	0/4mm	>32mm	>100mm
		Min.-max. values [mass-%]		
Conventional drill and blast (crystalline rock)	-	2-5	85-95	75-85
Back cutting technique (sandstone)	-	15-20	65-75	45-60
Roadheader drive (Jura limestone)	-	15-40	5-35	0-5
TBM with bits cutter	60-70	30-50	2-20	0
TBM drive with disc (sediments, crystalline rocks)	65-90	15-50	5-50	0-10
TBM drive with enlarged cutting roller spacing (Plutonit) [2]	86	45	20	0
	129	40	30	5
	172	20	35	15

Innovative TBM concept for the AlpTransit project

In order to be able to prepare a sufficient amount of concrete aggregates greater than 16mm (after crushing, washing, classifying), an effort is made to obtain as high a share of coarse components in the rock material cut by the TBM. The coarse share for its part largely depends on the mechanically-related TBM parameters. The spacing between cutter rollers exercises the most important influence on the grain size distribution of the cut material. The actual cutter spacing in the face area of a common hard rock TBM is about 80-90mm. An increased gap between the cutters enhances the component size and the quantity of coarser fragments in the muck (Table 1). At the same time, it is the only mechanically-related change that can easily be undertaken. Cutting tests in granodiorite revealed that cutter roller spacing of 130mm in the face area does not appear to be unrealistic and the tunnelling performance here is not negatively influenced (Büchi and Thalmann, 1995). The share of components >32mm in the raw material is almost doubled as a result.

The project engineers of AlpTransit Gotthard / Material Recycling Section have evaluated the feasibility of increased cutter spacing for the TBM tunnel drives. The tender documents indicate that the client is interested in coarse grained tunnel muck for concrete aggregate production.

TEST METHODS TO ASCERTAIN THE QUALITY OF THE MUCK

Starting position

Geological forecasts for tunnelling are not infrequently based on single borings, from which the often complex geology including the rock parameters have to be derived. As a result, geological forecasts bear a certain factor of uncertainty. Frequent quality changes of the excavated rock as a result of a lithological alteration, passing through fault zones or as a result of rapid alternation between high-grade and low-grade materials are not unusual. As the tunnel axis only very seldom runs perpendicular to the geological layers, it can happen that unsuitable muck is mixed with high-quality material within the same cross-section.

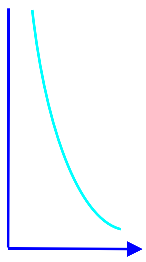
Quite often the in situ rock strength differs from the rock strength of the spoil that is produced. Above all, in rock zones with high load states (overburden and/or lateral pressures), the rock strength, which has been weakened through pressure relief, can be somewhat less than the in situ rock strength that is encountered. Rock relief expresses itself through micro-crack formation, spalling and/or caving. Pressure relief is visible on bore cores, through what is known as “disc chipping”.

Because of these differences, it is evident that the relevant rock parameters for assessing the rock material should be determined on the resulting cut material (muck).

First information sources relating to the quality to be tunnelled

In order to obtain as good an insight as possible into the rock types that are anticipated, various information sources should be used within the framework of an underground project, which can supply data relating to rock parameters (Table 2).

Table 2. Possible information sources which can be used for the re-utilisation of muck.

Point-in-time of the data information related to the excavation of rock material	Possibilities for determining the rock quality	Reliability of the finding small	 large
Before	Forecasts, experimental values Geophysical reconnaissance Boring; geophysics, cores		
During	Rock classification Geophysical reconnaissance TBM and bore parameter Cores, advance-boring Schmidt’s rebound hammer		
After	Pilot tunnel; geological recording and material examination Examination of the muck		

Existing geophysical and geological-geotechnical measurements which are carried out in tunnelling in the form of advance investigations, can provide initial appraisals relating to the further use of the muck. The geophysical advance investigation, possibly carried out during the drive, can provide pointers to a changing rock quality. Evaluations of TBM-specific and/or recordings of advance bores permit qualitative statements on the coming rock quality. Interesting data relating to the rock hardness can be obtained via Schmidt’s rebound hammer test providing it is used and assessed correctly. This method suffices as a simple test method (Thalmann, 1996).

