KORTREIST STEIN

Report

Local use of rock materials

– production and utilization

State-of-the-art

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Table of contents

Preface....6

Glossary....7

Summary in English 8

Sammendrag på norsk.... 8

1 Introduction 9

1.1 Background 9

1.2 Objective 9

2 Geology of Norway, and some other countries 10

2.1 The geology in Switzerland and Austria 10

3 Tunnelling.... 11

3.1 Drill-and-blast tunnelling 11

3.2 Drill & split.... 11

3.3 Cut & cover.... 11

3.4 TBMs.... 12

3.5 Excavated material.... 12

4 Crushing technology, mobile and stationary production plants.... 14

4.1 Background – why mobile aggregate production plants 14

4.2 Existing mobile aggregate plant image 14

5 Current technical requirements for rock materials 15

5.1 Technical requirements for rock materials in asphalt 15

5.1.1 Bituminous asphalt mixes for base layers 15

5.1.2 Aggregates for asphalt pavements.... 16

5.1.3 Asphalt mix 18

5.2 Technical requirements for rock materials (aggregate) in concrete 19

5.2.1 Aggregate size 19

5.2.2 Grading 19

5.2.3 Shape of coarse aggregate 20

5.2.4 Fines content 20

5.2.5 Resistance to fragmentation 20

5.2.6 Bulk density 21

5.2.7 Water absorption 21

5.2.8 Freeze-thaw resistance 21

5.2.9 Alkali-silica reactivity 21

5.2.10 Chlorides ... 21
5.2.11 Sulfur containing compounds ... 22
5.2.12 Constituents affecting the setting and hardening of concrete ... 22
5.2.13 Free mica ... 22
5.2.14 "Mud" (norwegian: slam) ... 23
5.3 Technical requirements for rock materials in road construction ... 23
5.3.1 National requirements ... 23
5.3.2 International requirements ... 25
5.4 Technical requirements for rock materials as ballast for railway construction/support ... 26
5.4.1 The Norwegian Ballast requirements ... 26
6 Use of excavated rock materials in asphalt ... 27
6.1 Introduction ... 27
6.2 Example projects ... 27
6.3 Positive and negative experiences ... 29
6.3.1 Mica and other weak minerals in asphalt mixes ... 29
6.4 Possibilities and suggestions for further work ... 30
7 Use of excavated rock material in concrete ... 30
7.1 Introduction ... 30
7.2 Example projects ... 31
7.2.1 Lyon-Turin ... 31
7.2.2 Gotthard Base Tunnel ... 32
7.2.3 Jostedal hydropower tunnel ... 33
7.2.4 Linthal 2015 Project ... 34
7.2.5 Koralm Tunnel ... 34
7.2.6 Brenner Base Tunnel ... 35
7.2.7 Follo Line Tunnel ... 36
7.2.8 E6 Fellesprosjektet (Mjøsa) ... 36
7.2.9 E39 Rådal-Svegatjørn ... 36
7.3 Positive and negative experiences ... 36
7.4 Further work ... 37
8 Use of excavated rock material in road construction ... 37
8.1 Introduction ... 37
8.2 Example projects ... 37
8.2.1 Norwegian Roads Recycling R&D program ... 37
8.2.2 E39 Romsdalsfjorden crossing ... 38

8.2.3 Pavement design for frost protection 38
8.2.4 Tunnel spoil as raw material for autobahn S10, Austria 38
8.2.5 Planning the handling of tunnel excavation material in Brenner Base Tunnel, Austria 39
8.2.6 Effect of processing of tunnel excavation material 39
8.2.7 Performance-based reuse of tunnel muck as granular material in road construction . 39
8.2.8 Proposed quality test regime from Slovakia 39
8.2.9 Waste regulations 40
8.2.10 Use of TBM excavation materials for road pavements 40
8.3 Positive and negative experience 40
8.4 Further work 41
9 Use of excavated rock material as ballast for railway construction/support 42
9.1 Introduction 42
9.2 Example projects 42
9.2.1 Farriseidet- Porsgrunn 42
9.2.2 Holmestrand-Nykirke 47
9.2.3 The Follo line 52
9.2.4 E6-The Dovre line (Mjøsa) 57
9.3 Positive and negative experiences 60
10 Literature 62

APPENDICES

Appendix 1: Information on example projects
A1 Lyon-Turin
A2 Gotthard Base Tunnel
A3 Linthal 2015 Project
A4 Koralm Tunnel
A5 Brenner Base Tunnel
A6 Follo Line Tunnel (Follobanen
A7 E6 Fellesprosjektet (Mjøsa)
A8 Melkøya
A9 Gevingåsen tunnel
A10 Strindheimtunnelen
A11 2.1. Austrian S10
A12 E39 Rådal Svegatjern
A13 E39 Romsdalsfjorden crossing
A14 Ulriken
A15 Farriseidet-Porsgrunn
A16 Holmestrand-Nykirke

Preface

This report has been written within the project “Local use of rock materials” (Kortreist stein). “Local use of rock materials” is an IPN-project in a program by the Research Council of Norways for User-driven Research based Innovation (BIA). Veidekke Entreprenør AS is the owner of the project.

The main objective of the project, is to develop new technological solutions and tools, smart business models and good regulation processes. This, to be able to utilize rock materials from infrastructure projects and local quarries in a superior and sustainable manner. Superior utilization means both use of local materials in unbound road- and railway construction as well as aggregates in asphalt and concrete.

The project aims towards energy effective materials production and optimized utilization of non-renewable rock resources. The project will facilitate and establish technologies to increase value for money with local materials. The innovation in the project is directed towards laws and regulations that control the utilization of local materials and methods of assessment for utilization of rock materials mainly from tunneling. In addition, an approach to methods for practical implementation of use of local materials will be covered.

A consortium of the following partners from industry, public administration and research institutes are currently working on these four main topics:

- Laws, regulations and resource planning
- Contracts, business models and incentives
- Production and utilization
- Sustainability and energy efficiency

“Local use of rock materials” has a 17 million budget (NOK) and a duration of three years (from 2016). It is financed through the Research Council of Norway (40%) and the industrial partners (60%).

The publications from "Local use of rock materials" have been prepared by professionals at the partners in the project. Every effort has been made to ensure that the content is in accordance with the common knowledge at the time the project was completed. However, errors or omissions may occur.

The authors and the project management have no responsibility for errors or omissions in publications and possible consequences.

It is assumed that the publication is used by competent and knowledgeable persons with an understanding of the limitations and assumptions that are used.

Eivind Heimdal

Project owner

Torun Rise

Project manager

Glossary

AADT: Annual average daily traffic

Crushed sand and stone: Sand and stone produced by crushing rock

Cut-and-cover: Minor tunnelling method

Drill-and-blast: Common tunnelling method where blasting is used

Drill-and-split: Minor tunnelling method which is more gentle than drill-and-blast

Excavated rock material: Material excavated from tunnels, slopes and similar. The material may be excavated by various methods.

Gravel:Coarse aggregate/stones as found in nature , see also natural sand.

Natural sand: Sand as found in nature, graded by natural processes during long periods of time

TBM – Tunnel-boring machine

Summary in English

During excavation of tunnels, large amounts of rock material are produced. This excavated rock material is utilized to a varying extent for road-, railway- and concrete purposes, but significant amounts are used as deposits on land, in fjords or lakes. For both economic and environmental reasons there is a great potential in increasing the utilization of excavated rock material locally in the same project or in neighboring projects. Initially, this report presents a brief introduction to the geology in Norway and some comparable European countries. This may give an indication which main rock type to expect in different areas during tunnelling. Further, the development within the main directions of tunnelling is discussed. Also, an overview of equipment and crushing technology is given. The boundaries of this report are excavated material used in asphalt, concrete, road construction and railway construction. For each area of utilization, a presentation of the current technical requirements for various uses of the material in Norway is given. Examples of projects where excavated material is utilized are presented. Finally, possibilities and obstacles when it comes to utilizing excavated rock material are discussed, and further work is proposed.

Sammendrag på norsk

Store mengder stein produseres ved tunnel- og anleggsdrift. Massene blir utnyttet i varierende grad til veg-, jernbane og betongformål, men en stor andel blir oftest bare deponert på land, i sjø eller bekkefar. Både økonomiske og miljømessige faktorer tilsier at det er et stor potensiale i å øke utnyttelsen av uttatte tunnelmasser lokalt i samme prosjekt eller tilgrensende prosjekter. Denne rapporten gir en kort innføring i geologien i Norge og sammenliknbare deler av Europa. Dette kan gi en viss pekepinn på hvilke hovedbergarter man kan forvente i de forskjellige områder under tunnelbygging. Videre er utviklingen innen de to hovedretningene innen tunneldrift diskutert. Det er også gitt en oversikt over utvikling innen utstyr og eksisterende knuseteknologi. Denne rapporten er begrenset til å se på bruk av tunnelmasser i asfalt, betong, veioppbygging og oppbygging av jernbane. For hvert enkelt anvendelsesområde er det gitt en oversikt over dagens tekniske krav som stilles til materialet i Norge per i dag. Deretter følger eksempler på prosjekter hvor man har utnyttet tunnelmasser. Til slutt diskuteres muligheter og hindringer for økt utnyttelse av tunnelmasser, og videre arbeid er foreslått.

1 Introduction

1.1 Background

In a time of higher environmental consciousness, attention needs to be drawn towards the utilization of excavated materials from tunnelling and road constructions. In 2015, an all-time high of 7 million m^3 rock material was excavated during tunnelling in Norwegian mountains [1].

The methods used for “hard rock” tunnel excavation are the drill-and-blast method and the tunnel-bore-machine (TBM) method. Other methods also exist for soft rock excavation, these are not dealt with here.

As of today, the excavated material from road and tunnel constructions is utilized to some extent, but it varies from project to project depending on local governmental plans, contract, location, geology, tunnelling method etc. Significant volumes are used as landfill deposits or deposited in lakes or fjords. However, this practice is becoming more and more controversial. The life cycle assessment for the use of excavated rock materials is the main topic in another work package in the present project (Kortreist Stein, H4).

1.2 Objective

This report focuses on excavated material from the construction of roads, railways and tunnels. Surplus materials from mining, natural stone production etc. are not included. Even though excavated material has numerous areas of applications, this report is focused on four areas of utilization:

- *Asphalt*
- *Concrete*
- *Road construction*
- *Railway construction*

This report intends to give an overview of experience gained in projects both in Norway and other countries where excavated material has been used to a small or large extent with focus on the material and its properties. Experience with excavated material from weak rock and soil is not included in this report, as it is not considered relevant to the project. Planning, handling, logistics and contracts are included in other parts of the present project.

The quality requirements for a rock material depends on the application. A summary of the current formal quality requirements will therefore be given, together with an introduction on how geology and tunnelling methods possibly affect the rock material. This information will form the basis for suggestions for further work in this on-going project and adaption to Norwegian conditions.

For simplicity, this report uses the term "tunnel excavation rock material" for both rock materials from tunnels, from rock slopes and similar sources.

2 Geology of Norway, and some other countries

The geology in Norway is very complex, and the suitability of the various rock types for construction purposes varies a lot between the different parts of the country

A simplified overview of the Norwegian geology is given below:

The oldest rock types – the precambrian bedrock - in Norway occur in Southern Norway, in Western Norway, at Finnmarksvidda and as local areas in Northern Norway. Dominating rock types in these areas are gneisses and granites, with elements of dark rocks as gabbros and amphibolites in addition to quartzite. These rocks have mainly good mechanical properties and are often well suited for technical purposes. However, some of the gneisses in Western Norway have a high content of mica. A high mica content gives the rock low mechanical strength, and a lot of mica in the fine fractions of sand is unfavourable in asphalt and concrete.

In Southwestern Norway and in Finnmark the late precambrian sandstones occur. These rocks have mainly good mechanical properties.

From Southwestern Norway and along the whole country rocks from the Caledonian range of mountains are present. These rocks have very varying mechanical properties, and they are dominated by altered sedimentary rocks, magmatic rocks and altered bedrock (metamorphic rocks). The mechanical properties of the altered sedimentary rocks vary a lot, e. g. phyllite has poor mechanical properties while the magmatic rocks have mainly good mechanical properties. Summarized; the properties of the rocks in the Caledonian range of mountains for technical use is very variable.

In the Oslo area sedimentary rocks of different types are present in addition to magmatic rocks. The mechanical properties of the sedimentary rocks are variable, while the properties of the magmatic rocks are mainly good.

Carbonate rocks are present in the Caledonian range of mountains and in the Oslo area. Such rock types are soft and not suited as road building materials [2]. Limestone used in concrete can affect the concrete's shear capacity.

Challenges regarding the utilization of aggregates from excavated rock material are, for example, contents of mica, high filler content, sulphur, alkali reactive minerals and mechanically weak minerals. These issues are addressed in later chapters.

2.1 The geology in Switzerland and Austria

Switzerland has much experience with tunnelling and some experience with use of excavated tunnel materials. The geology of Switzerland is similar to the Norwegian geology. Carbonate rocks, slate and other sedimentary rocks dominate the area of the country, but magmatic rocks as granites and metamorphic rocks as gneiss, mica schist and amphibolite are present as well. Many of these rock types are well suited for construction purposes, but the mechanical properties vary a lot.

The geology in Austria is complex as in Switzerland, with many of the same rock types.

3 Tunnelling

The general vision in underground construction is to become cheaper, faster, safer, sustainable and with a reduced maintenance cost. There are several research lines [3] involving drill-and-blast and TBM excavation methods: Improvements of the methodologies to assess geological conditions, development of information systems in order to streamline processes, computer simulation, innovations on shotcrete mixtures and grouting.

In the following section, a presentation of the main methods of tunnelling are given.

3.1 Drill-and-blast tunnelling

Research on full automation of drilling jumbo and remote control equipment is an important research line in drill-and-blast tunnelling [4] [5]. Technology to evaluate the drilling data will give an inferred picture of the geological conditions resulting in a more efficient process [5]. Rig remote access offers several advantages (e.g. production planning, maintenance) and is gaining acceptance in the tunnelling industry.

The use of electronic blasting enables the selection of unique delay times with millisecond accuracy, optimization of delay times that are best suited to site specific conditions and to desired results and reduces inventory, as there is no need for stocks of many different delays [6].

Regarding the explosives, the invention of pollution-free explosives [4] is a research goal in drill-and-blast tunnelling technology.

3.2 Drill & split

Drill and Split is a mechanical excavation method specifically developed for situations where the features mentioned below are encountered [7]:

- Vibration limits restrict the excavation work
- The total distance is relatively short
- The excavation design require some amount of flexibility
- The geology is comprised of hard rocks

Modern techniques are based upon inserting hydraulic wedges into accurately drilled holes. Once inserted, the wedge initiates a mechanical expansion that induces tension yielding in the surrounding rock. The method is explained in detail by Volden [7]. The excavated material will have similar characteristics to that from Drill-and-blast.

3.3 Cut & cover

Cut-and-cover is a simple method of construction for shallow tunnels where a trench is excavated (“cut”), a tunnel is cast in concrete, and backfilled (“cover”) or roofed over with an overhead support system strong enough to carry the load of what is to be built above the tunnel [8].

For rock materials, the method which is used for “cutting” the trench will decide the properties of the excavated material. Typical methods are blasting or wire-cutting.

3.4 TBMs

The intensification on the underground development in big cities has increased the use of TBMs in mixed and unpredictable underground environment. Development of 'hybrid' TBMs, focusing on what is likely the most common type: A cross between a hard rock single shield TBM and an EPB is underway. Hybrid TBMs, specifically EPB/Slurry and EPB/Hard Rock machines are increasingly becoming the best solution for these challenging conditions. Hybrid machines [9] [10] have the potential to lower risk and make difficult excavations possible, as long as accurate geologic information is available.

Cutter technology has experienced continuous development resulting in the reliable cutters in use today. Major economic limitations must be expected in the face of technical challenges. However, limitations resulting from the quality of cutter ring steel are yet to be overcome nowadays. A new generation of cutter material, allowing a higher thrust in hard rock conditions, will increase TBM penetration rates and cutter life. An increase of 15% in the thrust applied may result in as much as a 50% increase in penetration. This in turn may reduce excavation costs and thus extend the scope of application of the TBM method. Improvements in cutter ring capacity will require corresponding improvements in rolling bearing capacity [11].

