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Rock Material Recycling in Tunnel Engineering

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Abstract: In the construction industry, especially in tunneling or large-scale earthworks projects, huge quantities of excavation material are generated as a by-product. Although at first glance such material is undesirable, in many cases this material, if suitably treated and processed, can be recycled and reused on the construction site and does not necessarily need to be removed and deposited as waste at a landfill. In the simplest case, the material can be used as filling material with the least demanding requirements with regard to rock quality. Material of better quality often can be recycled as aggregate and be used as a substitute for conventional mineral aggregates. This approach generates numerous benefits regarding the costs for material procurement, storage and transport. In addition, reduction in environmental impact and demand for landfill volume can be achieved. The challenge lies in the fact that excavation material is not a standard aggregate in terms of geometric, physical and chemical characteristics and is subject to quality deviations during tunnel driving, mainly depending on the varying geology and applied excavation method. Therefore, preliminary research and experimental testing as well as specific evaluation and continuous examination of the rock quality during tunnel driving is necessary as well as ongoing adjustment of the rock processing plant to finally accomplish a high-quality level of recycled aggregates. This article illustrates the material investigations and treatment processes for the specific example of the Brenner Base Tunnel, the longest underground railway line in the world that is currently under construction. There, material recycling has already been successfully implemented.

Keywords: excavation material recycling; tunnel spoil; calcareous schists; aggregate for concrete

1. Introduction

In Europe, the mountain chains of the Alps stretch from the Gulf of Genoa to the lowland plains of Hungary, separating the main economic regions within the European Union. This is why tunnels and especially railway tunnels of significant length are essential to ensure the functional capability of the overall network. Numerous tunnels have been built in the past and are currently under construction or in the planning process. In this process, large quantities of excavation material from the bedrock are generated as an unwanted by-product or "waste", whereby handling and treatment of tunnel excavation material is a fundamental subject in a tunnel construction project, often deciding on the economic and environmental success of the construction project itself [1,2].

The aim of this article is to demonstrate the recycling process of tunnel excavation material as substitute for conventional aggregate by the example of the Brenner Base Tunnel in Austria, illustrating the scientific approach, experimental setup as well as the practical implementation accompanied by experimental verification due to its challenging geological bedrock conditions.

The strategy of an extensive material recycling has already been successfully implemented in the construction of some of the world longest tunnels: the Swiss base tunnels Lötschberg and Gotthard Base Tunnel [3,4]. There, a self-supply of the construction sites with recycled aggregate that was mostly produced in situ on site was implemented [4–6].

Apart from this, numerous other recently completed and currently ongoing research projects deal within this research question. For example, [7,8] gave an overview about the main aspects of tunnel muck recycling and its properties and application opportunities. Ref. [9,10] demonstrated the impact of different excavation methods, particularly examining the impact of excavation by a tunnel boring machine in contrast to blasting. Ref. [11] showed the recycling of tunnel excavation material in earthworks following the premise of maximum resource saving. In other research projects, it could be shown that, if complying certain conditions, the use of excavation material as aggregate resource for the construction of roads [12,13], power plants and concrete dam constructions [14] is feasible. Ref. [15] again concentrated on rock classification and the reuse possibilities of rocks from weak formations.

Moreover, the scientific approach concerning the usage of excavation material reaches from planning and decision processes by handling of excavation material [2] to the technological implementation [16], focusing on the technical developments in relation to material analysis and the realization of a raw material database to manage materials analysis, and also addresses legal considerations regarding the use of the recycled "waste" [17–19]. Therefore, large international research projects (i.e., [20]) have been conducted in the framework of sustainable raw material production and recycling. Not least, structural engineering considerations regarding tunnel design need to be performed when using recycled aggregate for construction concrete to fulfill the projected service lifetime of the tunnel structure [21,22] as well as consideration in regards to the functioning of subsequent fastening systems in concrete using recycled aggregate [23].

In conclusion—particularly in view of saving resources and environmental protection—the aim must be a maximum material recycling proportion of the a priori "waste", not depositing it as landfill material, and considering geological, technical and legal aspects, making it a very interdisciplinary area of research. As a result of this, there are also significant efforts to achieve an equally high level of recycling of tunnel excavation material during the currently ongoing construction of the Brenner Base Tunnel. There, excavated calcareous schists have already been processed and recycled during conventional tunnel driving of an access tunnel from 2014 to 2017, demonstrating the technological and logistical feasibility [24,25]. At the current construction section from Pfons to Brenner, that started in autumn 2018, the recycling of the excavated rock plays an important role in providing rock aggregate for the construction site. There, the reuse of rock material mostly excavated during continuous tunnel driving at a variable geology is a demanding task with a particular importance regarding quality management due to its use for high-grade concrete products such as lining or structural concrete.

2. Recycling Prediction at the Brenner Base Tunnel

In the course of its driving work, a total of ca. 43 M tons of excavation material are predicted for the Brenner Base Tunnel, from which ca. 25 M tons are attributed to the Austrian tunnel section.