Qualitative assessment of the muck

A final assessment of the muck relating to its further processing as concrete aggregates can be obtained from the excavated rock material that is produced. These material investigations pursue two main purposes: the test methods serve to assess the muck and to decide whether it is suitable for processing as concrete and/or shotcrete aggregates (or for other purposes) and further they are an instrument for quality control. As a result, client, site management, contractors as well as the separate preparation unit, are aware of the exactly defined raw materials, which are to be processed further as concrete aggregates.

Innovative test and quality control concept for the AlpTransit project

For the AlpTransit project a test and quality control concept was developed (Thalmann, 1996) which fulfilled the following requirements. The main strength class demanded for the concrete is B 40/30 (40 N/mm^2 after 28 days). The investigation of the rock material must not disturb or hold up tunnelling in any way. The test methods must allow both an assessment of all types of spoil (drill and blast, TBM drive, roadheader drive, rock material from bores) as well as the crushed aggregates derived from them. The equipment used for the tests must be in common use and have a high acceptance. A high relevant value and reproducibility of the tests is demanded. Finally, it must be possible to carry out these material examinations rapidly (initial results within 1 to 2 hours) and they must be economically acceptable. All this calls for a small field laboratory at the tunnel portal. The developed procedure itself is set up modularly and comprises a number of tests with different statements relating to the rock parameters. Depending on requirement or visual change of the rock quality, individual or several examinations can be carried out.

The test criteria for the raw material (muck) are a minimal rock hardness in a general sense and a sufficient quality of the petrography - particularly in the share of unfavourable components.

Rock hardness requirement of the raw material

An important criteria, which muck has to fulfil so that it can be processed to provide concrete aggregates, is a sufficient rock strength.

LCPC Breakability Index:
The test is carried out on 500g of the sample fraction 4/6.3mm. The material that is to be tested is filled in a cylindrical container, in which a metal plate (5x25x50mm, hardness Rockwell B60-75HRB) rotates for 5 min at 4'500 rpm. The apparatus is 45x22.5x47.4cm in size (LxWxH) and weighs some 60kg.

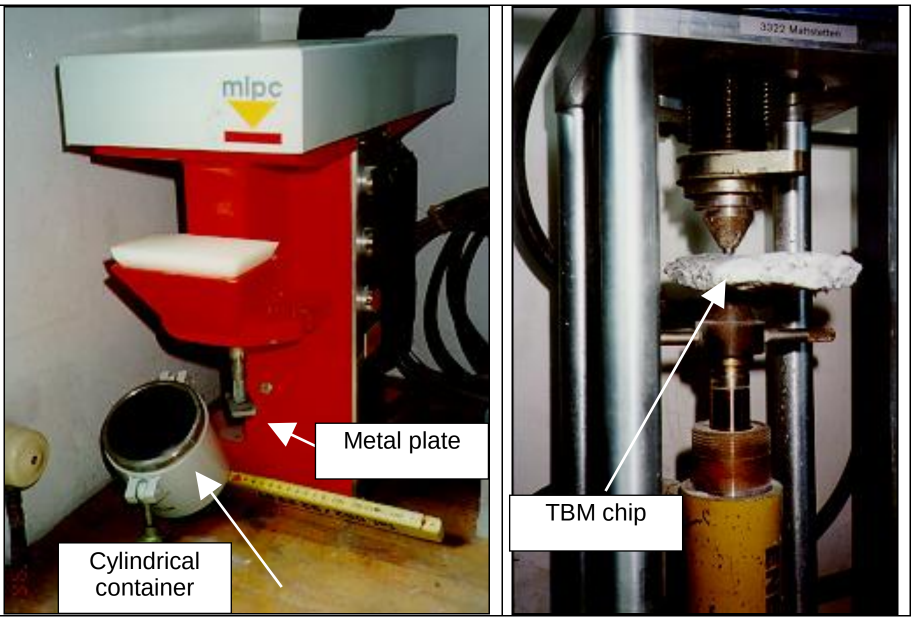


Figure 3. Left: LCPC apparatus to determine the Breakability and Abrasivity index. Right: Point-load apparatus to determine the point load strength.