Real-time monitoring of individual cutter thrust, cutter rolling, cutter wear and temperature would greatly improve TBM efficiency and provide a better understanding of the rock breaking and cutter wear processes. A measure of instantaneous cutter wear status for all cutters would be a relevant improvement, reducing the need for inspections and thus improving TBM efficiency. Slurry and EPB machines, which will be used more frequently in future hard rock boring projects, such cutter wear instrumentation would be even more beneficial due to cutter change complexity. The use of remote instrumentation and monitoring of specific cutter positions are currently under development, but are as yet not fully applicable.

3.5 Excavated material

Figure 1 by Girmscheid [12] illustrates a general difference between the grain size distribution of excavation rock material produced by TBM and by drill-and-blast, where the amount of fines is generally much higher in the material produced by TBM.

The volume of material excavated by TBM increases by a factor of around 1,7 from solid rock to TBM excavated rock material. The corresponding factor for drill-and-blastmasses is around 1,5 [13]. This may have to be taken into account when the masses are to be used as landfill.

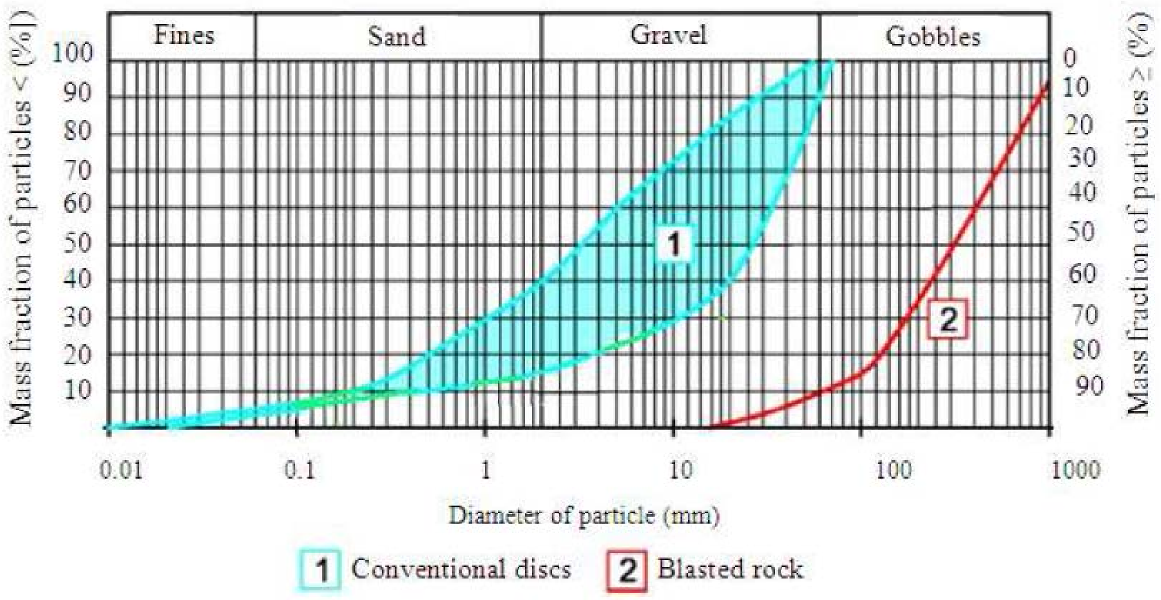

Figure 1: Grain size distribution for TBM (1) vs drill&blast (2) [12].

4 Crushing technology, mobile and stationary production plants

4.1 Background – why mobile aggregate production plants

Road construction projects in 2015 in Norway consumed 50% of the total production of aggregates. Unbound aggregates represent circa 73% of this volume [14]. In comparison to a typical concrete or asphalt production where usually production plants are static and fixed to a specific location, unbound aggregates may be placed directly after production into the road structure. This encourages the use of mobile aggregate production plants using the upcoming suitable rock material resources as a raw material to minimize the transportation needed. In addition, the work done on loosening the solid rock is utilized and handling of that material is reduced in a large proportion.

4.2 Existing mobile aggregate plant image

Installing crushing and screening equipment on mobile platforms can cause limitations on the processing flowsheet and optimal use of the equipment. Some generalities, like feeding a crusher or screen with constant and adequate feed rate, or the possibility to use optimal crusher feed grading to reach good end product quality, may be difficult to achieve.

5 Current technical requirements for rock materials

Depending on the utilization area, there are some technical requirements that the excavated rock material must fulfill. The requirements are both given in the standards and in specific handbooks if the project is owned by a public authority. Detailed examination of the excavated rock material has to be carried out in each case. If the excavated rock materials are to be utilized for different structural purposes, preliminary studies of the tunnel line can give a good indication of rocks types that could be expected along the line.

5.1 Technical requirements for rock materials in asphalt

The use of aggregates for road construction purposes is regulated through different standards and specifications. In Norway and other European countries, the EN-specifications are regulating the use of materials for construction purposes. Aggregates for use in asphalt should be declared by the NS-EN 13043 – Aggregates for bituminous mixtures and surface treatments [15] – and production of the asphalt mix should be approved according to NS-EN 13108-21 – Factory production control [16]. As for the aggregates, bitumen and asphalt mixture requirements, the specifications are found in NS-EN standards and are collected and specified by the Norwegian Public Road Administration (NPRA) in the Handbook N200 [17].

The specifications for bituminous mixtures in Handbook N200 are divided into two parts; Specifications for input materials used and specifications for the resulting asphalt mix. Asphalt mixtures can be used as base layers binder courses and wearing courses. In the following the Handbook N200 specifications for the aggregates and typical asphalt mixes for all three layers are given.

5.1.1 Bituminous asphalt mixes for base layers

In Handbook N200 the demand for asphalt in the base course is present for almost all types of roads. Only for the lowest traffic class A (less than 0,5 mill equivalent 10 ton axles over the pavement design period) there is still an option to use plain crushed rock as base layer.

All bituminous mixes have specified limits for the grading curve and the binder content, also when it comes to the gravel based asphalt concrete (AC) type of asphalt mixture for base layers – “Ag”, which is the most common type of asphalt for base layers. This is the most sophisticated asphalt mix for use in base layers in Norway and is given a load distribution coefficient of 3,0. This is the same as for all asphalt mixtures for pavements. The maximum grain size for use in base layers are limited to 32 mm. The Ag-maixture should be documented according to NS-EN 13108-1 [18] and the aggregates should have properties equal to, or better than the values given in Table 1.

Table 1: Material requirements for aggregates in base layers with Ag, from Figure 523.9 in N200 *[17]*.

Material requirements for aggregates in asphalt for base layers with Ag				
	AADT range			
Properties	< 5000		>5000	
	Value	Category	Value	Category
Flakiness Index	≤35	FI_{35}	≤30	FI_{30}
Los Angeles value	≤30	LA_{30}	≤30	LA_{30}
Nordic abr. value	≤19	A_N 19	≤19	A_N 19
Micro Deval	≤15	M_{DE} 15	≤15	M_{DE} 15
Degree of crushing		$C_{30/60}$		$C_{30/60}$

Another type of asphalt mixture for base layers is called “Ap”. This is a simple type of asphalt mixture, with a load distribution coefficient of 2,0. As can be seen from Table 2 the material is allowed to be quite flaky, but the mechanical properties should be the same as for Ag. This mixture type is an option if you have a flakier material that you want to use in the road construction.

Table 2: Material requirements for aggregates in base layers with Ap, from Figure 523.11 in N200 *[17]*.

Material requirements for aggregates in asphalt for base layers with Ap				
	AADT range			
Properties	< 5000		>5000	
	Value	Category	Value	Category
Flakiness Index	≤40	FI_{40}	≤35	FI_{35}
Los Angeles value	≤30	LA_{30}	≤30	LA_{30}
Nordic abr. value	≤19	A_N 19	≤19	A_N 19
Micro Deval	≤15	M_{DE} 15	≤15	M_{DE} 15
Degree of crushing		$C_{30/60}$		$C_{30/60}$

5.1.2 Aggregates for asphalt pavements

All aggregates, including filler, for use in asphalt mixes in Norway should be declared by the NS-EN 13043 [15]. The detailed specifications are given in the N200 handbook [17]. Specifications for Flakiness Index, Los Angeles value and Nordic abrasion value are given for the different asphalt mixes and for different traffic groups in Table 3 - Table 5.

Table 3: Requirements for Flakiness Index for aggregates in asphalt pavements, from Figure 622.5 in N200 *[17]*.

AADT	≤300	301-1500	1501-3000	3001-5000	5001-15000	>15000
Surface dressing						
Eo and Do	≤25	≤25	≤25			
Eog and Dog	≤30	≤25				
Hot mix asphalt						
Agb	≤30	≤30	≤30			
Ab	≤30	≤30	≤30	≤30	≤25	≤25
Ska				≤30	≤25	≤25
Ma	≤35	≤30	≤25			
Sta		≤30	≤30	≤30	≤25	≤25
Top		≤30	≤30	≤30	≤25	≤25
Da	≤30	≤30	≤30	≤25	≤25	
T			≤25	≤25	≤25	≤25
Cold mix asphalt						
Egt	≤35	≤30	≤25			
Asg	≤35	≤30				

Table 4: Requirements for Los Angeles value for aggregates in asphalt pavements, from Figure 622.6 in N200 *[17]*.

AADT	≤300	301-1500	1501-3000	3001-5000	5001-15000	>15000
Surface dressing						
Eo and Do	≤40	≤30	≤30			
Eog and Dog	≤40	≤30				
Hot mix asphalt						
Agb	≤40	≤30	≤30			
Ab	≤40	≤30	≤30	≤30	≤25	≤15
Ska				≤25	≤25	≤15
Ma	≤40	≤30	≤30			
Sta		≤30	≤30	≤25	≤25	≤15
Top		≤30	≤30	≤25	≤25	≤15
Da	≤40	≤30	≤30	≤25	≤25	
T			≤25	≤15	≤15	≤15
Cold mix asphalt						
Egt	≤35	≤30	≤30			
Asg	≤35	≤30				

Table 5: Requirements for Nordic abrasion value for aggregates in asphalt pavements, from Figure 622.7 in N200 *[17]*.

AADT	≤300	301-1500	1501-3000	3001-5000	5001-15000	>15000
Surface dressing						
Eo and Do	≤19	≤19	≤14			
Eog and Dog	≤19	≤19				
Hot mix asphalt						
Agb	≤19	≤19	≤14			
Ab	≤19	≤19	≤14	≤10	≤10	≤7
Ska				≤10	≤10	≤7
Ma	≤19	≤19	≤14			
Sta					≤10	≤7
Top					≤10	≤7
Da	≤19	≤19	≤14	≤10	≤10	
T			≤10	≤7	≤7	≤7
Cold mix asphalt						
Egt	≤19	≤19	≤14			
Asg	≤19	≤19				

In addition to these specifications the Handbook N200 [17] requires use of aggregates with weathering resistant minerals, not specified. If a high content of weak minerals is suspected, especially in the filler, further testing should be done. Handbook N200 does not give any maximum content of e.g. mica. In an earlier edition of Handbook N200 (at that time denoted Handbook 018) [19], the maximum allowed amount of mica was 12 %. Chapter 6.3.1 will give more information about the use of materials containing mica in asphalt mixes.

In Handbook N200 materials <4 mm are assumed to have similar properties as the coarser materials, so the same requirements for mechanical strength are valid for the fine fraction but tested on coarser material.

At AADT > 5000 all aggregates >4 mm should be according to the requirements for mechanical properties (LA and NBM). At AADT of 5000 or less the amount of material > 4 mm that cannot be documented should not be more than 6% of the total amount of aggregates.

5.1.3 Asphalt mix

All asphalt mixes should be produced and tested according to NS-EN 13108 – 21: Factory Production Control [18]. When it comes to the requirements regarding the asphalt mix it becomes more complicated. Here the mix design and the bitumen properties also plays an important role. The Handbook N200 [17] only gives recommendations for possible requirements on functional properties, in reality the specific requirements are set in each tender.

The requirements for the properties of the asphalt mix is divided into three; Deformation properties by Wheeltrack [20], cyclic load testing [21] and abrasion by studded tyres by Prall method [22].

Table 6: Requirements for resistance to permanent deformations determined by Wheel Tracking test, track depth in % of specimen thickness (Figur 603.2, *[17]*).

	AADT				
	≤1500	1501- 3000	3001 - 5000	5001 - 10000	>10000
Max allowed track-depth, % of specimen thickness	-	20	12	7	5

Table 7: Requirements for resistance to permanent deformations determined by cyclic creep, microstrain µε (Figur 603.3, *[17]*)

	AADT				
	≤1500	1501- 3000	3001 - 5000	5001 - 10000	>10000
Max allowed cyclic creep, Microstrain (µε)	-	40000	30000	25000	20000

Table 8: Requirements for resistance to abrasion by studded tyres determined by the Prall Method. For wearing courses (Figur 603.4, *[17]*).

	AADT				
	≤1500	1501- 3000	3001 - 5000	5001 - 10000	>10000
Max allowed Prall-value (cm^3)	-	40000	30000	25000	20000

5.2 Technical requirements for rock materials (aggregate) in concrete

Aggregates of right quality is crucial to produce concrete with satisfactory quality. The quality of the aggregates has to be stable with regard to humidity, sieving curves and fines content. It is also beneficial that the aggregate has a low water demand, which is governed by for instance cubic rather than flaky grain shape.

The formal requirements for aggregates for concrete production are given in NS-EN 12620:2002+A1:2008+NA:2016 Aggregates for concrete [23]. The properties that need to be declared according to the national addendum are discussed in the following.

The Norwegian Public Road Administration (NPRA) has established their own quality handbook, Handbook R762 Prosesskode 2 [24], giving specifications for concrete and its raw materials. The Norwegian National Rail Administration (NNRA) has adapted these specifications for concrete.

5.2.1 Aggregate size

Lower and upper grain size for the aggregate is expressed as d/D. Commonly used fractions for concrete in Norway are 0/8, 8/16 and 16/22. There are some local variations. For sprayed concrete the upper grain size is normally 8 mm.

5.2.2 Grading

Depending on the declared aggregate size, there are limitations on how much of the aggregate that can deviate from the declared size. For example, for a 0-4 mm aggregate, 95-100 % of the aggregate must pass the 5,6 mm sieve. 85-99 % must pass the 4 mm sieve.

NS-EN 12620 also gives tolerances for the grading curves, depending on the product. In Figure 2 an example curve for the declared values of a naturally graded sand and the minimum and maximum curves as a consequence of the tolerances in the standard are given.

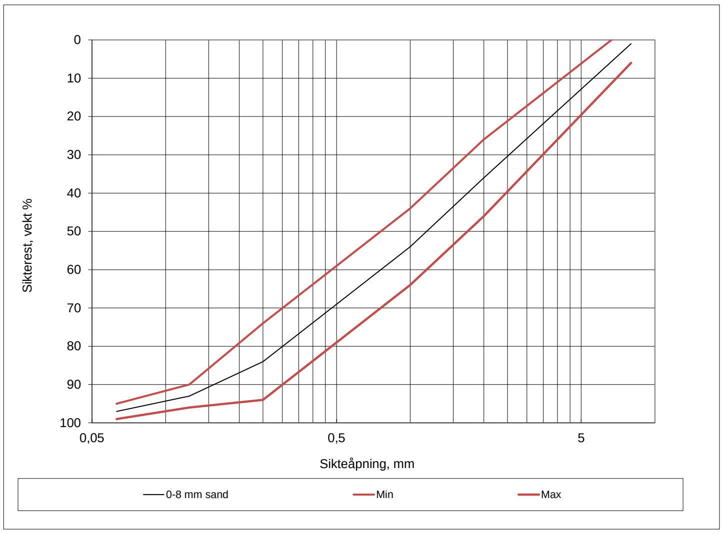

Figure 2: Declared value and upper and lower limits.

5.2.3 Shape of coarse aggregate

The flakiness of coarse aggregate must be declared, and for naturally graded aggregate, the flakiness index must be lower or equal to FI_{35} according to the national addendum to NS-EN 206:2013+NA:2014 [25]. In practical use in Norway, aggregates with grain size above 8 mm is considered as coarse, as opposed to NS-EN 12620 [23] where aggregates above 4 mm are considered to be coarse. The grain shape affects the workability of the concrete, and also the water demand, but not to the extent that the finer aggregates do. NPRA Handbook R762 [24] requires a flakiness category of FI_{20} or better.