Whether the excavated material from the Brenner Base Tunnel is suitable for its particular application is mainly decided by the type and quality of the excavated rock or soil. Forecasts concerning the possible recycling extent during the preceding environmental impact assessment in 2008 stated a recovery rate of only about 6% of the excavated rock to be used as aggregates for concrete and ca. 15% as filling materials [26,27]. However, this would mean that the remaining ca. 79% of the excavated material needs to be deposited, at least without any further treatment of the excavated rock material. The aim should be to reach the maximum possible recycling quota by optimizing the processing method and material management concept [28].

In view of these framework conditions, a landfill concept was established using possible depositional areas and shortest possible distances from tunnel portals and, more importantly, the access tunnels (Figure 1).

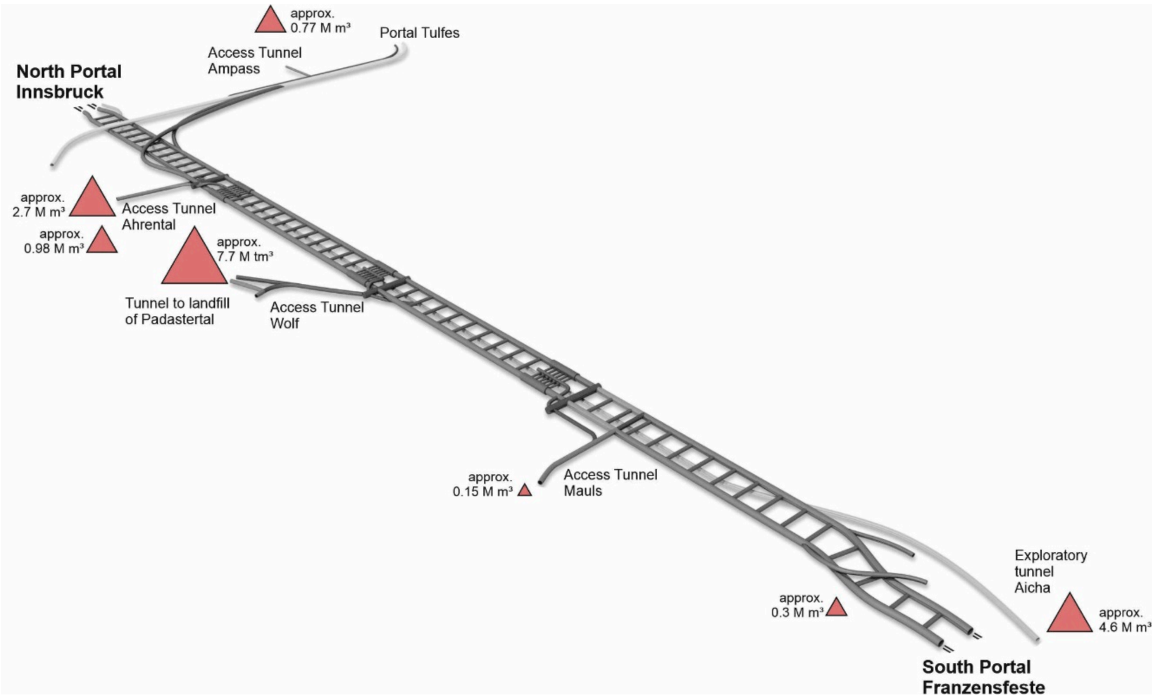
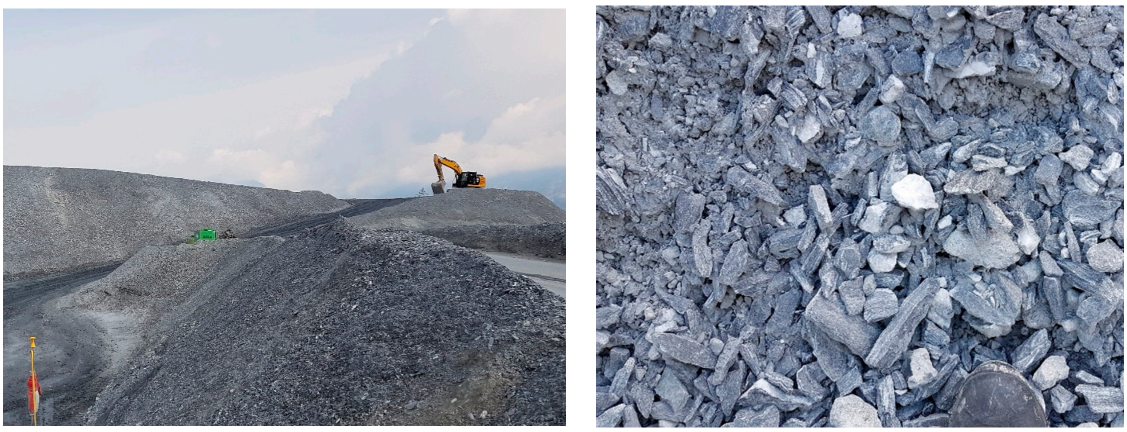


Figure 1. Planned landfill sites along the route of the Brenner Base Tunnel, cubatures in million cubic metres according to [28].