Concrete standards usually give no details about minimal compressive strength requirements for the aggregates. In actual fact, a minimum compressive strength of at least 100 N/mm^2 for concrete aggregate is sometimes proposed (Bundesverband Natursteineindustrie, 1993; Dubuisson, 1995).

Based on a large number of material examinations and on more than 200 laboratory and site concrete tests, which were undertaken in the scope of AlpTransit Gotthard (Kruse and Weber, 1995), a minimum rock strength of 75 N/mm^2 can be recommended as the standard parameter for a concrete of strength class B 40/30 (40 N/mm^2 after 28 days).

The Los Angeles Index introduced by the CEN standard (prEN 1097-2) assesses the strength of the aggregates indirectly on the basis of their wear behaviour vis-à-vis impact and fracturing. The wear behaviour depends on the rock strength. The Los Angeles method in accordance with CEN for concrete aggregates will scarcely be able to establish itself as a simple and rapid laboratory method, as the amount of time needed is too high. A similar but simpler test method which provides reliable, initial results within 1½ hours, is the LCPC Breakability Index (French norm AFNOR P18-579). During the same test series, an Abrasivity Index ABR can be also determined (Figure 3).

The rock sample is subjected to a wear process by the grinding effect of a rotating small plate; the result can be compared with the Los Angeles test. Figure 4 shows the linear relationship between these two methods.

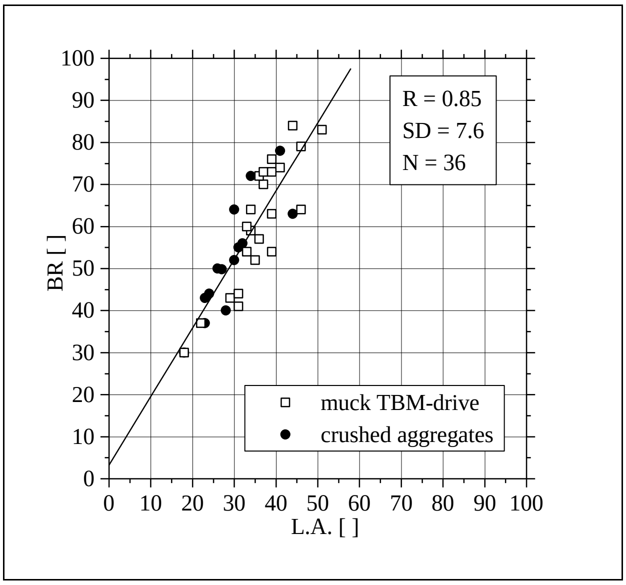


Figure 4. Comparison of the Los Angeles Index (L.A.) with the Breakability Index (BR)

The Breakability test is proposed as a daily test method within the scope of quality control. The Los Angeles Index serves as a reference method and can be applied as a calibrating method. The Los Angeles test will also be used for testing the crushed aggregates (prEN 1097-2).

The Point Load Index (indirect tensile strength), which is commonly applied and often used as a rock parameter in tunnelling, is recommended as a further means of determining the rock hardness (Figure 3). In order to ensure that the amount of time required for preparing the samples is kept to a minimum, these laboratory tests are carried out on the muck itself (TBM chips or rock fragments from drill and blast).