There are no standardized methods for determining the grain shape for aggregates below 4 mm. A standardized method would be helpful to increase the quality of crushed sand and excavated rock materials.

5.2.4 Fines content

A high content of fines is negative for the water demand and the workability of the concrete. It is in particular the particles smaller than 20 µm that increases the water demand, and close control of the fines is crucial to succeed with crushed sand. The material is given a classification according to NS-EN 12620 [23] depending on the amount of material passing a 0,063 mm sieve. For coarse aggregates, the NPRA has set a limit of 1,5 mass % (category $f_{1,5}$) and for the naturally graded 0-8 mm, the tolerance is 10 %, category f_{10}.

5.2.5 Resistance to fragmentation

The resistance to fragmentation is given by the Los Angeles test method. For naturally graded coarse aggregate, the Los Angeles value must be lower than 35 (LA_{35}) according to NS-EN 12620 [23]. This is the same requirement as the NPRA uses for aggregate in concrete with quality up to B45. For concrete of higher quality, from B55 and up, the Los Angeles value must be 30 or lower (LA_{30}).

5.2.6 Bulk density

The bulk density must be declared. Normal-weight aggregate is defined as aggregate with a density between 2000 and 3000 kg/m^3 according to NS-EN 206:2013 + NA:2014 Concrete - Specification, performance, production and conformity [25]. The narrow concrete density accepted by the NPRA, ranging from 2300 to 2500 kg/m^3 means that some aggregates are disqualified.

5.2.7 Water absorption

It is essential to have control of absorbed water in concrete production, and a high value is negative for the frost resistance. The NPRA requires that the water absorption for aggregates with grain size below 8 mm must be maximum 1,5 %, and for aggregates above 8 mm maximum 1,2 %.

5.2.8 Freeze-thaw resistance

If the aggregate's water absorption is 1 % or lower, the aggregate itself is considered to be resistant against freeze-thaw according to NS-EN 12620 [23]. As hardly no aggregates in Norway have water absorption values above 1 %, this testing is rarely done. To what extent such testing will be more relevant for excavated rock material is presently unknown.

5.2.9 Alkali-silica reactivity

Alkali-silica reactions are reactions between certain types of aggregates and the pore water in the concrete. This causes the formation of a swelling gel which in most cases will cause damage to the concrete. Reactive minerals typically contain fine grained or deformed quartz, and examples are different sedimentary rocks, cataclastic rocks, rhyolites, fine grained gneisses and fine grained quartzites. The precambrian gneisses and granites are mainly non-reactive, but exceptions are rocks close to deformation zones where cataclastic rocks occur. Fine grained gneisses can also be alkali reactive due to the small grain size of quartz minerals. The late precambrian sandstones are alkali reactive. The rocks types in the Caledonian range of mountains vary with respect to alkali reactivity, and the same is valid for the different rocks in the Oslo area.
The Norwegian addendum to NS-EN 206 [25] requires that the raw materials and concrete composition must comply with the Norwegian Concrete Association's publication number 21 "Durable concrete with Alkali Reactive Aggregates" [26]. This implies investigating the aggregates reactivity and if the aggregate falls into the category “reactive”, special precautions must be takenin the design of the binder composition in relation to the total alkali-content of the concrete mix.

There is not one common method for testing alkali-silica reactivity in Europe. However, Norwegian concrete producers have long experience in controlling the amount of alkalis in the concrete if the aggregate is reactive. A high share of the concrete produced in Norway today, is contains flyash, slag or silica fume which reduces the risk of alkali-silica reactions. This is not discussed further in this report.

5.2.10 Chlorides

Chlorides will not damage the concrete itself, but cause corrosion of the reinforcement. The only requirement in NS-EN 12620 [23] regarding chlorides is that the value must be declared, whereas Handbook R762 requires the chloride content of the aggregate to be lower than 0,01 %. NS-EN 206 [25] gives requirements for the total chloride content in the concrete, and the chloride from the aggregates must be included. Chlorides are seldom present in crushed rock. However, if the material is stored close to the sea, the material can be infected by water of high salinity.

5.2.11 Sulfur containing compounds

Iron sulphide minerals found in aggregates can cause disruption and deterioration of concrete. It is first of all the mineral pyrrhotite ($Fe_{1-x}S$) that has been reported causing damage. Weathering quite easily, this mineral is very seldom observed in glaciofluvial or alluvial sand/gravel. However, it can in some cases be found in crushed hardrock, e.g. from tunnel work. The chemical reaction leading to deterioration requires the presence of moisture and oxygen. Oxidation of pyrrhotite results in the formation of sulphuric acid. The acid attacks the cement paste, affecting the strength. Sulphate attack also leads to expansive forces within the concrete by the formation of ettringite.

On the other hand, pyrite (FeS), which is a more frequently occurring mineral, will only have aesthetical importance due to dis-coloration during oxidation.

In Norway a limit of 0,1 % total S applies when presence of pyrrhotite is observed [23]. Some other countries, like Canada, set the limit to 0,10 % (informative Annex). Numerically these values are different, since 0,1 in a worst case can allow 0,149. By calculation we can see that 0,10 % S means a sulphide mineral content of 0,275 %, while 0,149 % S means as much as 0,410 % sulphide minerals – in other words almost twice the amount. If we agree to be conservative, the 0,10 % limit should apply. This is also from Quebec concluded to be a safe limit below which no cases of deterioration were identified in the Trois-Riviere project. On the other hand, serious damage was observed with 0,2 – 0,3 % S.

When it comes to identifying pyrrhotite, DTA is the standard method in Norway. However, DTA as per today cannot be used for quantification. Besides, usable equipment for this method is available only very few places. Some countries, like Canada, use petrographic examination on polished sections to estimate pyrrhotite by volume. Obviously, with very small volumes, this is also a method with uncertainties. And few geologists are trained to do this.

Today we have insufficient knowledge regarding reliable test methods for sulphide minerals and insufficient understanding regarding their harmfulness in concrete under different conditions. What we do know is that three pre-conditions are needed for a harmful reaction to take place: A content of pyrrhotite, presence of moisture and finally availability of oxygen. This means that a dense, good-quality concrete is better protected than a poor one. But again; necessary values for all these three factors are still uncertain. So is the knowledge concerning influence of binders (cement type, content of silica fume or fly-ash). In the future this will probably be a tool of even less availability, since there will be less fly-ash and silica fume on the market, and sulphate resisting cement will not be regularly offered by the cement factories in Norway.

5.2.12 Constituents affecting the setting and hardening of concrete

The aggregate must not contain organic or other types of material that prolongs the setting time of mortar more than 30 minutes or reduces the compressive strength of mortar samples more than 5 % at 28 days. This is both according to the NPRA and the national addendum in NS-EN 12620 [23]. Organic compounds is an example of a material which can affect the setting time.

5.2.13 Free mica

Free mica is negative for concrete in the way that the water demand increases and the compressive strength decreases. The NPRA has set a maximum limit of 20 % content of free mica in the fraction 0,125/0,250 mm of the aggregate.

5.2.14 "Mud" (norwegian: slam)

The content of "mud" is not mentioned in NS-EN 12620 [23]. However, this is considered an essential property both among concrete producers and the NPRA as a high content of "mud" increases the concrete's water demand. This is reflected in Handbook R762 [24] stating that the maximum amount of "mud" allowed in fine aggregate or naturally graded 0-8 mm sand is 15 %.

5.3 Technical requirements for rock materials in road construction

5.3.1 National requirements

Unbound aggregate materials are used for several purposes in road construction, including in base, subbase, and frost protection layers, as fill material, and in drainage. Each purpose is subject to different requirements regarding quality and composition. The most common quality requirements are connected to aggregate sizes and amount of fines.

Figure 3 illustrates the principal of a Norwegian pavement structure, consisting of unbound aggregates in subbase and frost protection layer. While the base layer is often constructed of hot mix asphalt, it can also consist of unbound materials. For road construction in Norway, pavement design specifications and aggregate quality requirements are given in Handbook N200 [17]. Where the annual average daily traffic (AADT) is less than 8000, 180 cm is the maximum full pavement thickness. For roads with AADT > 8000, the corresponding maximum thickness is 240 cm. Four lane highways with AADT > 8000 are designed for a 100-year statistical frost volume, while other roads are designed for a 10-year statistical frost volume.

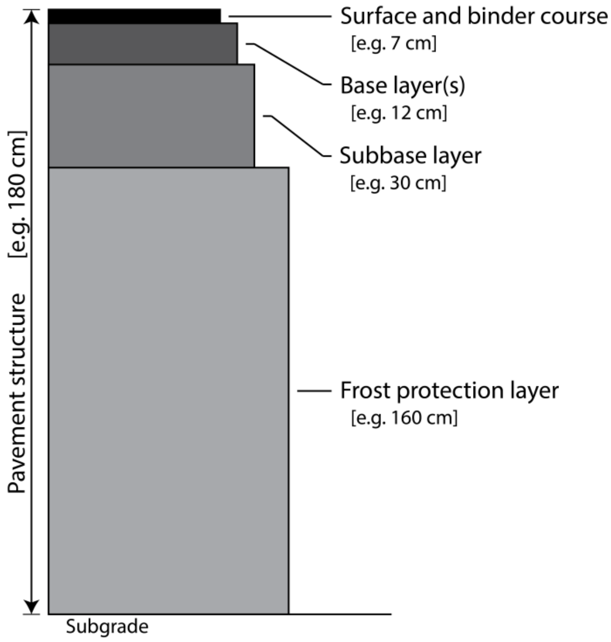

Figure 3: Norwegian pavement structure, example.

The requirements in the design manual Handbook N200 [17] do not differentiate unbound materials regarding origin; reused or recycled materials should all meet the same quality requirements as "new" quarried materials. Mechanical and geometrical requirements are set for materials used in the main pavement structure: base, subbase, and frost protection layers. Requirements for resistance to fragmentation and resistance to wear apply for all unbound aggregate materials used in base and subbase layers.

Table 9 refers the requirements for crushed rock materials in the subbase layer. This layer can have thicknesses from 30 to 90 cm. Blasted rock is not allowed used directly in the subbase layer; all material must be crushed.

The requirements for unbound crushed rock used as frost protection material is shown in Table 10. The thickness of the frost protection layer will depend on climatic conditions, subgrade conditions and the amount of traffic.

Table 11 summarizes the material requirements for unbound aggregates base layers. An unbound base layer will have a thickness of 10-20 cm.

Material fractions used in the unbound layers are specified as d/D (e.g. 0/32, 22/120), d being the lower sieve size and D the upper sieve size that limits the grain sizes in the fraction. Some under- and oversize is tolerated, D_{max} is the sieve size that 100 % of the material shall pass through.

Table 9: Requirements for subbase materials. Translated from table 522.1 in Handbook N200 *[17]*.

Properties	**Requirements**
All materials, mechanical strength	
Los Angeles value	≤ 35
MicroDeval value	≤ 15
Gravel and all-in crushed rock	
Amount of oversized grains	≤ 20 %
Coefficient of uniformity	≥ 15
Amount of fines (< 0,063 mm), depending on size [1)]	
0/22	≤ 7 %
0/32 and 0/45	≤ 5 %
0/63	≤ 3 %
Largest fragment	$^{2}/_{3}$ of layer thickness, maximum 125 mm
Coarse crushed rock	
Amount of oversized fragments	≤ 20 %
Amount of undersized fragments	≤ 20 %
Amount of fines (< 0,063 mm)	≤ 7 %
Largest fragment	$^{2}/_{3}$ of layer thickness, maximum 125 mm
Share of material < D/2	20 – 70 %

1) The amount of fines is calculated as share of materials <22,4 mm.

Table 10: Requirements for frost protection materials. Translated from Handbook N200 *[17]*.

Properties	**Requirements**
Largest fragment	½ of layer thickness, maximum 500 mm
Amount of material smaller than 90 mm	≥ 30 %
Amount of fines (< 0,063 mm) [1)]	2 % - 15 %

1) The amount of fines is calculated as share of materials <22,4 mm

Table 11: Requirements for base layer materials (crushed gravel and crushed rock). Translated from table 523.1 in Handbook N200 *[17]*).

Properties	**Requirements**
Los Angeles value	≤ 35
MicroDeval value	≤ 15
Flakiness index	≤ 35
Amount of crushed grains	$C_{50/30}$
Amount of fines (< 0,063 mm) 1)	
0/22	≤ 7 %
0/32 and 0/45	≤ 5 %
0/63	≤ 3 %
Amount of oversized grains	≤ 15 %

1) The amount of fines is calculated as the share of materials <22,4 mm.

Fill materials and materials used in drainage are subject to fewer requirements than the above-mentioned materials. Requirements are given in Handbook N200 [17]. As fill material, the maximum grain size is connected to the layer thickness, and the amount of humus (biological material) is restricted to maximum 3 %. Materials used as fill materials in drainage ditches shall not be frost susceptible (limited amount of fines). Maximum grain size is restricted according to type and size of drainage pipes, from 16 to 120 mm.

5.3.2 International requirements

The relevant European standards are to a great extent incorporated in the Norwegian design guidelines and material requirements, e.g. Handbook N200 [17].

The most relevant CEN standards regarding aggregates for road construction are the product standards EN 13242 *Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction* [27] and EN13285 *Unbound mixtures – Specifications* [28]. These standards specify product categories for material properties tested by the methods specified in the EN 933 and EN 1097 series.

The scope for both EN 13242 and EN 13285 are restricted to materials with an upper sieve size of 90 mm. However, in Norwegian practice for road construction, more coarse materials are widely used. For these materials, the standards do not apply, and all requirements should be described in other specifications and guidelines. There is currently an ongoing work in the Norwegian aggregate business, chaired by the Norwegian Standardization Agency, to create a Norwegian standard for coarse construction materials outside the scope of EN 13242 and EN 13285.

Fladvad et al. [29] have compared international practice for aggregate use and presents results representing 18 countries, including Norway. From the results, it is seen that although the practice for aggregate use is divergent, quality requirements in the studied countries meet equivalent standards. The results also show that traditional quality assessment methods are dominating, as none of the participating countries mentions performance-based quality requirements, only traditional material property tests.

5.4 Technical requirements for rock materials as ballast for railway construction/support

5.4.1 The Norwegian Ballast requirements

The Norwegian requirements for ballast are presented in Table 12. The requirements are anchored in two documents, the European standard EN 13450:2017 Aggregates for railway ballast and Bane NOR's Technical Specification for railway ballast [30].

Table 12: The Norwegian ballast requirements.

Construction layer	Grading	Mechanical strength	Course depth
Ballast course	31.5/63 mm (Category C in EN 13450:2017)	Los Angeles ≤ 24 or 20 % (depends on tonnage and maximum speed). Micro-Deval ≤ 15 % (category $LA_{RB}24/20$ and category $MD_{RB}15$ in EN 13450:2017)	350 mm (under sleeper), 200 mm in crib (between sleepers)
Sub-ballast course	Blasted rock 0/300 mm, alternatively 22/150 or similar (requirements under local revision)	No requirements	700 mm (minimum)
Frost protection course	Blasted rock 0/500 mm, alternatively 22/150 or similar (requirements under local revision)	No requirements	1450 mm (depends on winter climate and design standard)

6 Use of excavated rock materials in asphalt

6.1 Introduction

Asphalt is a material used as relatively stiff but flexible layers in a road construction, acting as protection for the unbound materials further down in the construction. The asphalt layer both protects the unbound materials from water and the high stresses coming from the traffic. In Norway the choice of thicknesses and the overall material choices are usually based on information about the annual average daily traffic AADT, including information about the number of heavy vehicles, temperature in the area and the existing materials in the subgrade divided into sections with similar strength/bearing capacity.

In general asphalt materials consist of approximately 95 % aggregates and 5 % bitumen by weight. The aggregates can have their origin from quarries of rock materials or from natural gravel. The optimal composition of aggregates and bitumen is found through a mix-design process where the aim is to find an end product that meets all specification in the project.

One of the biggest obstacles today for using tunnel materials in asphalt is the missing information about the usefulness in the early phase of a road project. In Norway a general geological report from the area usually follows the tender. It is not possible today to be certain about the quality of the materials before the material is crushed into different sizes. Shortness of time and rigid specifications often disqualifies the material for use in asphalt early in the project.