The main landfill area in the Padastertal Valley is thereby located centrally at the access tunnel Wolf. From a lithologic point of view, the Padastertal Valley deposit lies in the middle of the Bündner Schists, while the Ahrental deposit covers the excavation material mainly from the Innsbruck Quartz Phyllite unit as well as from the northernmost part of the Bündner Schist unit. At the Ahrental landfill, excavation material from the Bündner Schist unit was also deposited (Figure 2) from the exploratory tunnel by a tunnel driving machine with a diameter of approximately 5 m.



(**a**) (**b**)

Figure 2. (**a**) View from the Ahrental landfill with tunnel boring machine material from Bündner Schist rocks; (**b**) Detailed view of the excavation material from Figure 2a (fines washed out by rain at the surface).

3. Geological Overview of the Brenner Base Tunnel

The Brenner Base Tunnel, with a total length of 64 km, including the bypass of Innsbruck, is the centrepiece of the Scandinavia–Mediterranean Corridor, cutting through the Brenner massif between

Innsbruck (Austria) and Franzensfeste in Southern Tyrol (Italy). The tunnel passes just east of the Wipptal Valley and runs approximately parallel to it. From a geological viewpoint, the Wipptal Valley is delimited by the Tauern Window (Penninic) in the east and the Eastern Alpine Kristallin to its west. North of the Brenner mountain massif, the Northern Limestone Alps are located. To its south, segregated by the Periadriatic Fault, the Southern Alpine with the Brixner Granite and, further to the south, the Southern Calcareous Alps are situated [28,29].

The rock types that are excavated belong—with the exception of the Brixener Granite—to metamorphic rocks. From a quantitative point of view, the major part of the tunnel runs through the Bündner Schists, followed by the Innsbrucker Quartz Phyllites, Central Gneisses and the Brixener Granite, whereby the Austrian tunnel section is almost entirely located within the first two, as shown in Figure 3 [29].

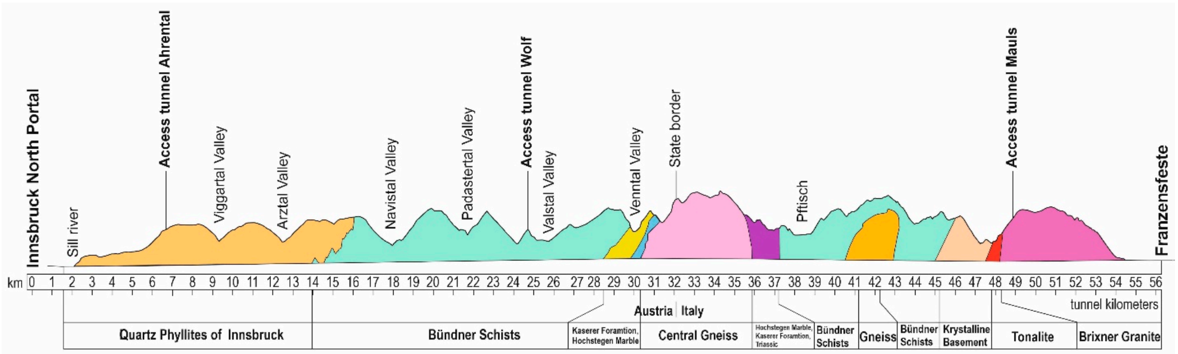


Figure 3. Simplified geological cross section through the Brenner Base tunnel according to [29].

The rocks of the Central Gneiss and the Brixener Granite show high rock strength with more than 100 and 130 N/mm^2, respectively, and solid rock properties suitable for a wide use with regard to recycling. In contrast to that, Bündner Schists and Quartz Phyllites are metamorphic rocks, showing a significant schistosity due to quite large amounts of sheet silicates and a rather low to moderate rock strength is present [30].

4. Rock Characteristics of Quartz Phyllites and Bündner Schists

4.1. Rock Quality of the Source Rocks

In general, if recycling of the excavated material is considered, the prospects depend mainly on two factors. Fundamentally, the (1) type of source rock determines the quality of the excavated rock aggregate. While in the planning phase of a tunnel, the local geological subsoil is investigated in detail, the tunnel route is determined in accordance with other criteria than the recyclability of the source rock: next to technical framework conditions, like tunnel gradient, building logistics and conservation concept, legal issues and political decisions are of primary importance [16,17,19]. Thus, the existing rock material is applied to an optimum utilization at the given conditions by adapting the sorting and processing to the local conditions. Furthermore, the (2) method of tunnel excavation—drill and blast or tunnel boring machine driving—affects the geometric properties and therefore significantly influences the extent of recycling, see Section 4.2.