The Breakability and the Los Angeles test methods understandably relate to gravel or crushed aggregates with isometric grain forms and not to TBM muck. The Point Load Index is carried out with bored cores or more or less identically shaped test objects in accordance with ISRM standard. The application of these test methods has shown that the grain influence of the platy-spiky rock samples – in particular, in the case of TBM raw materials – on the test result is excessive, and thus executing the test in accordance with norm is not possible. By means of suitable sample preparation (sieving with slotted screens) and modified evaluation formulae for the Point Load test (decisive fracture plane for TBM chips), the influence of the form factor could be minimised and kept constant. These adjustments permit a representative assessment both of the muck from TBM, roadheader and drill and blast drives as well as the crushed aggregates.

Petrographic requirements of the raw material

Apart from ascertaining the rock hardness, the petrographic description provides a further criterion for evaluating the muck. A macroscopic description and classification of the rock material in conjunction with the CEN norm prEN 932-3 is sufficient for an initial appraisal. As far as re-utilising the crude sand from the TBM raw material is concerned the content of unsuitable components must be determined.

According to need, it is advisable to carry out aggregate examination of representative rock samples (specimens from the surface or from pilot tunnels, bore cores, etc.), in regard to, frost, thaw behaviour, chloride contents, sulphate components, radioactivity of the rock material, etc. during the pre-investigatory phase for an underground project.

In the case of the AlpTransit project the main part of the tunnels will be bored in the central Alpine region which consist of crystalline rocks. They possess a high content of layer silicates (mica) which are frequently <2mm in diameter, and these enrich the finer fractions during the preparation process. Free mica (not bonded into the rock mass), which comes into contact with combined water and cement, has a negative effect on fresh concrete and the properties of set concrete (Fookes and Revie, 1982). As the mica content increases, the water quantity for constant workability also increases. Laboratory mortar tests have shown that not only the quantity but also the grain size and type of free mica influences the parameters (Empa, 1998). They have also shown that mainly mica greater than 0.125mm exercises a negative influence. Fine mica (< 0.125mm) did not influence the mortar properties negatively; on the contrary, the slump and the tensile strength were even increased. With regard to the effect of the mica type on the mortar quality, the tests indicate that muscovite is more harmful than biotite or chlorite.

Evaluation of the free mica content in the entire sand fraction 0/4mm is a relatively time consuming analysis. The mortar tests with aggregates from the AlpTransit project showed that the sand investigations can be done on the sand sub-fraction 0.125/0.5mm; this is representative of the entire sand 0/4mm (Fig. 5).

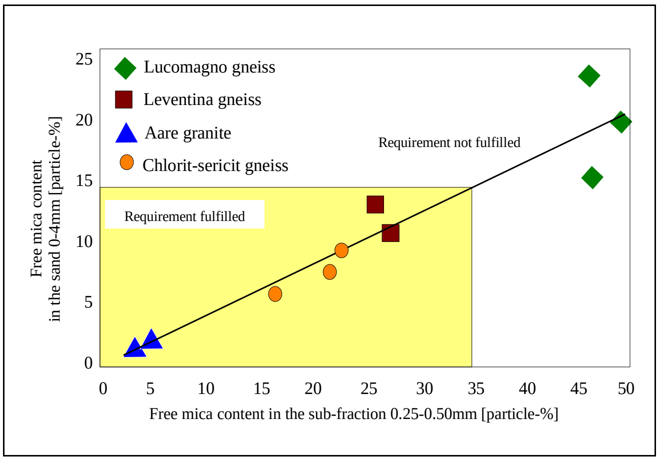


Figure 5. Free mica content in the sand sub-fraction 0.25/0.5mm compared with the content in the entire sand fraction 0/4mm. Sand samples with mica content in the grey zone fulfil the requirements for a concrete of strength class B 40/30.

The AlpTransit project will accept a sand 0/4mm with a total free mica content of less than 14 particle-%. This means that maximum mica content in the sand sub-fraction 0.25/0.5mm must be less than 35 particle-%.