The authors have not found much relevant literature dealing with the use of local or weaker materials in asphalt. The reason for this is probably because the material is used as a normal material if it meets the specifications, and not used otherwise. In Norway the possibility to use lower quality materials in the road construction and also as material for asphalt are present, as we have much stronger materials in general than many European countries.

6.2 Example projects

The authors have not succeeded in finding relevant information from projects dealing with the use of excavated rock materials in asphalt mixes. However, it is known that attempts have been made in a few projects, for instance the SIV project.

The research project called “Steinkvalitet og sporutvikling i vegdekker” – SIV [31], translated title: “Aggregate quality and rutting in pavements”, was established in 2001 as a collaborative project within the industry.

The main objective of this research project was to contribute to a higher level of knowledge about the effect of aggregate properties on the functional behavior of wearing courses, especially wear from studded tyres. This knowledge is important to optimize the use of aggregates for wearing course purpose. The project also aimed to evaluate the Nordic abrasion test and find correlation between laboratory results and wear in field.

The reason why this project is mentioned in this report is that two of the materials used in laboratory and field tests were very weak, and in that sense the results therefore illustrates the consequences of using weaker materials.

The weak materials used in the project was a Larvikite from Hedrum and the other one was a sandstone from Bremanger. Only the Larvikite was used in the field trials in Vestfold. The values for Los Angeles and Nordic abrasion for these two materials are given in Table 13.

Table 13: Los Angeles and Nordic abrasion values for selected materials, from table 3 in *[31]*.

Rock type	**Los Angeles Value**	**Nordic abrasion Value**
Larvikite from Hedrum	32,5/36,1*	17,1/15,5*
Sandstone from Bremanger	16,9**	20,4**

*material tested at two different places, NTNU/VTI, **material tested at VTI

4 different field locations were established in the project, all on existing roads.

- RV 80 Fauske, Nordland county
- EV 6 Klett, Sør Trøndelag county
- RV 20 and RV 206 in Hedmark county
- EV 18 in Vestfold county

In addition, the unique Road Simulator at VTI in Linköping Sweden [32] was used to run tests under more controlled environment.

The testing done in the Road Simulator is mainly focused on abrasive rutting from studded tyres, not on rutting from permanent deformation. In field the abrasion from studded tyres is dependent on the number of vehicles with studded tyres, which varies a lot around the country. Permanent deformations are also an important contributor to rutting. As an example the field trials from Klett [33] shows that the wear from studded tyres only represent about 50 % of the total rutting, while permanent deformations represent the remaining 50 %. Permanent deformations are influenced by many factors. Horvli et al [33] suggests initial deformations caused by compaction from traffic, especially during the first summer and some problems also caused by reduced adhesion between binder and aggregate in the asphalt mix.

Horvli and Værnes [31] also made another important finding during the project regarding the mortar phase (binder and fines<2 mm). A mechanically strong material (>4mm) were mixed with fines (<4mm) from a weak material and vice versa. The results from the wear testing in the Road Simulator shows that the mortar has a large influence on the resistance to abrasion from studded tyres. A strong mortar gives a higher resistance to studded tyres. Increasing the amount of coarse aggregates also have a positive effect on wear resistance.

One of the main relevant conclusions from the SIV project [31] is that the correlations between winter-related rutting and Nordic abrasion value are pretty good, meaning that the Nordic Ball Mill method is a good method to classify aggregates regarding resistance to abrasion from studded tyres. Also the wear related rutting found by using the Road Simulator gave good correlation to Nordic abrasionvalue. In the Road Simulator the weakest materials (Hedrum and Bremanger) also gave the lowest resistance to abrasion from studded tyres.

The Abrasion parameter is important for the resistance to abrasion from studded tyres Equation 1. By increasing the amount of material >4mm in the asphalt mix, one can to some extent compensate for a lower Nordic abrasion value.

Equation 1: Abrasion parameter = (Nordic Ball Mill Value/% material > 4mm)*100 *[31]*.

6.3 Positive and negative experiences

6.3.1 Mica and other weak minerals in asphalt mixes

In Sweden comprehensive research is done on the effect of mica in the fines on the asphalt mix. Peet Höbeda at VTI has been the main contributor to this work [34].

In 2013 Hellmann [35] summarized the current knowledge on the effect of Mica content in the road construction, also in asphalt mixes. As Hakim and Said [36] found that the properties of the asphalt mix were dramatically influenced by the amount of mica. The amount of mica should be expressed by volume, as the mica particles have a large specific surface. This is well illustrated in Figure 4.

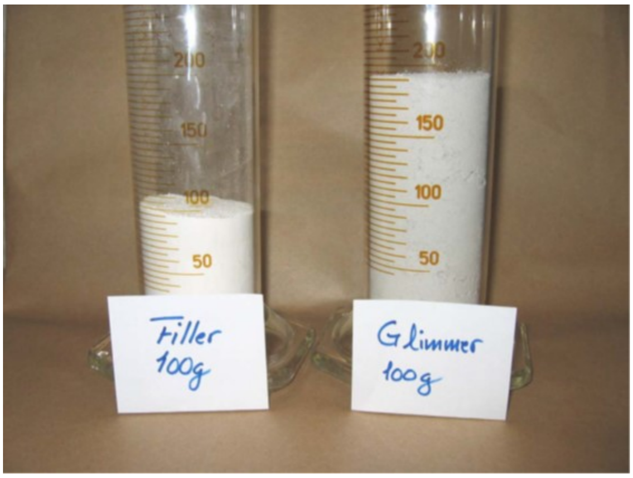

Figure 4: Regular fines (left) vs. fines of mica (right) *[36]*.

Other challenges with mica in the fines in asphalt mixes is adhesion, the fact that the mix demands high binder content and high void content in the pavement due to compaction resistance. Some of these issues are well illustrated in Figure 5. Misovsky [37] where the void content increases rapidly with a mica content of more than 2-3 %. The figure also shows that the indirect tensile strength is highly influenced by the mica content.

Hellmann [35] points out that one of the main challenges with mica in the fines is that mica is a great source to variation, which causes great challenges in asphalt production. In general all part materials variation is experienced very probematic for both asphalt and concrete producers.

In Norway we have a lot of mica in different rock types, so this is absolutely relevant for the use of excavated rock materials in asphalt.

In NVF-report on asphalt mortar [38] the Icelandic contribution mentiones montmorillonite (swelling clay) as a problem. Montmorillonite has a negative effect on the asphalt mix, quite comparable to the influence of mica.

The lack of requirements for mica content, swelling clay and other weak minerals is very unfortunate considering the great influence on both fresh and hardened properties of the asphalt. In the NVF-report a big project at Gardermoen airport in 1998 is mentioned, where mica in the aggregates caused big problems with the asphalt mix.

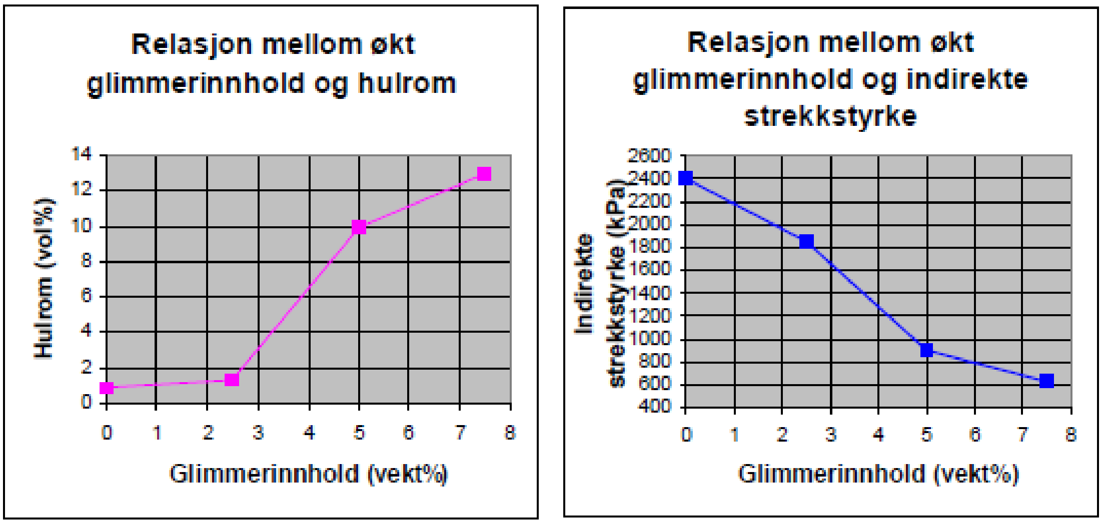

Figure 5: The relation between mica content and void content and indirect tensile strength *[37]*.

6.4 Possibilities and suggestions for further work

The relevant questions that we recommend to look into in further work in Kortreist Stein is:

- Document the use of excavated and processed rock material in asphalt according to NPRAs current requirements
- Alternative use of materials: If a material is weak – how can parts of it be used in an optimal way in asphalt mixes used in different layers in the road construction?
- Properties found by different performance tests may give a better picture of the behavior of the total mix
- Can something be done in the mix design phase of a project to improve the asphalt mix
    - More coarse material in the mix
    - Mix weak and strong material
    - Modify bitumen
- Abrasion-parameter (sliteparameter)
- Can innovative pavement design compensate for the use of weak(er) materials?
- Can the water susceptibility of materials containing fines be improved or compensated for?

7 Use of excavated rock material in concrete

7.1 Introduction

The dissertation of Thalmann [39] demonstrated the suitability of TBM excavated rock material as aggregate in concrete and shotcrete. In his work, excavated material from TBM-projects were collected and characterized. The particle shape of TBM rock material is typically flat and elongated, and the fines content is high (8 mass-% below 0,063 mm). The sand content (0-4 mm) varied between 25 and 35 mass-%, depending on the geology, whereas the fraction above 32 mm was 20 mass-% of the total material. One interesting finding was that material taken directly from the TBM and washed could be used directly in concrete without any further crushing. The combination of

TBM-material together with crushed material from the same source was shown to enhance the utilization rate significantly.

In a paper from 1998, Olbrecht and Studer [40] reports from five large scale trials where TMB material is used in concrete. Their goal was to produce a pumpable concrete with a cube compressive strength of 35 MPa after 28 days. The TBM excavated rock material was collected from various tunnel projects in Switzerland and no further processing was done to the material, see Figure 6. The mixes required considerably more cement and admixtures than concrete produced with naturally deposited alluvial gravel.

Figure 6: TBM material from Polmengo tunnel [40].

7.2 Example projects

7.2.1 Lyon-Turin

For details on the project, see Appendix A1.

The excavated material was split into three classes where material in class number 1 was used for concrete production.

A set of material specifications, which were similar to the specifications for the Gotthard base tunnels, were used to evaluate the material. The examinations performed were grinding and point load indexes, macroscopical and microscopical petrography, content of free phyllosilicates and alkali-silica reactivity. The fractions produced were 0/4 mm, 4/8 mm and 8/16 mm.

In the Chartreuse tunnel, the masses consist of limestone, marls and mollasse. Only the limestone was found acceptable for use in concrete, generating 1 269 000 tonnes of aggregates for the production of concrete linings and tunnel segments. This corresponds to 25% of the total masses excavated. In the Maurienne-Ambin Base Tunnel, the materials gneiss, shale, mica schist and sandstone were present [41].

7.2.2 Gotthard Base Tunnel

For details on the project, see Appendix A2. A testing plan for the approval of aggregates for concrete was carefully developed. The test plan included the following parameters [42]:

- Visual assessment: Petrography at the tunnel face
- Breakability index
- Point load index
- Los Angeles index
- Determination of petrography
  - Microscopic petrography (thin section)
  - Petrographically unsuitable components
  - Free bed silicates in sand (mica)
- Sieve analysis sand 0/1 and 1/4
- Sieve analysis gravel fractions 4/8, 8/16, 16/22
- Grain shape gravel fractions 4/8, 8/16, 16/22
- Potential alkali reactivity
- Bulk density and voids content
- Water content sand/gravel fractions

An approval system was also established for the concrete mixes. Mixes were approved for the various sections of the tunnel with the relevant aggregate. The properties for the mixes that were tested were [42]:

- Workability time due to warm climate and 3 hours transportation
- Technical requirements
  - Compression strength
  - Early strength
  - Water proof quality
  - Resistance to chemical attack
- Consideration of durability
  - Limitation of water/cement ratio
  - Limit value for change of length in sulphate tests
  - Minimum cement content

Technical innovations

According to Thalmann et al. [43], the project led to several innovations in the tunnelling and material industries. It contributed to the development of superplasticizers for concretes with high contents of mica, and it demonstrated the possibility to produce concrete with 100 % crushed aggregate. The project also accelerated technical improvements when it comes to grain rounding (hurricane) and sand-sizing devices. Finally, a method to remove mica from the aggregate was established. The 0/1 mm fraction of the sand was washed with water and collectors in a flotation cell. The phyllosilicates adhere to the collector and segregate to the surface where the foam is evacuated by overflow. This method reduced the content of mica by more than 50 % in the 0/1 mm fraction [43]. For the Sedrun section of the tunnel, the content of muscovite gneisses were found to be around 40% in the 0/1 mm fraction. These unfavorable ingredients were however reduced by to below 20 % by minimal flotation [44].

In total, these innovations enhanced the material recovery rate to up to 80 % [43].

Material balance

In the Lyon-Turin project 28 million metric tonnes of rock were excavated in total, and the demand for aggregates for concrete and shotcrete production was more than 9 million tonnes. Out of the 28 million tonnes, 23,0 % was used as aggregate for concrete production [44]. The material balance for the total project is shown in Figure 7.

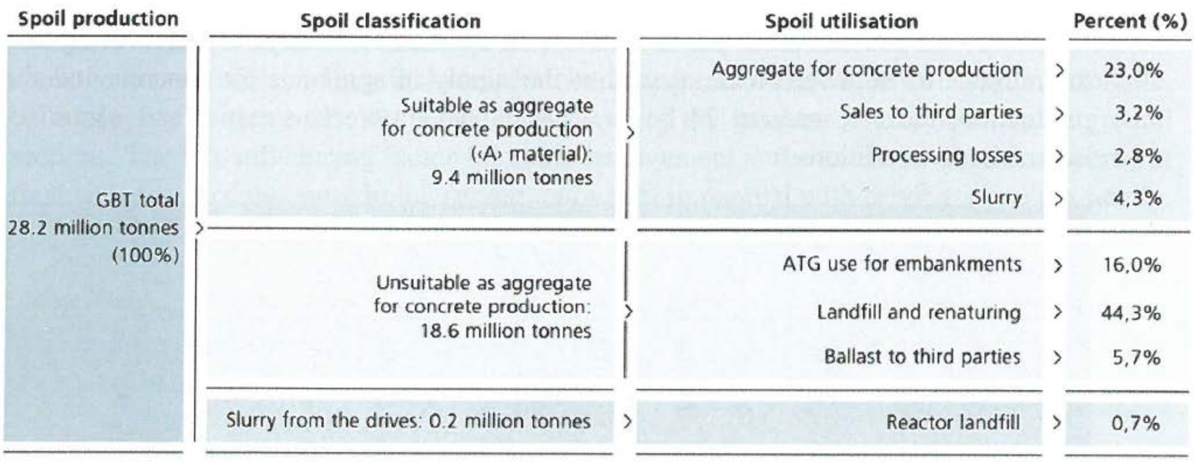

Figure 7: Material balance for the Gotthard Base Tunnel [44].

7.2.3 Jostedal hydropower tunnel

The concrete was made with approximately 70% TBM material and 30 % natural gravel or crushed stone. There was a great variety in the concrete quality, and the compressive strength varied between 15 and 45 MPa. The variations were caused by insufficient quality control of the TBM material [45].

7.2.4 Linthal 2015 Project

For details on the project, see Appendix A3 .

Among the methods that were used were both Drill and blast and TBM.

The excavated rock material was mainly limestone without any siliceous content, and the amount of mica was negligible. The material was therefore well suited for the production of aggregates.

Crushing and screening plants were established at two locations. One of them was a wet processing plant. To compensate for the low content of fines in the washed manufactured sand, this was mixed with a dry manufactured sand with an easily-controllable fines content. Crushing and screening plant number two was established as a dry processing plant.

7.2.5 Koralm Tunnel

For details on the project, see Appendix A4 .

The excavated material consisted of schistose gneisses and gneisses with inclusions of mica schist, amphibolites and marbles. The average content of mica in the fraction 0.125-0.250 mm was 25 %. Concrete of quality C35/45 and C25/30 were produced.