In the case of the Brenner Base tunnel, the a priori uncertain rock units of the Innsbruck Quartz Phyllites and Bündner Schists were evaluated regarding its recycling potential. Quartz Phyllites and Bündner Schists are metamorphic rocks showing a significant schistosity due to quite large amounts of sheet silicates as well as rather low to moderate rock strength. Due to this, rock material from the Bündner Schist and Quartz Phyllite was tested including large scale processing experiments. A wide range of rock examinations concerning the geometric, physical and chemical properties as well as intensive concrete production and testing were herein performed. The feasibility study finally showed the suitability for recycling of calcareous rocks of the Bündner schist unit [30,31].

As a first step, excavation material derived by drill and blast tunneling of the Innsbruck Quartz Phyllite as well as the calcareous Bündner Schists—the latter were obviously most suitable for processing and recycling—was tested. Physical, chemical and geometric rock parameters were obtained with regard to is suitability as aggregate for concrete (Table 1) [25,31].

Table 1. Main physical and chemical rock properties of Quartz Phyllites and Bündner Schists [25].

Rock Properties	Quartz Phyllite Arithm. Mean *	Bündner Schist Arithm. Mean *	Evaluation
Bulk density [g/cm^3]	2.7	2.7	required > 2.3
Water absorption [%]	0.4	1.7	low and rather high
Unconfined compressive strength [N/mm^2]	45.0	76.0	required > 50 MPa
Los Angeles value	25.9	31.7	LA_{30}, LA_{35}
E-Modulus [GPa]	24.8	38.2	-
Tensile strength [N/mm^2]	4.8	8.5	-
Point load index Is [N/mm^2]	4.0	5.8	-
Schmidt hammer [N/mm^2]	45.0	52.6	-
Freeze/thaw resistance [%] (EN 1367-1)	0.4	0.5	F1
CAI Cerchar	4.2	1.3	very abrasive and abrasive
LCPC LAK [g/t]	326.6	593.3	abrasive and very abrasive
LCPC LBR (%)	54.9	52.3	highly crushable
Equiv. quartz amount [%]	56.8	43.8	-
Amount of mica and chlorite [%]	28.0	29.8	-
Acid-soluble sulfate [%]	-	0.58	required < 0.8%
Water-soluble chloride [%]	-	0.0042	required < 0.01%

* at least three individual measurements.

As shown in Table 1, water absorption, as an indication of rock porosity and aggregate frost resistance, is low in the case of the Quartz Phyllite rock material. This means that only very little water is absorbed by this rock type, unlike the Bündner Schist rocks, which show rather high absorption values on first examination, but finally, without having a negative impact on freeze/thaw resistance, attain top class F1 in both cases (according to European standard EN 12620 'aggregate for concrete').

The compression test results for the Quartz Phyllite rock type, as well as point load testing and Schmidt hammer test as indirect compressive strength test methods, show rather low rock strength, only marginally acceptable for many applications. In the case of the Bündner schists, rock strength is mediocre, but still satisfactory. Both rock types, especially the Quartz Phyllites, show a rather low E-modulus compared to standard aggregate meaning that concrete made of these aggregates will also have rather low E-modulus values. Concerning elastic deformation of, e.g., concrete linings, this is an advantage because of reduced crack development, though also suffering higher deformation rates, see [22].

Resistance against impact and abrasive loads, expressed by the Los Angeles (LA) value (according to the European standard EN 1097-2), in both cases is mediocre, possibly causing increased loss of material as fines during material processing because of increased crushing. In addition, both rock types indicated abrasive to very abrasive rock characteristics expressed via Cerchar (see European standard EN 14157 regarding the determination of abrasion resistance) and LCPC values (developed by the 'Laboratoire central des ponts et chaussées', France, tested according to French standard AFNOR P18-579) and via the equivalent quartz amount (evaluated via rock thin section examination under the microscope), causing increased processing machine ware and maintenance costs during aggregate production.

The amount of mica and chlorite is typically high as expected for Phyllite and Schist rock types, complicating the processing and adversely affecting the geometric properties of the produced aggregate. Mainly because of this fact, the very first outlook for rock recycling in [26,27] was rather negative, as mentioned in Section 2.

The Bündner Schist rock was additionally tested regarding the suitability as aggregate for concrete, investigating the acid-soluble sulfate and water-soluble chloride according to European standard 'Tests for chemical properties of aggregates—Part 1: Chemical analysis' EN 1744-1. The latter showed good results, lying below the normatively required limit value, while the amount of acid-soluble sulfate is too high, making concrete mix adjustments necessary, above all imposing cement types with low alkali content and the use of additives like fly ash or slag sand [25].

All physical properties considered, the properties of calcareous Bündner Schist rocks generally allow the reuse of crushed rock aggregate for the production of concrete at medium to high abrasion of the processing plant and a special focus on its geometric properties especially its grain size distribution as well as schistosity and layered rock texture. Normative requirements should be feasible by reasonable effort in material processing through proper crushing, screening and washing [25,30].

4.2. *Tunnel Driving Method and Its Impact on Rock Material Quality*

Next to the physical properties of the rock material itself, the excavation method has a major effect on grain size distribution, percentage of fines and shape of the aggregate which are the decisive factors with regard to usability.