Alkali aggregate reaction and sulphate attack

Because of the climatic conditions prevailing in underground projects, - high humidity and temperatures – an alkali aggregate reaction (AAR) may possibly be caused. The best known of these is the alkali silicate reaction (ASR), which takes place in concrete between soluble alkalis (K^+, Na^+), and soluble silica or reactive silicates in the aggregates. The product of this reaction is an expanding gel, which can lead to cracks in the interior or the surface of the concrete. No common standardisation regarding the AAR has been arrived at internationally, as the possible reactions depend on the given type of the geological region. There are no standards relating to AAR in Switzerland, as previously there were scarcely any cases that became publicly known (Thalmann et al., 2001). The AAR tests carried out within the scope of the AlpTransit investigations revealed that some geological zones, mainly gneiss with retrograde metamorphose, must be taxed as potentially reactive (Figure 6).

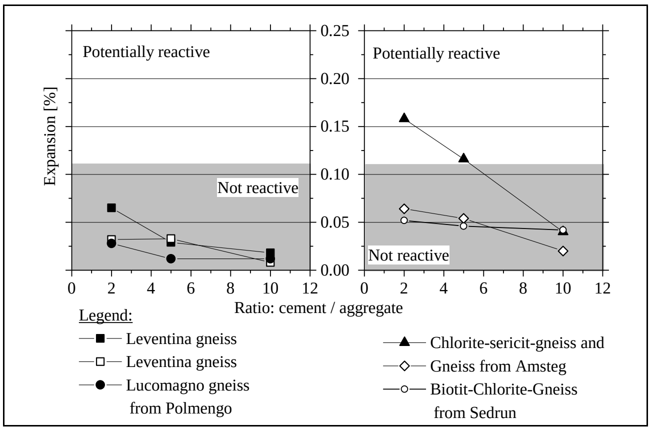


Figure 6. Alkali aggregate reactivity in accordance with French norm AFNOR P18-588.

Raw material requirements for the AlpTransit project are summarised in Table 3.

Table 3. Rock hardness and petrographic requirements of the raw material for the AlpTransit project.

Rock hardness requirement

Test method:	Standard	Minimum value	Frequency of the tests
Breakability Index	AFNOR P 18-579 procedure modified for TBM muck	≤ 70 [-]	15 TM; tunnelling meter
Point Load Index I_{S50}	ISRM 1985 procedure modified for TBM muck	I_{S50} parallel: ≥2.5 [N/mm^2] I_{S50} isotropic: ≥3.5 [N/mm^2]	75 TM

Petrographic requirement

Test method:	Standard	Minimum value	Frequency of the tests
Macroscopic petrographic analysis		Mica content: ≤ ca. 20 particle-%	± daily (during geological mapping)
Microscopic petrographic analysis		Mineral description; weathering; AAR-reactivity	150 TM
Unfavourable components in the fractions 1/4,4/22,22/128mm (without free mica *)	Definition AlpTransit and Swiss concrete standard SIA 162 / 1	≤ 10 [weight-%]	150 TM
Fee mica* in the raw sand (0.25-0.50mm)	Definition AlpTransit	≤ 40 [particle-%]	150 TM
Alkali-Reaktivität AAR	AFNOR P18-588 AFNOR P18-589	Expansion ≤ 0.10 [%] Non reactive	1’000 TM

* Free mica: not bonded into the rock mass

PREPARING SUITABLE TBM MUCK FOR CONRETE AGRREGATES

An optimal preparation of concrete aggregate from rock material cut by TBM calls for additional technical measures in contrast to the spoil obtained from drill and blast. TBM muck must, first of all, be cleaned intensively in washing drums in order to remove the finest particles. This, in turn, requires powerful dewatering presses which allow reasonable handling of the mud (< 0.063mm); this mud fraction can in the case of TBM muck reach 12%. It is also necessary to crush the a priori small TBM rock fragments gently by means of suitable methods so that no excessive sand surplus results. In this connection, the vertical crusher system, in which the components are broken through grain-to-grain contacts, has proved to be effective. Numerous preparation tests have revealed that only the raw TBM material over 8mm grain size must be crushed - in some cases even over 12 to 16mm. The uncrushed grains smaller than 8mm have often already fulfilled the specification for concrete aggregate components and can be mixed with those of the crushed fractions.