The TBMs had crushers that produced 0/150 mm which was split into the fractions 0/16 mm and 16/150 mm. The 16/150 mm fraction is sent to the processing plant where it was crushed and cubified into the fractions 0/3 mm, 3/8 mm, 8/16 mm and 16/32. The 3/8 mm, 8/16 mm and 16/32 mm fractions are wet sieved, and can be seen in Figure 8. The grading curve for the 0/3 mm fraction is given in Figure 9.

Figure 8: Fractions 3/8 mm, 8/16 mm and 16/32 mm [46].

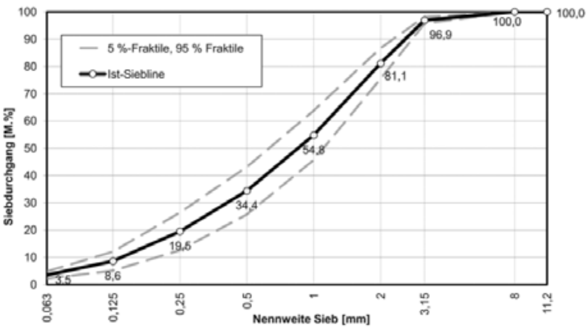

Figure 9 Grading curve for 0-3 mm [46].

7.2.6 Brenner Base Tunnel

For details on the project, see Appendix A5.

The tunnel was constructed by using TBM.

Voit and Zimmermann [47] performed concrete mixes with three types of aggregates from the excavated rock masses. The three aggregate types were quartz phyllite, schist and gneiss as shown in Figure 10.

Figure 10: Aggregates used in concrete mixes by Voit and Zimmermann [47]. (a) quartz phyllite, (b) schist, (c) central gneiss.

Both fresh and hardened concrete properties were tested. The aggregates were crushed, washed, sized and assembled and different compositions were tested. It was seen that the quartz phyllite needed modifications, and the 0/2 mm and 0/4 mm fractions were replaced by conventional sand. Results from initial testing of compressive strength with various qualities of cements is shown in Table 14 . As is seen from the table, the concrete produced with gneiss had the highest compressive strength, followed by schist, and finally quartz phyllite. The low compressive strength of the concrete with quartz phyllite is due to smooth grain surfaces and relatively low rock strength.

Table 14: Compressive strength of concrete with various types of cement and aggregates. Cement content was 220 kg and w/c-ratio was 0,55 *[47]*.

Cement type	Compressive strength [MPa]		
	Quartz phyllite	Schist	Central gneiss
CEM II 42.5 R	22.57	25.44	30.46
CEM V/A 32.5 R[a]	21.76	24.02	30.28
CEM V/B 32.5 R[a]	17.64	22.58	26.13
CEM V/A 32.5 R[b]	22.67	26.00	29.87
CEM V/B 32.5 R[b]	20.60	23.49	24.93

Product of:
[a] Austria.
[b] Slovakia.

The difference between washed and unwashed aggregates was also investigated. The mixes were performed with two levels of cement at a w/c-ratio of 0,5. The highest effect of the washing on the compressive strength was seen on the quartz phyllite. Although quart phyllite initially had the lowest compressive strength in concrete initially, the highest improvement after washing was seen for this type. The increase was as high as 20 %.

7.2.7 Follo Line Tunnel

For details on the project, see Appendix A6 The project is also described in 9.2.3.

In the Follo line prosjekt (presently on-going), the goal is to use a significant part of the TBM excavated rock material the production of concrete for the lining segments. From the excavated material that is considered acceptable, the fraction between 20 and 80 mm is crushed and used for aggregate production, giving 0-8 mm, 8-11 mm and 11-22 mm. The concrete mix contains about equal amounts of natural sand and sand produced from the excavated rock material, in addition to 8-11 and 11-22 mm aggregates delivered by an external supplier is necessary because the own production from the tunnel does not give sufficient amounts.

The main challenges using the excavated rock material as concrete aggregate were the high amount of water in the 0-8 fraction, the LA-value and the variation in the sieving curve.

7.2.8 E6 Fellesprosjektet (Mjøsa)

For details on the project, see Appendix A7.

The project supplied the concrete producer with all the required aggregates in the fractions 8-16 mm and 16-22 mm for a period of time until the excavated rock was needed elsewhere in the project. It was decided not to use the 0-8 fraction due to the high amount of fines. The excavated rock material consisted mainly of granite [48].

7.2.9 E39 Rådal-Svegatjørn

For details on the project, see Appendix A12.

In this project, a commercial aggregate and concrete producer has produced aggregate by crushing rock from the same area as the tunnel is situated. This aggregate is used both in sprayed concrete and ordinary concrete for construction purposes. Trial tests on excavated rock material for use in sprayed concrete have been performed. In this case, 75 % of the aggregates originated from the tunnel.

The producer finds the requirements in NS-EN 12620:2002+A1:2008+NA:2016 challenging as these are not intended for mobile chrusing [49].

7.3 Positive and negative experiences

The decision to take advantage of the excavated material in a project may force participants to innovative thinking. This was seen in the Gotthard Base Tunnel project, resulting in several innovations.

Geology is an important parameter when tunnels are located, but location is not chosen to give the best possible aggregate. This means that concrete producers are not in the position to select the aggregates they use in production, and the contractors may have to adapt to this. As an example, it may be difficult to produce high strength concrete if the excavated material gives a low quality aggregate.

Mass balance must be handled in all production of aggregates, and production from excavated rock material is no exception. It may be challenging to find areas of utilization if the volumes of fines are large. The mud content for masses from the TBM method lies between 10-15 %, and the corresponding number for drill and blast is 8-10 % according to Thalmann et al [43].

Another major challenge is the stability of the quality of the excavated rock materials. The geology, the shape, the grading and the water content may vary considerably throughout a project, and cause variations in the concrete quality.

As reported by Olbrecht and Studer [40], concrete produced with TBM material required considerably more cement and admixtures compared to concrete with alluvial gravel. The increase in cement and admixture content is negative both of economic and environmental reasons. These results are not supported by the Follo Line project where the aggregates from excavated material has almost the same water demand as the [50].

7.4 Further work

Aggregate made from excavated rock material and the effect on the water and cement demand in concrete needs to be investigated closer, since high demand is negative both economically and environmentally. Cement is the most expensive part material in concrete. And, a 20 kg increase in the cement content of one cubic meter concrete, increases in the CO_2 emission by approximately 12-15 kg or approximately 5 %. Calculations can determine whether an increase of the cement content can be justified by the advantages of the use of excavated material. The environmental aspects is treated in another work package in the project (Kortreist stein, H4).

A master thesis at NTNU in spring 2017, which is included in the present project (Kortreist stein), will look into the application of excavated material in sprayed concrete. Material from one or two on-going tunnelling projects in Norway will be tested.

Closer investigations should also be done on the differences between various TBM masses and drill-and-blast masses. Possibly, the excavation method influences suitability in either concrete or other applications, and whether this may lead to preferable methods for aggregate production from the excavated material. These issues need to be looked into. This may be a parameter taken into account when selecting tunnelling methods in the future.

8 Use of excavated rock material in road construction

8.1 Introduction

Tunnels are an important part of Norwegian road construction, as the Norwegian road network comprises a total of over 1100 tunnels, over 30 of which are subsea tunnels. The surplus of rock materials from tunnel construction have been utilized in various ways, from fjord fillings and landfills to aggregates in road construction.

8.2 Example projects

8.2.1 Norwegian Roads Recycling R&D program

The research program Norwegian Roads Recycling R&D program (Norwegian title: Gjenbruksprosjektet) was initiated by the Norwegian Public Roads Administration (NPRA) and was carried out over the period 2002-2005. Petkovic [51] describes the purpose of the project:

The Norwegian Roads Recycling R&D Program (in Norwegian “Gjenbruksprosjektet”) was motivated by national environmental aims of minimizing waste volume and improving waste management. The main objective of the program was to facilitate more frequent and environmentally safe applications of recycled materials in road construction. The program aimed at increasing the general level of knowledge about recycled materials and revising design rules and building processes.

This project focused on secondary materials, reuse and recycling of waste materials as aggregates in road construction, e.g. crushed concrete and milled and crushed asphalt. In Norwegian road construction, reuse or recycling often comprise external materials like concrete, brick and glass, while rock materials are simply considered normal material use.

8.2.2 E39 Romsdalsfjorden crossing

An example project highlighting efforts to utilize excvated material is the E39 Romsdalsfjorden crossing. In this upcoming highway project, a fjord will be crossed by a 16 km long twin tube subsea tunnel. This project will create a significant surplus of blasted rock, and during the planning process, the possibilities for commercial utilization of the surplus have been investigated. It is decided that in order to be able to utilize the surplus rock, it is necessary to use conventional drilling and blasting as the construction technique for the tunnels [52].

A similar example is the Ryfast project, which is a subsea tunnel project with connected road infrastructure on land. In the project, a total of 52 810 m of tunnels is constructed using drill and blast, resulting in a surplus of 4 000 000 m^3 excavation material. Due to the geological conditions, most of the materials could not be used in the pavement structure. Where the rock quality allowed for it, excavation materials was crushed for use in base and subbase layers. Most of the materials have been used for private and public land area development, where the developers bought the materials from the construction project.

8.2.3 Pavement design for frost protection

In the period 2009 – 2011, the NPRA experienced frost heave problems on newly built roads. This lead to an increased research effort into frost heave and frost protection in the following years. In 2014 the Norwegian pavement design system was altered to incorporate new requirements for frost protection of roads.

The report Frost protection of Norwegian roads [53] describes the basis for changes in the pavement design manual. An important change that was introduced from this work is that all aggregate materials for use in subbase and frost protection layer shall be crushed. Previously, blasted rock could be used as aggregates directly, this is no longer allowed. The requirements for aggregate quality are otherwise the same. The need for crushing equipment to produce aggregates for road construction from local excavation materials from tunnels or other sources have created an increased interest in mobile crushing equipment.

8.2.4 Tunnel spoil as raw material for autobahn S10, Austria

For details on the project, see Appendix A11.

While planning the Austrian S10 autobahn from Unterweitersdorf to Freistadt, the construction company ASFINAG identified a need for utilization of tunnel spoil, as tunnels comprise about a third of the road length [54]. A share of the tunnel excavation materials was used in load bearing layers in the pavement structures on the project. While the total surplus volume in the initial was calculated to 4 000 000 m^3, 10 % of this volume was judged to be suitable for use as bearing course material. After careful sorting and quality assessment of the materials, the project succeeded in using a total of

400 000 m^3 excavation material as aggregates for the pavement structure. The tunnel excavation materials in this project were produced by drilling and blasting. Mlinar et al. [54] point out that waste legislation makes it difficult to distribute the materials for external use outside the current construction project.

8.2.5 Planning the handling of tunnel excavation material in Brenner Base Tunnel, Austria

For details on the project, see Appendix A5.

In a case study from the construction of the Brenner Base Tunnel in Austria, Ritter et al. [55] apply a simulation approach for the planning of tunnel excavation material handling. A major challenge in the planning phase is the number of uncertainties regarding geological conditions, material flow and processing capacity. Through simulations, time-volume plots for demand and supply of aggregates within the construction project are calculated. The main part of the tunnel excavation materials in this project was produced by drilling and blasting. Although the main focus for the simulation was concrete aggregate production, a similar approach will also be applicable for other use aspects.

8.2.6 Effect of processing of tunnel excavation material

The REMUCK project aimed at developing innovative methods to face the problems posed by waste muck disposal and of optimising the management of waste recycling, in order to take economic advantage from the reuse of excavated waste materials. One of the research areas in this project was comparing tunnel excavation materials in their natural state to the performance of the same materials after treatment with crushing and screening [56]. The materials compared come from five different tunnel projects, with different excavation methods. The properties compared was the shape/flakiness index and the resistance to fragmentation (Los Angeles test) and wear (MicroDeval test).

The results of the tests show that grain shape of the excavation material is improved by crushing. The mechanical properties are less affected by the treatment with crushing and screening. TBM materials with flaky particles will be improved by crushing before being applied as aggregates.

8.2.7 Performance-based reuse of tunnel muck as granular material in road construction

Experiences from seven Italian construction projects are gathered by Riviera et al. [57], with focus on unbound use of surplus materials in road construction. The tunnels described are constructed using several different construction methods such as cut and cover, drill and blast and TBM. The focus of the research is to find performance-based test methods to evaluate aggregate suitability to replace traditional specifications. Using performance-based test methods opens for the use of new material types not covered by traditional contract specifications.

8.2.8 Proposed quality test regime from Slovakia

A methodology for evaluation of possible utilization purposes for tunnel excavation materials is described and demonstrated by Grunner et al. [58] for Slovakian construction materials. This methodology includes extensive material testing, focusing on the most quality-demanding construction purposes first, ruling out the material samples that do not comply with the strictest requirements. In this way, the materials are sorted from highest value to lower value utilization potential and decisions can then be made involving both degrees of utilization and value of utilization of the surplus materials.

8.2.9 Waste regulations

Several authors publishing articles about the use of excavated rock materials from tunnels focus on waste regulations; e.g. Posch et al. [59], Entacher et al. [60], Entacher et al. [61], Kwan and Jardine [62], and Erben and Galler [63]. There is a conflict of interest when a natural resource like rock material is defined to be waste, while at the same time, the material is shown to be suitable for use in construction purposes.

8.2.10 Use of TBM excavation materials for road pavements

Gertsch et al. [45] gathered experiences about the use of excavated materials from TBM tunnels in several countries. From a list of 13 projects, materials from five of them are used for some kind of road purpose. However, some of these are temporary construction roads and not regular highways built by road authorities. Accordingly, they are not subject to the same quality requirements as a normal road pavement.

In one of the projects where TBM materials were used in a pavement structure, the experience showed that the material was too weak to withstand the traffic loads. This resulted in material crushing within the structure, which in turn resulted in frost heave problems and asphalt damages due to uneven frost heave. Other projects highlighted by Gertsch et al. (2000) describe use of aggregates stabilized by cement or other agents, but no successful direct use of unbound material from TBM.

A challenge for the use of TBM materials in the pavement structure is the grading curve. The materials generally contain too much of the smallest fines and contain too little of the coarsest part of the grain curve. The coarse particles are thin and elongated, making them vulnerable for crushing and generation of fines in the structure. As only a limited percentage of fines are allowed in the different pavement layers, a lot of fines need to be sieved away from the material and will result in waste.

Similarly, Grunner et al. [58] point out that the size of aggregates from TBM excavation is suitable for use as aggregates, but when assessed as a construction material, the shape of the materials is unfavourable, and the amount of fines is excessive.

8.3 Positive and negative experience

The E39 Romsdalsfjorden crossing is an example of early efforts made to achieve utilization of excavated materials from a tunnelling project. As construction have not yet started, the effects of the efforts are unknown.

We see from the example projects that the Norwegian regulations allow for distribution of excess excavation materials between construction clients and public or private developers. This is a clear contrast to the experiences from Austria, where waste regulations often act as an obstacle for excavated rock material utilization.

A limited amount of information is found regarding the use of TBM materials for load bearing layers in pavement structures. The Norwegian experience in use of tunnel excavation materials is largely based on tunnels constructed using drill and blast. The experiences with TBM materials described here are negative, and the materials described are often used in temporary construction roads, not public roads. The gathered information about the use of TBM materials is not sufficient to draw general conclusions on the applicability of such materials as aggregates for road construction.

Using the simulation approach described by Ritter et al. [55] it can be possible to compare different solutions for production equipment and material use purposes. Applying this kind of planning for a tunnel construction project will give a better overview of the material flows and mass balance in the project. This will make it easier to plan utilization of the excavation materials and should be applicable not only for concrete production but also other purposes like the production of aggregates for unbound use.

8.4 Further work

In general, there are no requirements regarding the origin of unbound aggregate materials in road construction in Norway. The design manual allows for the use of local materials, as long as the requirements from Statens vegvesen [17] are fulfilled.

As the mechanical properties are the main factor which decides if a material can be used as construction aggregates for roads or not, further research should be made into the applicability of the current tests and requirements. The aim of this research should be to achieve better mechanical properties for the local aggregates, thereby allowing them to be utilized in the pavement structures.

Performance-based test methods and requirements are not in widespread use for aggregates for road construction. Research into suitable performance-based tests will allow for assessment of alternative materials side by side with the traditional construction materials.