4.2.1. Excavation by Blasting

During drilling and blasting, tunnel driving is carried out in individual working steps that can be assigned to three main work processes [32]:

1. Breaking of rock: drilling, loading with dynamite, blasting and ventilation
2. Mucking: material transport via dump trucks, on rails or by conveyor belts
3. Support: rock-face sealing with shotcrete, using anchors, tunnel arches, etc.

Rock fragments generated by drill and blast are generally significantly larger than using a tunnel boring machine. The character of the excavation material is given by the progress of explosion itself: in homogenous material, the explosion effect is spherical and decreases with increasing distance from the explosive charge. As rock is usually inhomogeneous, joint faces as well as fractures influence the progress of the explosion; research and modelling on this topic is, inter alia, shown in [33–35]. Within the closest proximity, the rock is completely crushed through the developing gas pressure. This is followed by a slinging area, where rock is ejected from the bedrock formation with the emergence of radial cracks. At even greater distances, the rock is no longer crushed actively, but is subjected to strong vibrations and cracks. Finally, rock size is determined by the quantity of explosives—in tunneling, the amount of explosive material is much greater than in quarrying sites, thus receiving smaller sized aggregates [36].

4.2.2. Excavation via Tunnel Boring Machine (TBM)

By continuous tunnel driving via TBM, the removal process is done in one process throughout the entire cross section. The cutting discs at the drilling head are pushed at high pressure against the tunnel face (Figure 4). In the course of the discs' rolling movement, rock is excavated in the form of chips. Thereby, the penetration throughout one rotation is ca. 10 to 15 mm. The cuttings are conveyed by scrapers and removed by a conveyor belt.

Common cutting discs show a diameter of ca. 17 to 19 inches, and the contact pressure is about 200 to 300 kN, causing tensile stress in the rock [36]. The tensile strength is exceeded, radial cracks are developed and the rock bursts chip-shaped (Figure 4).

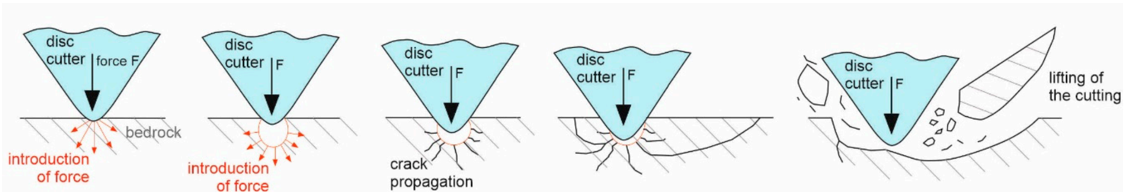


Figure 4. Chip-shaped rock removal by cutting discs according to [32].

The quality of the excavated rock is— from a mechanical perspective—mainly influenced by the contact pressure. If the pressure increase is too high, intensified crack development is the consequence and the cuttings show damage by cracks. Also, rock fragmentation has a major influence on excavated aggregate characteristics [37,38]. The presence of schistosity or foliation favors the occurrence of stem-like or platy aggregate shapes [30].

4.3. Geometric Characteristics of the Excavated Rock Material

In the case of the Bündner Schists at the Brenner Base Tunnel, the grain size distribution after excavation can be characterized as follows (Figure 5): fine particles smaller that 0.063 mm in the case of blasting amount to ca. 4.4%, and in the case of continuous driving to ca. 9.4%. In the latter case, the pathway of the particle size distribution shows a steep curve shape between 4 and 30 mm, while through blasting a generally more continuous curve shape is achieved. For comparison purposes, the particle size distribution of Quartz Phyllites from drilling and blasting is also shown in Figure 5.