These technical tests proved that the re-utilisation value of the TBM materials is somewhat higher than was assumed.

Thus, on average, 35% of a concrete mixture 0/26mm and 45% of a shotcrete mixture 0/8mm can be produced from prepared TBM materials (with vertical crusher system). The mean "surplus" amounts to 20% (Figure 7).

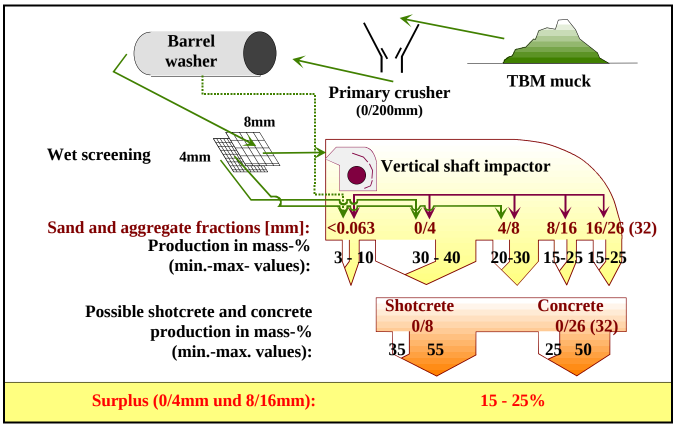


Figure 7. Re-utilisation values of TBM rock material.

Innovative processing plant system for the AlpTransit project

To guarantee an unproblematic processing system for the mainly TBM rock material the tender documents from AlpTransit Gotthard ask for certain mechanical equipment. Either a vertical shaft impactor, or a blow-bar primary impactor is prescribed; These cause no overbreak of the a priori small TBM rock particles, and do not produce too much sand. To round off any sharp edges, and to smooth the often rough surfaces of the aggregates after crushing, a friction mill (type Hurricane), is to be installed as the grinding system. A positive effect of the grinding is the improvement in workability, with a consequent reduction of plasticisers – up to 50% - resulting in an overall reduction in the cost of the concrete. In addition, powerful dewatering presses which allow reasonable handling of the mud (<0.063mm) are required.

Several attempts were made by AlpTransit Gotthard to find, or develop a processing system with the aim of separating the free mica from the others minerals in the sand. Micas are usually thin layered minerals with a large surface area (biotite and muscovite). The density of mica (2'600 to 3'200 kg/m^3) is higher than quartz and feldspar (2'600 to 2'700 kg/m^3) which are the main mineral groups in the crystalline sand. The test series showed that a separation with an upwards water current system is not effective; a considerable amount of fine sand is also washed out. At the moment, some interesting investigations are being carried out on the separation of mica with the flotation technique. The test series showed that the free mica content in the sand sub-fractions 0.063/0.125mm and 0.125/0.25mm could be reduced by 73% and 90% without important loss of suitable minerals (quartz and feldspar).

The grading requirements, and shape of the prepared aggregates have been laid down; the aggregate shape will be measured by the Flakiness Index (prEN 933-3).

CONCRETE WITH CRUSHED AGGREGATES

Constructions with crushed aggregates and - inclusive crushed - sand are rare in Switzerland so that there is no rich experience in practice. Also the Swiss concrete standards (SIA 162/1) are based on rounded aggregates and can not be applied one to one for crushed aggregates. For the AlpTransit project more then 200 laboratory and field tests on concrete and shotcrete have been carried out with crushed aggregates. These investigations indicate that it is possible to make high quality concrete and shotcrete for tunnelling and other purposes with suitable and upgraded aggregates from excavated rock material. Based on the greater void content of crushed aggregates (ca. 40 Vol-%) compared to rounded gravel and sand (ca. 25%) the concrete with crushed aggregates needs more cement (350 to 400 kg/m^3). The main differences between concrete and shotcrete out of round gravel or crushed aggregates are listed in Table 4.