The focus area of the Norwegian Roads Recycling R&D program illustrates the fact that use of local materials are not regarded reuse in Norway, as it is seen from other countries. As use of excavation materials as aggregate is regarded normal practice, little research is published on these subjects.

Production of coarse aggregates for use in road pavements is generally a topic where little research have been conducted. The new requirements given in Handbook N200 [17] regarding crushing of unbound aggregates have increased the use of crushed aggregates in the pavement structures. The effect of crushing on the quality of coarse aggregates are unknown, and there is a need for verification of international research to Norwegian conditions.

Within the new requirements for frost protection materials in Handbook N200 [17], new opportunities for the use of aggregates are given which has not yet been explored fully. Materials for frost protection are not subject to quality requirements for mechanical properties. This means that there are good opportunities for utilization of local excavation materials in the frost protection layer. Depending on traffic, subgrade conditions and climatic conditions this layer can have thicknesses up to 2 meters, so substantial amounts of materials are needed.

There are little information on the use of excavated material from TBM as aggregates for road construction in existing research. The material's applicability for unbound use after aggregate processing is an area where further research is needed.

9 Use of excavated rock material as ballast for railway construction/support

9.1 Introduction

The ideal starting point for any infrastructure project is to have an even mass balance within the project. This will ease the need of transporting masses back and forth from the project. However, there are many challenges in a railway project which has to be considered, such as limits to where the tracks can be laid with regards to maximum vertical radius and minimum horizontal radius which decreases the planner's ability to control the mass balance. Together with the challenges the Norwegian topography, this often results in an overbalance of the excavated masses in the projects.

In this report, four big infrastructure projects have been studied with regards to the topic of mass balance and the possible reuse of the excavated rock material.

9.2 Example projects

9.2.1 Farriseidet- Porsgrunn

For details on the project, see Appendix A15.

Geology Porsgrunn-Farriseidet

The dominating rock mass in all tunnels except the Eidanger tunnel is the rare plutonic rock mass called Larvikite (Monzonitt). The Larvikite rock mass is mostly coarse grained, with a typical grain size of 1 -2 cm. About 90 % of the Larvikite is made out of the mineral Feldspar, but it also contains small amounts of darker minerals such as amphibole, olivine and biotite. Larvikite is known as a hard and competent rock and has been used as a natural stone for buildings since the 18th century and are even today mined in several quarries around Larvik [64] [65].

The rock mass in the Eiganes tunnel is sedimentary and consists of limestone, clay slate and sandstone that are variously affected by contact metamorphosis. The metamorphosis has made the rock mass hard and massive, and can be classified as hornfels. The degree of contact metamorphosis is higher towards the Larvikite in the east. The rock mass is presented in the geological bedrock map, Figure 11.

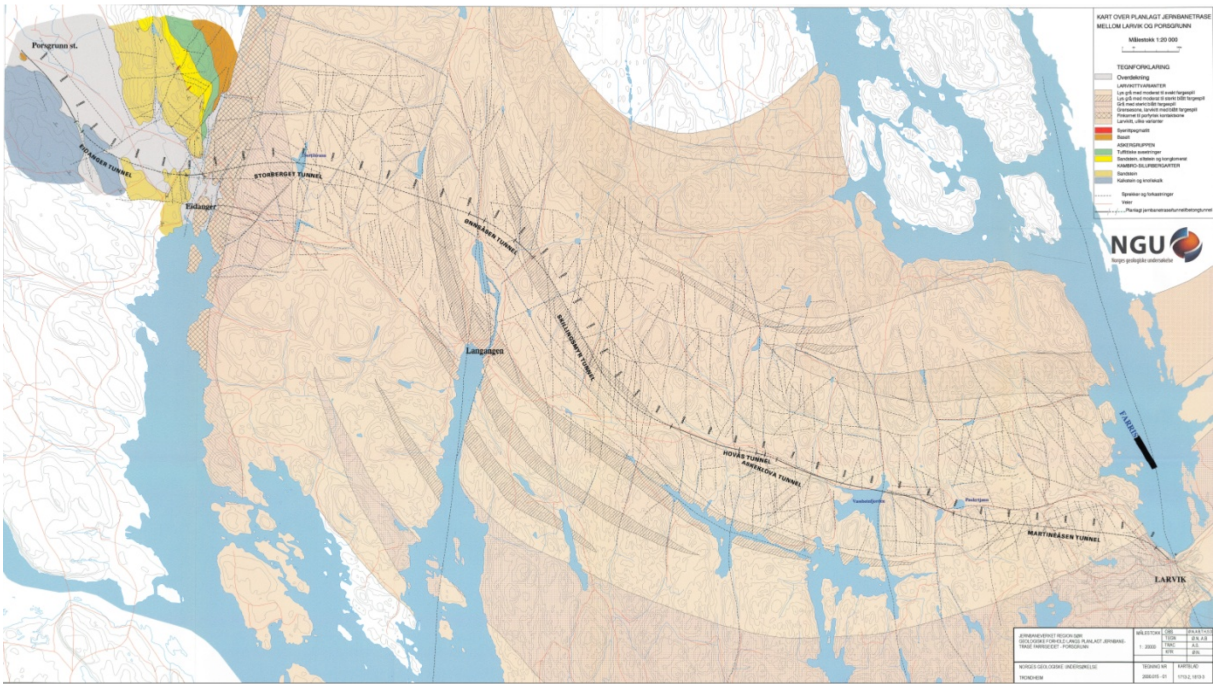

Figure 11: Geological bedrock map over the rock mass in the project.

<u>Pre-investigations with regards to rock mass properties</u>

No investigation or measurements of the rock mass, rock mechanical properties with regards to the use of the rock mass for railroad ballast was performed during the project. However results from previous measurements of the rock mass Larvikite conducted by NTH/NTNU/SINTEF was available, presented in Table15 [64].

Table15: Compressive strength and Elastic modulus of the rock mass Monzonite (Larvikite rock mass).

Rock mass	Location	Compressive strength (MPa)	E-module (GPa)
Monzonite	Larvik	-	66,28
Monzonite	Larvik	-	87,09
Monzonite	Larvik	57,06	73,00

No tests were performed in order to determine if the rock mass could be used for ballast, like for example tests of LA-value.

<u>Recommendations about the use of the rock mass from the tunnel in the geological report</u>

In the geological report for the detail plan of the project a few remarks were made about the use of the rock mass Larvikite from the tunnels, the rock mass hornfels was not mentioned in the report. The following remarks were made:

"The Larvikite normally has a high compressive strength and is not alkalin reactive. At the same time it has a low grade of mica minerals. This renders it to be likely usable as concrete aggregate.

The Larvikite is considered to have acceptable properties, to be used for filtration, frost protection and in reinforcement layers.

It is assumed that the Larvikite has mechanical properties that are close to the limit values for ballast." [64]

The directive given in the geological report was to perform tests in the next phase of the project, to deduce whether the rock mass could be used as ballast aggregate and for road pavement or not. The following tests that were supposed to be conducted in the next planning phase were:

- Los Angeles test
- Flakiness index test (Flisighetstest)
- Nordic Abrasion test (Mølleverditest)

It seems that these tests were never conducted, since no documentation of the test results exist. [64].

Farriseidet – Telemark border

Rock fill

The total capacity of the rock fills in the plan was 730.000 m^3 and had such an overcapacity of approx. 195.000 m3. This was deliberately planned for since experience shows that you should have a slight overcapacity for the flexibility to handle unforeseen extra masses.

The majority of the overbalance came from the Kleiver tunnel, therefore the landfills' location was preferred to be close to the tunnel, in order to ensure a cost and time effective production during excavation of the tunnel. However the location of the Kleiver tunnel is located in a valuable nature and recreation area which was considered to be an unwanted location for a landfill. The rock fill locations that were worked in to the detail plan of the project is presented in Table 16 [66].

Table 16: Rock fills in the detail plan for the stretch Farriseidet-Telemark border.

Deposit location	**Maximum capacity (m^3)**	**Area (m^2)**
Paulertjønn vest	122.000	16.700
Vassbotn vest 1	15.000	6.000
Vassbotn vest 2	30.000	5.000
Tjønnemyr	35.000	15.500
Solumn øst	160.000	15.000
Solumn vest	295.000	29.000
Skillingsmyr	17.000	5.500
Total maximum capacity	**674.000**	**92.700**

Transportation of excavated rock out of the project

As an alternative to a local fill within the project, transportation of masses out of the project to local recipients was evaluated. At the planning stage the following possible recipients were considered:

- Breivik Harbor, distance 27 km.
- Larvik Harbor, distance 14 km.
- Svartebukt dock in Mörjefjorden, distance 17 km.

Use of the excavated rock material as fill material in the line and for the superstructure of the railway

All of the excavated rock material was at the planning stage considered to be usable as fill material in the line or for leveling of the terrain. It was concluded that if the excavated rock mass were to be used for the superstructure of the railway, crushing and sorting equipment would be necessary. It was also concluded that if the excavated rock materials were to be used as ballast in the superstructure of the railroad the excavated rock material properties had to be tested thoroughly. No documentation or proof of that these tests were conducted has been found [67].

Telemark border - Porsgrunn

Rock fills

The total amount of excavated rock masses from the stretch Telemark border – Porsgrunn was 2.998.000 m^3. A total of 14 (initially 16) rock fills were placed along the line resulting in a total capacity of 3.770.000 m^3 of loose rock and had such an overcapacity of approx. 770.000 m^3. The excavated rock mass distributed on the separate key locations of the project is presented in Table 17. All the rock fills were located along the line within reasonable transportation distance from each of the excavation sites [66].

Table 17: Excavated rock volume (loose) presented for each of the separate excavation sites.

Location	**Volume (m^3)**
Skillingsmyr tunnel	837.000
Ønnsåsen tunnel	120.000
Storberget tunnel	1.164.000
Eidanger tunnel	477.000
Railway line in the open	400.000
Total	2.998.000

Transportation of excavated rock material out of the project

As an alternative to a local fill within the project, transportation of masses out of the project to local recipients was evaluated. At the planning stage it was considered to use the excavated rock material from the tunnels as filling material to create a new industrial area and at the same time cover a Mercury contaminated area of seabed in the Gunneklevfjord in Porsgrunn. Approximately 2.100.00 m3 of loose rock would have been needed for this purpose. This was however never realized due to holdups in the Gunneklevfjord project [66].

Use of the rock mass as fill material in the line and for the superstructure of the railway

No tests have been conducted to determine the usability of the rock mass as a construction material. As a part of the detail plan for the project, Sweco wrote a report with focus on how the project will be carried through, were the following remarks were made:

"Results from other locations with Larvikite shows that the rock mass generally is in the borderline, but it is assumed that it unlikely to be usable as ballast, that it has acceptable quality as a filter-, frost protection- and as a reinforcement- layer and that it has a good quality for use as a filling material. It is uncertain if the masses can be used as concrete aggregate and it is unlikely that the masses can be used for asphalt production." [68, p. 11].

9.2.2 Holmestrand-Nykirke

For details on the project, see Appendix A16.

<u>Geology Holm-Nykirke</u>

For the line between Holm and Holmestrand the dominating rock mass is the Ringerike sandstone, rockmasses that belongs to the Asker group; Schiffer, sandstone and conglomerate and rock masses that belongs to the B1-formation; Basaltic lava flows intervened with layers of red silt- and sandstone, tuff, agglomerate and lava conglomerate. Approximately 11% of the tunnel between Holm and Holmestrand will go through the Ringerik sandstone and about 86% of the tunnel will go through the B1-formation, most likely will the tunnel not come in contact with the Asker group.

For the line between Holmestrand and Nykirke, the dominating rock mass is magmatic basalt and rhomb porphyry of Permian age. The basalt consists of several lava streams that are assumed to have a thickness of 5-10 m. between the lava flows there most likely was a gap of time without lava flows, during this time gap the uppermost layer of the lava eroded and alien material transported through water and air sedimented on top. This period was then followed by a new period with lava streams. The creation process has created sub horizontal layers in the rock mass with a lower strength than the surrounding rock mass.

Both the Basalt and the Rhomb porphyry are strong rockmasses and can be suitable for construction purposes. However the creation process of which the Basalt at Holmestrand-Nykirke was created indicates that weaker layers exists in the rock mass.

Pre-investigations with regards to rock mass properties

The rock mass properties were investigated by testing of core samples from the different types of rock mass in the line. The test results are presented in Table 18.

Table 18: Results from analyses conducted on core samples with regards to the rock mass properties *[69]*.

	Rhomb porphyry	**Basalt**	**Sandstone**
DRI	34	30	44
BWI	33	45	43
Sound speed (m/s)	4954	4952	4664
Compressive strength (MPa)	285,5	249,3	273,4
S_{20} 11,2-16,0 mm	32,6	30,5	39
Flakiness	1,3	1,19	1,29
Packing value	0	0	0
Density (g/cm^3)	2,61	2,73	2,64
Siever's J-value (SJ)	14,5	8,7	28,9
Wear value hard metal (AV)	1,5	3,0	19,5

The results indicate that the Basalt, the Rhomb porphyry and the sand stone have strong mechanical strength and that they have a relatively high density. These properties are usually sought after when you want to use the rock mass as a construction material and the results indicate that the rockmasses could be used as construction material.

Based on results from analyses with regards to the quality of the masses that was conducted by Statens vegvesen in connection with the planned construction of E18, the masses were considered to be usable as bearing and reinforcement layers in road construction. No investigation or measurements of the rock mass, rock mechanical properties with regards to the use of the rock mass for railroad ballast was performed during the project. [69] [67].

Recommendations about the use of the rock mass from the tunnel in the geological report

No recommendation regarding the use of the rock mass has been found in the geological reports for the project.

Mass balance in the project

In the regulation phase the project consisted of two tunnels and Holmestrand station out in the open, for this phase in the project the following details was given regarding the mass balance and handling of masses.

For the regulation phase the total theoretical volume of solid excavated rock for the Grette tunnel was 700.000 m^3 and for the Ramberg tunnel was 820.000 m^3. With a swelling factor of 1.6 the volume of loose excavated rock was calculated to be 2.400.000 m^3.

After the regulation phase, decisions were made to change the line in order to meet the demands for a high speed line with regards to radius and curvature. Instead of having two tunnels and a station in the middle at Holmestrand, the project was now changed to consist of one long tunnel and a station in a mountain hall at Holmestrand.

The theoretical volume of solid excavated rock from the station was 550.000 m^3. With a swelling factor (sf) of 1.6 the volume of loose excavated rock was calculated to be 880.000 m^3. This resulted in that the amount of loose excavated rock changed from 2.400.000 m^3 to approximately 3.296 000 m^3, the numbers are presented in Table 19 [67].

Table 19: Volumes of excavated rock from Holmestrand- Nykirke, the volumes are presented in theoretical solid volumes and handled loose volumes, calculated with a swelling factor of 1.6.

	Volume, solid (m^3)	**Volume, loose (sf. 1.6) (m^3)**
Regulation phase		
Grette tunnel	700.000	1.120.000
Ramberg tunnel	800.000	1.280.000
Total	**1.500.000**	**2.400.000**
Construction phase		
Tunnel Holm-Nykirke	1.830.000	2.928.000
Holmestrand Station	230.000	368.000
Total	**2.060.000**	**3.296.000**

Rock fill

According to the reports from the project, it can be concluded that no permanent deposits within the project were established, instead almost all of the excavated rock was first temporary deposited within the project and then transported out of the project to several recipients. No detailed information has been found with regards to the capacity of the temporary deposits and reloading areas or how much area that had to be reserved for them [67].

Transportation of excavated rock out of the project

The main alternative presented in the regulation and construction phase for handling of the excavated rock material was to transport the masses to local quarries in the vicinity of the project. The masses could then be sold by the quarries as fill material or be processed in order to be used as ballast. The backgrounds for this choice were both the areal limitations with regards to few possible locations for deposits as well as environmental concerns and economic benefits. It was further considered to be visually favorable to deposit the masses in an existing quarry instead of establishing deposits in open grounds. There were three quarries in the close vicinity of the project that accepted to take the masses from the project, presented in Table 20.

Table 20: Local quarries were the masses were planned to be transported to, in the regulation phase.