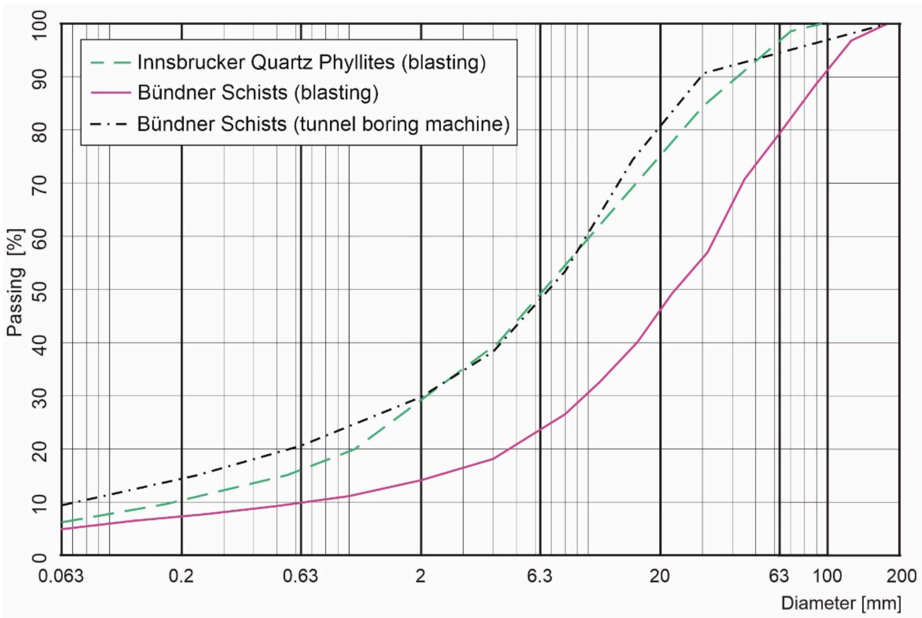


Figure 5. Grain-size distribution from tunnel excavation material (Quartz phyllite from blasting ca. tunnel km 7; Bündner Schists from blasting ca. km 22; Bündner Schists from tunnel boring machine ca. km 15; see Figure 3).

Looking at the aggregate shape, the following picture emerges (Table 2): the a priori existing schistosity of the calcareous schist causes very high shape index values (the shape index SI is defined as the percentage of aggregate weight, at which length to width ratio is ≥3, determined via caliper according to European standard EN 933-4) in both cases, by blasting as well as continuous tunnel driving. On closer observation, the grain shape is even more cubic in the case of continuous driving. This may be explained by the fact that the driving direction of the TBM is perpendicular to the dip direction of the schistosity that slightly counteracts the plate-shaped grain shape.

Table 2. Grain shape characterization via shape index (percentage of aggregate weight, at which length to width ratio is ≥3) depending on aggregate size and driving method.

Aggregate Characterization	Blasting			Tunnel Boring Machine		
Particle size group (mm)	4/8	8/16	16/32	4/8	8/16	16/32
Shape Index [%]	68	81	84	66	73	74

Figure 6 shows an example of typical grain shapes for Bündner Schist aggregate (non-processed) for the particle size group 8/16 and 16/32 mm from tunnel boring machine driving, resulting in an overall shape index SI of 73 and 74 (see Table 2), respectively. The elongated and plate-like grain shapes indicate a high grade of flakiness (see also Section 5.3). The geometric character of the non-processed aggregate therefore is not suitable in regard to the handling, processing and installing of the aggregate and needs to be improved during raw material processing.

(**a**)

(**b**)

Figure 6. (**a**) Bündner Schist aggregate 8/16 and (**b**) Bündner Schist aggregate 16/32 mm from tunnel boring machine driving (washed, but without any processing) illustrating the elongated and platy shape of particles.

4.4. Concrete Mix Design Experimentation

Before starting concrete production at the industrial plant at the construction site, extensive research was performed to develop applicable concrete mixtures with regard to binder composition as well as fresh and hardened concrete characteristics, particularly concrete strength and durability. In one approach, the fine grain sizes up to 4 mm in diameter were replaced by conventional quartz sand. By doing so, the enriched contents of mica and chlorite in the particle size group 0/4 mm were discarded, consequently improving the workability of the fresh concrete by reducing its water demand. The following concrete mix design (Table 3) was elaborated, providing satisfying fresh and hardened concrete characteristics, as shown in Table 4 [30].

Table 3. Recycled aggregate concrete mix design [30].

Concrete Components	kg/m^3	Specification
Cement	260	CEM II/A-M (S-L) 42.5 N
Hydraulically effective additives	60	Fly ash, slag sand
Water	169.4	Water/Binder ratio = 0.55
Aggregate for concrete	1937	0/4 mm quartz aggregate, 4–20 mm aggregate from Bündner Schist and Quartz Phyllite in each case
Additives: Plasticizer	3.8	BASF ACE GleniumSky

Table 4. Fresh and hardened concrete properties of concrete mix design from Table 3.

Mix	Consistency Fresh Concrete [mm]	Compressive Strength f_c [N/mm^2]	Bending Tensile Strength f_{ct} [N/mm^2]	Specific Fracture Energy G_F [N/m]
Bündner Schist aggregate	605	47.7	3.6	167.7
Quartz Phyllite aggregate	590	42.5	3.4	238.4

All measurement data as arithmetic mean from at least three individual measurements.

Water penetration testing (according to Austrian standard ONR 23303, pressurizing the test specimen using 1.75 bar water pressure) for these mixtures shows low water permeability and a dense concrete structure, as indicated in Figure 7.

(a)

Figure 7. *Cont.*

(b)

Figure 7. (a) Concrete specimens cut in half made from Bündner Schist and (b) Quartz Phyllite after water penetration testing showing only a short water penetration distance.

The average penetration depth in case of Bündner Schist aggregate is 19 mm, and for Quartz Phyllite aggregate 20 mm, indicating a dense concrete structure for both aggregate types. Therefore, the mixtures reach the highest exposure class, XC4, regarding carbonation (according to the European standard EN 206-1 for specification, performance, production and conformity of concrete), verifying the usability of recycled rock as aggregate for concrete manufacture [30]. All things considered, the preliminary concrete tests showed that concrete production using recycled aggregate is possible, also in the case of application of processed excavation rock material for all particle size classes.