Table 4. Main differences between concrete and shotcrete of crushed aggregates and concrete and shotcrete of rounded gravel.

Property	Concrete	Shotcrete
Cement contents (CEM I 42.5)	5 - 20% higher	At least 450 kg/m^3
w/c ratio	< 0.5 possible	< 0.5 possible
Additives	Superplasticising admixture is necessary	Superplasticising admixture, retarder, accelerator
Workability	Often sensitive	Liable to breakdowns (higher pump pressure)
Rebound	-	low (4 - 13%)
Compressive and tensile strength	normal or even higher	normal or even higher
Elasticity modulus	up to 50% lower; depends on the type of aggregates	up to 50% lower; depends on the type of aggregates
Watertight concrete	Possible	Possible
Shrinkage	Higher but without cracks because of the low E-Modulus	Higher but without cracks because of the low E-Modulus

An interesting observation for concrete of crushed aggregates is the low elasticity modulus, especially with crystalline aggregates. Figure 8 shows that the known relationship (SIA 162/1) between the modulus of elasticity (EM) and compressive strength (CS), for concrete with rounded gravel, does not apply to concrete with crushed aggregates. The EM-CS relation depends also on the petrographic type of the crushed aggregates; crystalline aggregates give a lower EM than limestone. Increasing mica content of the crystalline aggregate causes even lower EM. For tunnelling constructions, the use of concrete and shotcrete with low moduli of elasticity is not negative - on the contrary, the cracking and damage behaviour to punctual pressure is better than with high EM-concrete.

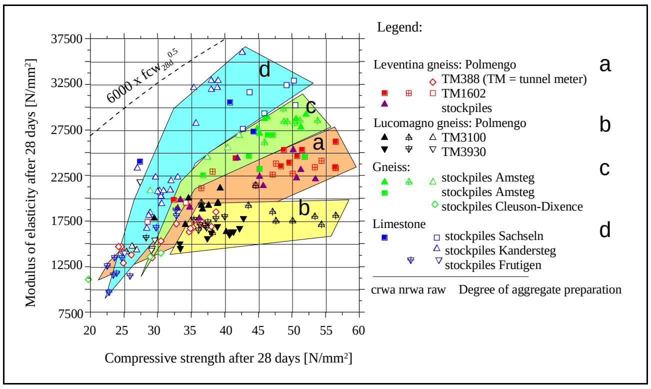


Figure 8. Compressive strength versus elasticity modulus grouped by petrography of the aggregates and degree of the preparation (crwa: crushed and washed aggregates; nrwa: uncrushed but washed TBM raw aggregates; raw: raw TBM muck 0/32mm used directly as concrete aggregates). For comparison the known relation for "usual" round gravel is indicated (EM = 6'000 x CS$^{0.5}$).

AlpTransit concrete with high resistance against alkali aggregate reaction and sulphate attack

To improve the durability of the concrete especially in water zones with high sulphate content or by the use of potentially reactive (AAR) aggregates special cements will be used. The cements consists of supplementary cementing materials such as fly ash (25 – 30% cement replacement), blast furnace slag (50% cement replacement) or silica fume (7% cement replacement). Also the combination of two or more of this supplementary cementing materials – so called ternary blends - are in use.

SUMMARY

Rock excavation material from underground projects (including TBM muck) will increasingly be used as a gravel substitute product in future. An optimal control concept for the recycling of rock material begins with the choice of the right excavation method (TBM with greater cutter spacing or drill an blast). In order to ensure that these concrete aggregates can fulfil the required demands relating to concrete, their suitability vis-à-vis quality assurance has to be determined by means of practice-friendly test methods. The preparation of aggregates from excavation rock material needs special processing (especially for TBM muck). Great attention must finally be paid to the production, treatment and placing of the concrete.

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