Loose m^3, Total of 2.4 million.	**Hanekleiva Pukkverk**	**Solum Pukkverk**	**Skåne Pukkverk**
Site: Holm	392.000 (100%)		
Site: Sjøskogen		922.000 (100%)	
Site: Peter Pan		560.000 (50%)	560.000 (50%)

There were also limitations with regards to the workhours during the tunnel construction; Drilling and blasting were only permitted between 07:00 and 23:00 and loading and hauling outside the tunnel were only permitted between 07:00 and 19:00. Furthermore the transportation to the quarries would have a significant negative effect on the traffic situation in the area and would have to be conducted during hours with less traffic. This meant that temporary deposits had to be established within the construction site. The main site for temporary deposit was placed in the station hall and the widened tunnel connected to it, there was also established reloading areas at the crosscuts. After the construction work had finished the reloading areas would have to be emptied and the environment would be reestablished. An overview from the regulation phase over the planned transportation and the locations of the quarries is presented in Figure 12 [67].

Fra	Til	Avstand	Rutefarve	Se även tegn. nr.
Rambergtunnelen Påhugg Holm	- Hannekleiva pukkverk	8,5 km		UVB-50-X-22823, UVB-50-X-22827
Rambergtunnelen Tverrslag ved Sjøskogen	- Hanekleiva pukkverk - Solum pukkverk - Skaane pukkverk	15,1km 9,6 km 14,4 km		UVB-50-X-22824, UVB-50-X-22827, UVB-50-X-22828
Grettetunnelen Tverrslag Peter Pan	- Solum pukkverk - Skaane pukkverk	4,2 km 8,6 km		UVB-50-X-22825, UVB-50-X-22827, UVB-50-X-22829
Grettetunnelen Påhugg Nykirke	- Solum pukkverk - Skaane pukkverk	5,7 km 7 km		UVB-50-X-22826, UVB-50-X-22827

Figure 12: Overview over the transportation of excavated rock material from the project and the location of the quarries that can serve as recipients, from the regulation phase *[67]*.

After the change in the line the volumes changed in the project and no exact figures or details have been found on how much excavated rock material that was actually deposited at each of the quarries has been found. However, it can be assumed that the volumes were less since the author has been informed through contact with the project that during the excavation a significant part of the excavated rock material also was transported to the following recipients:

1. Drammen harbor – Fill material for expansion of the existing harbor.
2. Koppstad – Planned freight terminal.
3. E18 – material for road construction.

The E18 project was already in the regulation phase mentioned as a possible recipient. However it was also noted that the possibility that the two project could benefit from each other was connected with a great uncertainty since much of it depended on how well synchronized the two projects could be with respect to each other [67].

<u>Excavated rock material from the tunnel as a construction resource</u>

No information has been found regarding if any of the masses were used as fill material in the line or as construction material for the superstructure of the railway.

9.2.3 The Follo line

For details on the project, se Appendix A6.

<u>Pre-investigations with regards to rock mass properties</u>

The environmental burden of an infrastructure project with the size of the Follo line project is substantial. Therefore, the Follo line project imposes environmental requirements, in accordance to Norwegian laws, regulations and the corporate goals of the Norwegian National Rail Administration (NNRA). The possible reuse of the excavated material was considered in an early phase of the project and a substantial testing program with focus on the use of the material as spoil as quality fill was conducted.

A field investigation on predicting rock mass quality regarding building purposes (road, railway and concrete) was reported in December 2011 over 16 pages (Aas-Jakobsen). Seven surface samples from five locations along the tunnel line were collected and analysed. The report was published before the tunnel drilling method was decided, but one of the conditions for drawing conclusions have been drilling and blasting as tunnelling method. If we consider the volum of the report, the low number of places for rock sampling, and the fact that some of the conclusions are based on the use of wrong analyses (railway) and that the rock mass in some area is possible subjected to chemical weathering (not any topic in the report) based on quite high values for water absorption, it looks like that the very important subject ”application of excavated rock material” has been handled with a pretty light hand.

Table 21: Overview over all the performed tests and analyses. It was also conducted measurements on natural radiation (not in the table).

Prøve		Flisighets-indeks	Densitet	Absorbert vann	Innhold av risiko-bergarter volum%	Sammen-lignings-verdi	Sulfat-innhold	Svovel-innhold	Los Angeles - verdi	micro-Deval-verdi
Nr.	Sted/Bergart	FI	Mg/m^3	%	rb_{stein}	S_v	% SO_3	% S	LA	M_{DE}
1	Vestbrynet 14 Gneis	16	2,75	0,8	0,0	5,0	<0,002	0,23	40	22
2	Vestbrynet 14 Amfibolitt	26	3,08	0,6	0,0	5,0	<0,002	0,43	32	23
3	Kantarellen Gneis	19	2,67	0,7	0,6	6,2	0,005	0,18	34	14
4	Kantarellen, Amfibolitt	29	3,06	0,6	0,0	5,0	0,006	0,37	35	28
5	Taraldrud Gneis	23	2,68	0,6	0,0	5,0	0,006	0,14	30	13
6	Tårnåsen Gneis	21	2,77	0,7	0,0	5,0	0,007	0,13	38	15
7	Ødegårdsveien 10 Gneis	15	2,69	0,7	0,0	5,0	0,007	0,07	42	18
	Fraksjon analysert mm	0/30	8/30	8/30	1/2+2/4	1/2+2/4	0/30	0/30	10/14	10/14

Based on the results from the analyses of the excavated rock material, the following conclusions regarding the usability of the excavated rock material were made, presented in Table 22.

<u>Recommendations about the use of the excavated rock material from the tunnel in the geological report</u>

Several possible uses of the excavated excavated rock material were investigated in the planning stage of the project; a summary of the conclusions from these investigations is presented in Table 22.

Table 22: Conclusion about the usability of the excavated rock material from the project, based on the test results.

Construction type	**Usability**
Railway construction:	
- *Ballast*	No
- *Base*	Yes
- *Subbase*	Yes
- *Frost protection*	Yes
Road construction	To a limited extent
Concrete aggregates	Yes (but grain shape has to be improved by crushing)

Most of the excavated rock material from the Follo line project will be deposited in temporary deposits for later use as filling material. The following text is extracted from the geological report *Application of TBM spoil as quality fill for the Gjersrud/Stensrud township*, created by NGI for the construction phase of the project [70].

“Experience from former TBM tunnels in Norway show that TBM spoil is a good fill material. The particle size distribution is close to the ideal distribution for aggregates for fill and lean concrete (Füller's curve). In an ideal fill material, the fine particles shall barely fill the pores between the coarser particles. In TBM spoil, the fines content is slightly higher than the ideal fill, but the fines content is not so high that the coarse particles are "floating" in a matrix of the fines. In the case of TBM spoil, the coarse particles are in contact with each other and creating a stiff skeleton with high shear strength.

The TBM spoil is slightly water and frost sensitive. Consequently, the material must be handled with care from the time it is exiting the tunnel adits until it is placed and compacted in the platform. As long as the spoil does not soak up too much water nor freeze during handling before compaction, the criteria for compaction of quality fill can be easily satisfied. To avoid spontaneous collapse settlement upon wetting, experience show that the spoil should be compacted to minimum 95 percent of the maximum dry density when compacted on the wet side of optimum, and to maximum 5 percent air voids when compacted on the dry side, based on Standard Proctor.
The procedure for placement of the TBM spoil should be tested when the initial spoil becomes available. The guideline given for the test fill is to use four different layer thicknesses and vary the compaction effort to explore the optimal procedure (based on cost / benefit evaluations). An "Intelligent compaction" system should be applied for compaction and documentation of the "as built" properties.

A programme of control testing during the entire construction period should be established based on the results from the test fill. Inspection and control testing should be operative whenever spoil is being placed in the platform.
At the end of the placement of TBM spoil, the entire area should be characterised in terms of building ground properties. The control testing result plus a seismic survey should form the backbone for zoning of the platform with respect to the building ground properties. Light and medium heavy

structures may always be founded directly on the platform. However, for heavy structures, improvement of the ground, e.g. by dynamic compaction or by piling, may be required.

In summary the following conclusions may be drawn [71, p. 5]:

- TBM spoil has properties that make it well suited for construction of a "building platform".
- TBM spoil must be handled and placed under consideration of its properties, especially the water and frost sensitivities.
- Properties of TBM spoil do not have issues that will influence the future use of a "buildingplatform".
- TBM spoil should be considered as a material resource in any tunnelling projects”

Mass balance in the project

The Follo line project had focus on the handling of the excavated rock at an early stage in the project and performed an investigation with the topic of the handling of the masses, [72]. The investigation states that approximately 3.500.000 m^3 (9.2 million Ton) of solid rock has to be excavated, with a swell factor (sf) of 1.6 this corresponds to 5.600.000 m^3 of loose excavated rock material. The majority of the masses will be excavated within a period of 2.5 – 3 years. This indicates that approximately 160.000 – 190.000 m^3 of excavated rock material will have to be transported and deposited every month. The extra traffic burden in the most intensive part of the construction is estimated to be between 0.6 to 3.3 % in addition to the traffic level before the start of the project. The estimated cost for handling of the excess masses from the project was 467.000.000 NOK/2016. In the Oslo region approximately 10 million ton of rock is used every year and the Follo line project will be able to deliver approximately 9 million ton, this indicates that the masses should be viewed on as a resource [72], [73].

An overview of mass handling is presented in Table 23. The calculation is made on handled masses (transported and then compressed) but shows the relation between the different use of the masses. The swell factor that has been used for this calculation is unknown but it has most likely been calculated with a factor of 1.40 - 1.45. This also corresponds to the numbers of the solid volume [74].

Table 23: Summary of the project alternatives for deposits/use of the excavated rock material *[74]*.

Planned deposit/use	**Volume (m^3)**
Transported out from the project at Åsland to external deposits.	2.000.000
TBM masses + blasted rock. Used as filling in the line at Åsland.	750.000
Unregulated for.	700.000
Deposit in the closed quarry at Åsland	1.100.000
Concrete production for the tunnel.	400.000
Total sum	**4.950.000**

Rock fill

Since the choice of excavation method was a TBM machine, the majority of the masses will be of a finer fraction which to a lesser extent can be put to use for other than filling material. The strategy in the project was to deposit as much of the excavated rock material as possible at a temporary deposit in the closed quarry at Åsland in order to minimize the cost and environmental burden that the transportation will impose. These masses can later be used as filling for the planned township Gjersrud –Stensrud. It was also considered that the excavated rock material could be crushed and treated so that it eventually could be used in the superstructure and as ballast in the line [74].

Transportation of excavated rock material out of the project

A total of 3.100.000 of excavated rock will be placed in deposits. Approximately 2.000.000 m^3 will be deposited in external deposits and approximately 1.100.000 m^3 of excavated rock will be placed in a temporary rock fill at Åsland which will be able to serve the project, *New Townhip Gjersrud – Stensrud* with filling material [74] [72].

Excavated rock material from the tunnel as aggregate for concrete

Approximately 400.000 m^3 of excavated rock will be crushed and treated for use as aggregates for concrete in the tunnel.

9.2.4 E6-The Dovre line (Mjøsa)

For details on the project, see Appendix A7.

Geology

The road and railway line both runs along the lake Mjøsa and crosses a number of different types of rock masses with varying width and properties which make it difficult to store the stone masses in units with similar quality regarding mechanical strength. The area consists of middle to coarse grained red granitic gneiss and augen gneiss, granodioritic augen gneiss with biotite and amphibole (middle to coarse grained minerals), metamorf sedimentary rocks like middle to fine grained mica-schist, meta-greywacke, quartzite and meokose.

Pre-investigations with regards to rock mass properties

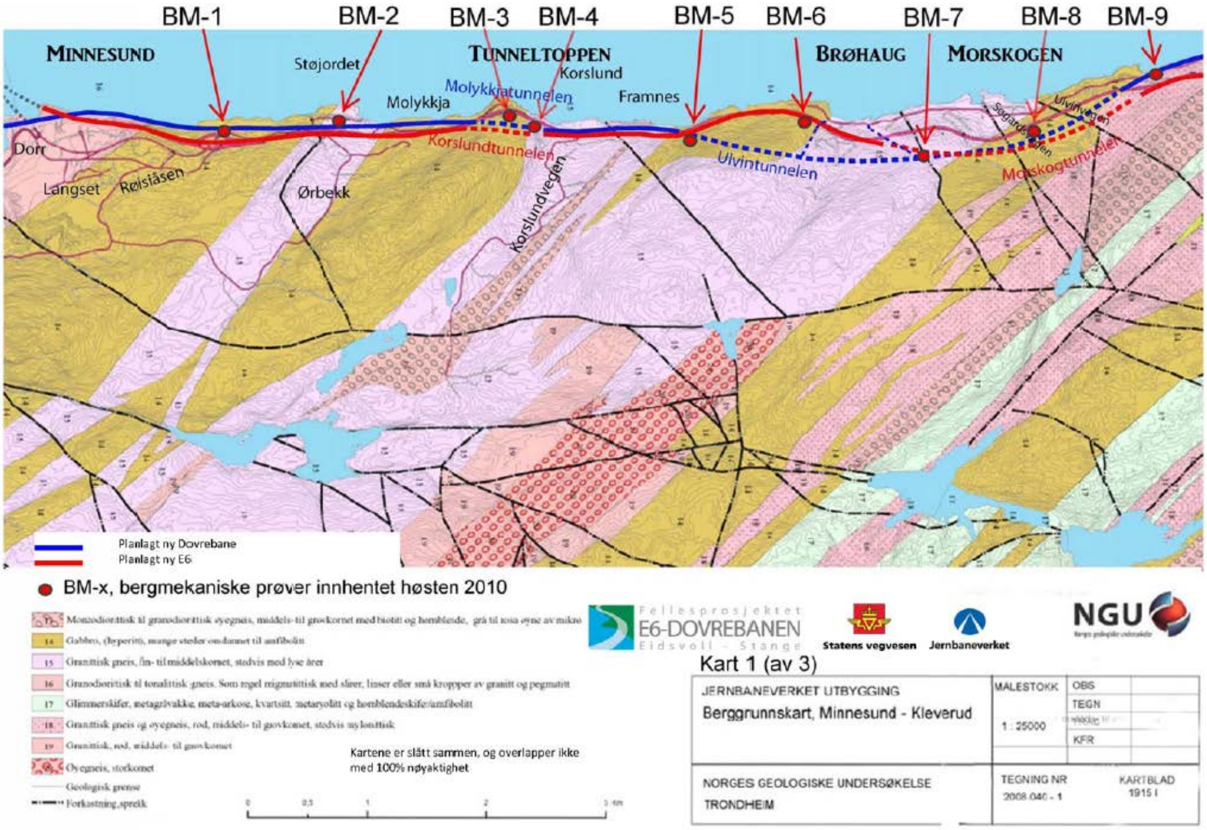

Figure 13: Bedrock map M 1:12500 (example, part one of three), NGU.