5. Excavation Material Processing at the Brenner Base Tunnel

5.1. General

Preliminary practical studies started in 2010 followed by large-scale processing experiments during an early stage of tunnel driving. On the basis of the results, a material processing and plant concept was developed and subsequently implemented during tunnelling at the construction section Wolf II in Steinach/Brenner (see Figure 3). There, an access tunnel towards the main tunnel tubes with a length of four kilometres was conventionally excavated in the period between 2013 and 2016. For this construction section, recycling of excavation material was not intended upfront, because the quality of the expected rocks of the Bündner Schist unit was not considered appropriate for reuse. The access tunnel is situated in Bündner Schist rocks that can be characterized as carbonate-rich schists and phyllites in alternating strata. There, the utilized excavation material consists of compact grey calcareous schists with an unconfined compressive strength of approximately 80 N/mm^2 with anisotropic, laminated to banked appearance (see Table 1). During blasting, grain diameters from 0 to ca. 700 mm were obtained.

These calcareous schists of higher quality have been recycled at the processing plant that was installed in 2014 using a three-stage rock crushing system followed by a high performing wet-processing (washing and sieving) of the aggregates at the area of the Padastertal landfill site (Figure 8). The processed material was used primarily as supply of draining gravel of the particle size groups 16/32 and 32/63 mm, aggregate for structural concrete, lining concrete as well as shotcrete. In November 2014, the entire concrete production of shotcrete—that was needed for the excavation of the access tunnel Wolf—was rearranged entirely using aggregate from the processed excavation material of the Bündner Schist unit [39].

Figure 8. Processing plant and aggregate production near the tunnel portal at the access tunnel Wolf.

5.2. Plant Concept

At first, the excavated rock material is led across a grid (ca. 70 mm of screen aperture) to get rid of the fine-grained aggregates. Via this selection process, small and concurrently inferior components—from a petrographical point of view—are excluded and thereby the overall quality of the to be processed raw material is improved. Thereupon, the preconditioned rock material experiences a pre-crushing and a second screening (ca. 32 mm of screen aperture) of the fines. The aforementioned processing happened in the tunnel for logistic reasons up to this point (Figure 9).

Figure 9. Processing plant and aggregate production in the access tunnel Wolf (compare Figure 3).

Close to the tunnel portal via a processing plant installed at the landfill area, the preconditioned material is processed via impact mill and vertical mill, followed by a separation of the different particle size groups 4/8, 8/16 and 16/32 mm by wet-screening (washing and sieving at once). Processing of the sand fraction 0/4 mm is done via a bucket wheel. The accumulated fines <0.063 mm are flocculated and separated by filter bags in the provided filter basins (see Figure 7). Filtered water passes across a pipe system to the water protection system (setting of the pH-value and further deposition of remaining fines), finally reaching the receiving water. A compilation of the different processing steps is shown in Figure 10 [39].

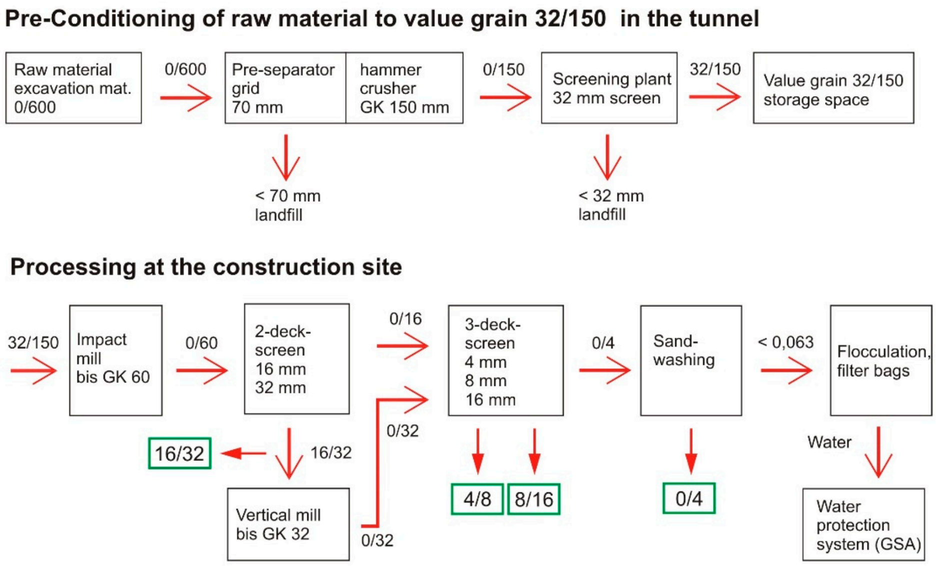


Figure 10. Processing concept of excavated tunnel spoil [39].

Continuous supervision and monitoring of the aggregate quality were done within the scope of the European standard "aggregates for concrete" EN 12620 and Austrian standard "testing methods for concrete" ONR 23302. With an interval of one week, evaluations of grain size distribution and content of fines were carried out. Grain shape and concrete compressive strength of test specimen were evaluated on a monthly basis. Depending on this information, the concrete mix (above all cement content and water/binder-ratio) was constantly adjusted. The examination of grain density and water absorption, freeze-thaw resistance, content of chloride and calcium carbonate as well as sulphur and humus content were conducted several times a year. In a pre-measure, inferior rock material like calcareous and graphitic phyllites are sorted out through rock identification at the tunnel face via the geologists. Inferior material is disposed and therefore does not enter the conditioning process [39].

5.3. Characteristics of Produced Aggregate

Aggregate that was produced in the implemented processing plant (Figure 8) is showing adequate properties in terms of grain size distribution, grain shape and content of fines. Particle size class 0/4 mm demonstrates a continuous grain size distribution with a content of fines <0.063 mm of 4.4% and <0.02 mm of 2.2%, respectively.

The flakiness index (percentage of aggregate weight having an average least dimension of less than 0.6 times their average dimension; determined via grid sieves according to European standard EN 933-3)—showing an appropriate magnitude for processed aggregate—is illustrated in Table 5 showing clear improvements in comparison to non-processed aggregate, compare Section 4.3 and Table 2.

The material properties as shown in Tables 1 and 5 demonstrate the usability for diverse applications of the processed aggregate from the Bündner Schist rocks. Even high-quality applications for the compensation of standard aggregate in concrete production are possible, reaching compressive strengths for structural concrete of ca. 41.8 N/mm^2, and in the case of shotcrete, ca. 42.8 N/mm^2 during concrete production at the construction site at the access tunnel Wolf [39,40].

Table 5. Flakiness index and fines for processed excavation material at the access tunnel Wolf.

Particle Size Class	Flakiness Index FI [%] [a)]	Category of Fines [a)]
4/8 mm	7	$f_{1,5}$
8/16 mm	12	$f_{1,5}$
16/32 mm	17	$f_{1,5}$

[a)] in accordance with EN 12620.

5.4. Current Stage Regarding Excavation Material Processing

At present, in the case of the currently ongoing large-scale construction section Pfons–Brenner, that started in autumn 2018, the reuse of rock material is a top priority. The construction lot itself includes the excavation of ca. 37 km of the main tunnel section, ca. 9 km of exploratory tunnel as well as the construction of an emergency cavern. The rock will mostly be excavated by continuous tunnel driving via tunnel boring machine, affecting the properties of the excavated material (above all size and shape of the rock aggregate; see Section 4.2). Significant attention will be devoted to quality management due to material use for high-grade concrete products such as inner shell or structural concrete.

6. Conclusions

Recycling of tunnel spoil is becoming increasingly important. This is not only because of the large amounts of rock mass that are excavated that otherwise must be disposed of, but also because of rising shortage of mineral raw materials like sand and gravel in the Alpine valleys. In times of sustainability, resource efficiency and minimisation of emissions it is a logic decision to recycle and reuse excavated tunnel spoil within the framework of the possibilities depending on rock material characteristics, processing effort and local demand for rock aggregate. By the given example of the Brenner Base Tunnel, it could be shown that even despite a restricted forecast concerning the possible recycling extent due to moderate rock properties, Bündner Schist rocks could be recycled at the construction site to produce value grain for drainage gravel and concrete aggregate manufacture.

In this paper, it is shown that for a successful recycling realization, extensive preliminary research concerning rock quality and concrete mix design, as well as an excellent technical implementation of the processing and concrete mixing plant are necessary. In an initial step, comprehensive rock characterisation is needed to identify the range of the existing rocks and their mechanical and chemical properties, whereby rock properties are dictated by the existing rock types. These experiments are followed by aggregate test production from excavated raw material recording data of attained aggregate characteristics and processing procedure. Here, the aim is to test different crusher and mill types, finding the optimal machines as well as instrument combinations for crushing and sieving to optimize the geometric properties of the produced aggregates. The implementation of an efficient and powerful processing facility plays a key role with regard to the recycling implementation success. In the case of the current example, a three-stage crushing system using a jaw crusher, impact mill and vertical mill as well as an efficient wet processing including washing and sieving was applied to improve grain shape to a preferably cubic shape as well as to significantly reduce the amount of fines. After optimizing the aggregate quality, concrete testing—also in accordance with the chemical composition of the source rock—is needed to find concrete mix designs for the different concrete types and applications ensuring high stability and durability of the concrete structures.

In the current example of the Brenner Base Tunnel, the extracted value aggregate could be processed and optimized for the application as aggregate for shotcrete, inner lining and structural concrete as well as filter gravel. Thus, the purchase and transport of aggregate from local quarries was minimized, and therefore resources were saved, accompanied by a financial benefit. In summary, through this example, it can be noted that reuse of tunnel spoil will also play an important role for future tunnel projects because of ecological and economic reasons.

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