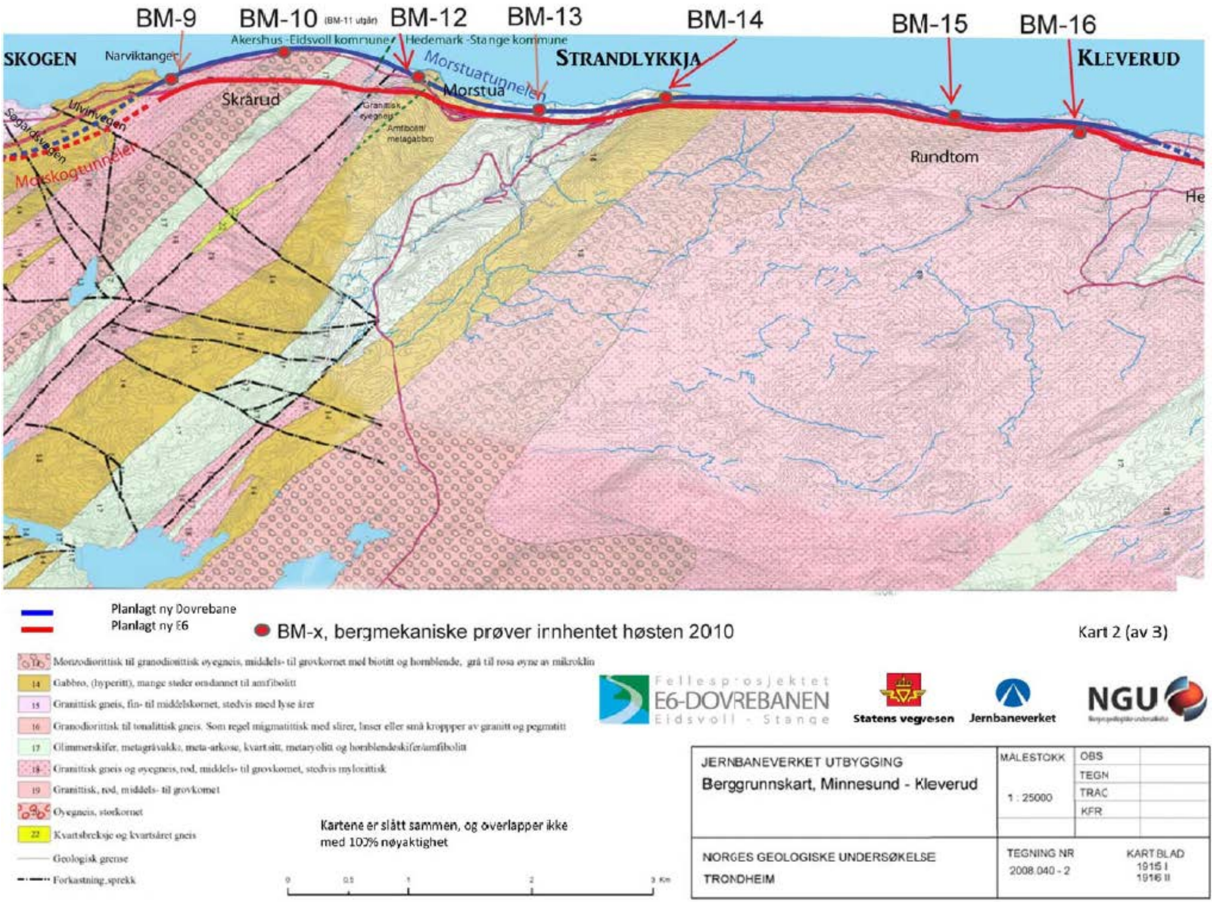

Figure 14: Bedrock map M 1:12500 (example, part two of three), NGU.

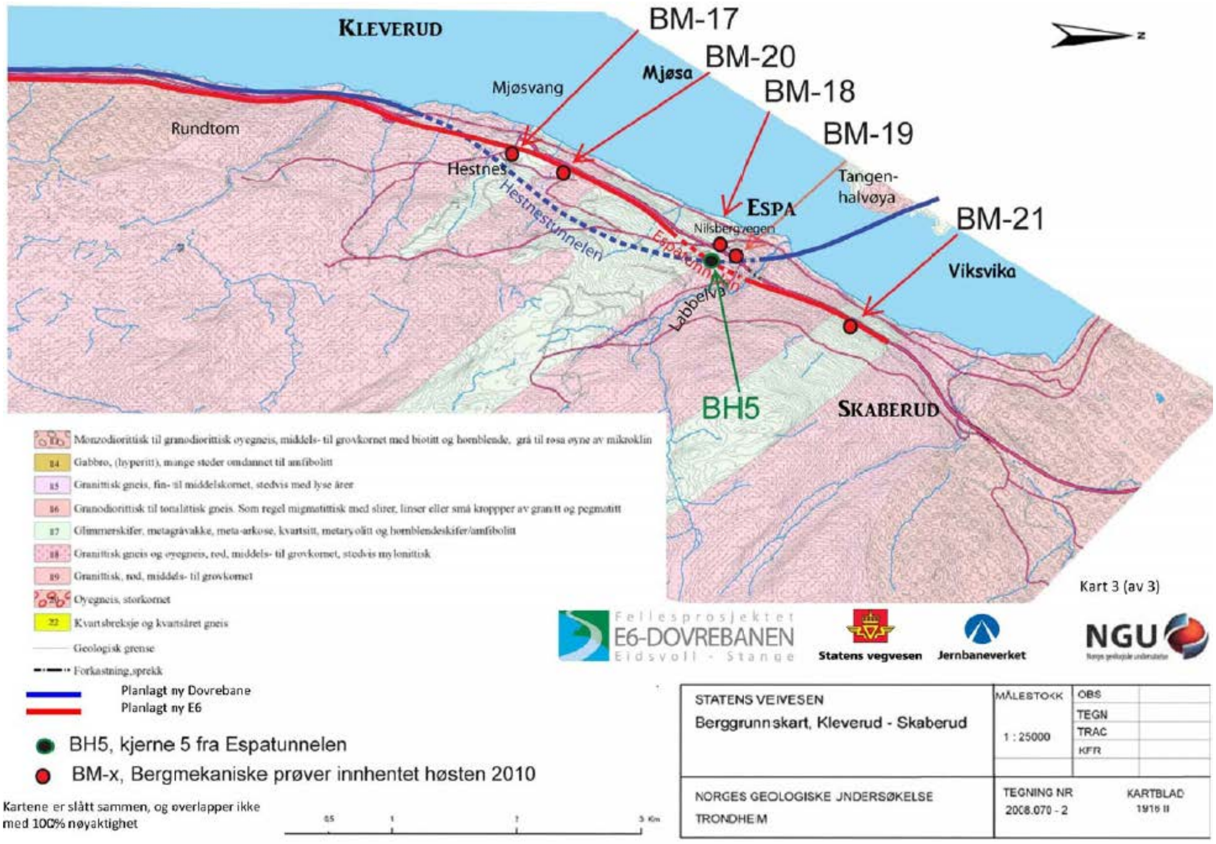

Figure 15: Bedrock map M 1:12500 (example, part three of three), NGU.

Recommendations about the use of the excavated rock material from the tunnel in the geological report

The project has investigated a lot of work in mapping bedrock properties with regards to construction purposes. This includes both samples from rock surface, mapping of rock cuttings and from drilled rock cores. This is far more than what is usual. The final report from February 2011 covering the laboratory analyses consists of 150 pages.

However no report has been found, that describes the potential of using the excavated rock material for other purposes than as fill material. No documentation has been found that proves that the project planned to use the excavated rock material as construction material. The high reuse of the excavated rock material in the project can likely be explained with that several areas were reserved for deposits of excavated rock material and that there were a great need for construction of new local roads. The possibility to reuse the excavated rock for these purposes was further enabled by the fact that the line cuts through scarcely populated areas and runs parallel to the existing road and railway.

Mass balance in the project

The total volume of blasted rock is calculated to 5.200.000 m^3 of loose rock included both tunnels, railway and road cuttings.

Rock fill

The excavated rock that was sent to rock fill was deposited at a temporary rock fill at Eidsvoll along with several deposits along the line. No exact figures of the volumes that have been sent to rock fill have been found, but 800.000 m^3 have been stored at temporary deposit at Kolomoen and is planned to be used at the neighboring E6 infrastructure project (Strandlykja – Kolomoen 21 km).

Transportation of excavated rock out of the project

E6 Strandlykja – Kolomoen with filling material.

Excavated rock material from the tunnel as a construction resource

Several tests were performed in the planning stage and the results were implemented in the contract documents so that the contractors could decide wether they wanted to crush or buy ballast, all the contractors choose to crush the fractions 8 – 12 and 0 – 250 at site. Application has been embankments for roads and railway, frost protection course, subgrade course as well as concrete purposes. Aggregates for asphalt and railway ballast has been taken from elsewhere, including *Hamar pukk og grus* at Sørli.

250.000 m^3 of construction concrete was produced at the site.

Table 24: The usability of 20 examined rock samples.

NBTL's nummerering 10266-	Jernbaneverket nummerering BM	Tilstandsklasse (klif)	Betongtilslag: Inneholder klorid	Betongtilslag: Alkalireaktivt	Jernbaneballast: Krav oppfylt	Veidekke: krav oppfylt	Vei: Bærelag: krav oppfylt	Vei: Øvre forsterkings-lag: krav oppfylt	Vei: Nedre forster-kingslag: krav oppfylt
1	**1**	3	nei	nei	ja	nei	ja	ja	ja
2	**2**	1	nei	nei	ja	nei	ja	ja	ja
3	**3**	1	nei	nei	ja	nei	ja	nei	ja
4	**4**	1	nei	nei	ja	nei	ja	ja	ja
5	**5**	2	nei	nei	nei	nei	nei	nei	nei
6	**6**	2	nei	nei	ja	nei	ja	ja	ja
7	**7**	1	nei	nei	ja	nei	ja	ja	ja
8	**8**	1	nei	nei	ja	nei	nei	ja	ja
9	**9**	1	nei	nei	ja	nei	nei	ja	ja
10	**10**	1	nei	nei	ja	nei	ja	ja	ja
11	**12**	1	nei	ja	ja	nei	ja	ja	ja
12	**13**	1	nei	nei	ja	nei	ja	ja	ja
13	**14**	1	nei	nei	ja	nei	nei	ja	ja
14	**15**	1	nei	nei	ja	nei	ja	ja	ja
15	**16**	1	nei	nei	nei	nei	ja	ja	ja
16	**17**	1	nei	nei	ja	nei	ja	ja	ja
17	**18**	3	ja	nei	nei	nei	nei	nei	nei
18	**19**	1	nei	ja	ja	nei	ja	ja	ja
19	**20**	1	nei	ja	ja	nei	ja	ja	ja
20	**21**	1	ja	ja	ja	nei	ja	ja	ja

9.3 Positive and negative experiences

Based on the results from this study the following conclusion can be drawn. All of the tunnel projects that have been analyzed in this study have excavated tunnels partly or completely through bedrock with rock mass which are generally considered to be competent. Most of the projects have conducted tests to determine the rock mechanical properties with regards to excavation issues. From these test results it can be confirmed that a majority of the rock mass which have been excavated have properties such as for example high density and high strength. These are novel properties for excavated rock material and the utilization degree as aggregate.

However, it would seem that the general view on the excavated rock material from the tunnels is that it is a burden for the project rather than a resource that actually can be put to use within the project. The emphasis on investigations and tests that can deduce if the excavated rock material can be used as a construction material is nearly nonexistent in the planning stage.

During this study several statements and recommendations has been found in the documentations from the regulation phase, where thorough investigations of the rock mass mechanical properties was recommended to be conducted during later stages of the planning process. In the Follo line project, the ambition to treat the excavated rock material as a resource was emphasized in the project already from the start and therefore investigations to deduce the usability of the excavated rock material were conducted at an early stage of the planning process.

10 Literature

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Appendix 1 Information on example projects

A17 Lyon-Turin

General information

Owner	Reseau Ferre de France/ Rete Ferroviaria Italiana
Length	300 km
Start of the construction	2008-2010
End of the construction	2018/2020
Volume masses	60 million tonnes
Diameter	2 parallel tubes of 8,40 m diameter
Total production of aggregates	12,5 million tonnes
Saving time	1 hour

The rail link project between Lyon and Turin is a major part of the European 5 corridor between Lisbon and Kiev. The use of the excavated material from two of the main tunnels, Chartreuse Tunnel and Maurienne-Ambin Base Tunnel is described by Burdin and Monin [41].

The project has been split into three sections. France is tasked with building a 75 km high-speed passenger railway between Lyon and Chambery, plus a freight line between Lyon and la Combe de Savoie and a passenger and freight line between la Combe de Savoie and Saint Jean-de-Maurienne totalling 120 km. This stage is being managed by Reseau Ferre de France (RFF).

Italy's Rete Ferroviaria Italiana (RFI) is building the section between Turin and Bruzolo to create a connection with the southern portal of the base tunnel. This forms part of the common French-Italian section of the route, and is being project managed by Lyon Turin Ferroviaire (LTF)

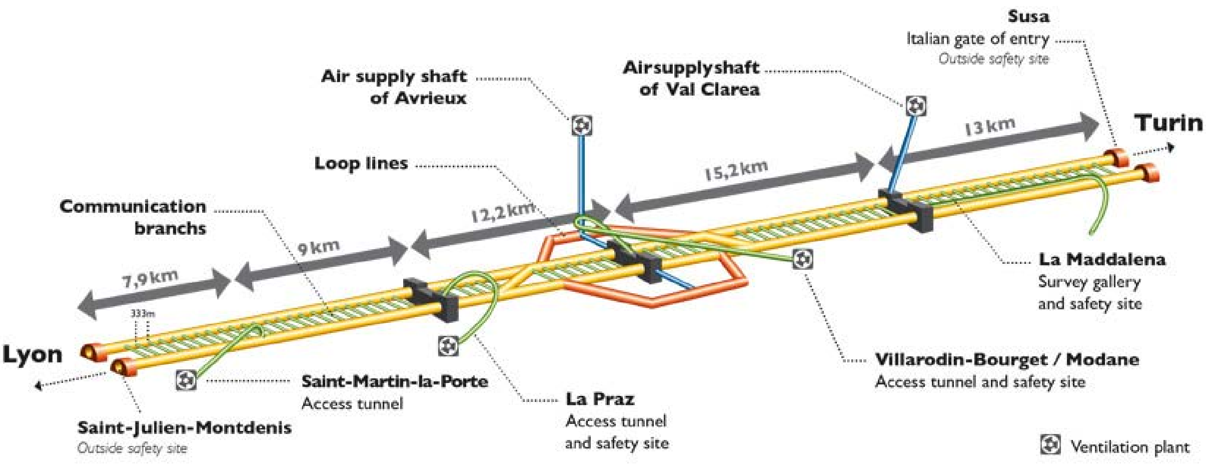


Figure 16 Section of the infrastructure. Source: http://www.tunneltalk.com

Driving method

The drilling methods in this project are both **Drill & Blast** and **TBM**.

A brief explanation of how **Drill & Blast** method work follows:

- Grouting: 21-24 meter long drilled holes around the tunnels section. Concrete mass is pumped into the holes under high pressure. The cracks are sealed thereby in the mountains where the tunnel will be blasted, so that groundwater does not leak into.

- Drilling and charging: It drilled approximately 5 meter long hole being charged with explosives. Drilling and charging take place simultaneously with the same machine. There are arms going in and charging holes gradually, while new ones are being drilled.

- Blasting: to reduce the chattering of the surface divided each burst into many small bursts. They fired in rapid succession (5-6 milliseconds between each). The ointments adjusted according to the environment and the mountain nature.

- Charging: the blasted mountain masses are loaded onto dump trucks and transported to a storage area outside the tunnel area. Here the material is transferred to masses trucks before they are transported to the delivery point.

- Scaling and securing: resolved mountain pigged down with a large hydraulic hammer. To avoid bad conditions, it is necessary to secure the roof and walls with bolts, shotcrete or reinforcement arcs. Afterwards, the geological conditions of the mountain have to be checked, in case of necessary safeguards.

On the other hand is **TBM method**:

- Tunnel Boring Machine (TBM) method TMB is used as an alternative to drilling and blasting (D&B) methods.

- TBMs are used to excavate tunnels with a circular cross section through a variety of subterranean matter; hard rock, sand or almost anything in between.

- As the TBM moves forward, the round cutter heads cut into the tunnel face and splits off large chunks of rock. The cutter head carves a smooth round hole through the rock -- the exact shape of a tunnel. Conveyor belts carry the rock shavings through the TBM and out the back of the machine to a dumpster. Tunnel lining is the wall of the tunnel

- It consists of precast concrete segments that form rings, cast in-situ concrete lining using formwork or shotcrete lining

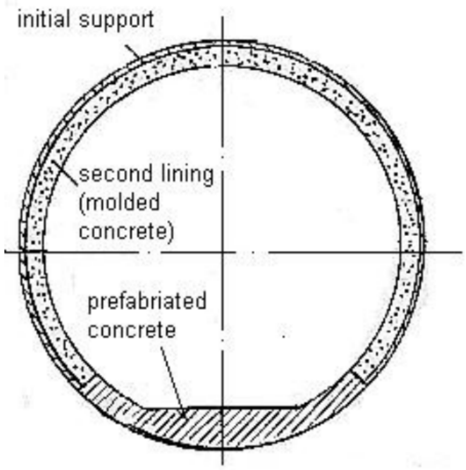


Figure 17: Section of a TBM tunnel *[75]*.

Characteristics and use of the material

The excavated material is slip into three classes where only the material from class 1 is used for concrete production.

In the Chartreuse tunnel, the masses consist of limestone, marls and mollasse.

Only the limestone was found acceptable for use in concrete, generating 1 269 000 tonnes of aggregates for the production of concrete linings and tunnel segments. This corresponds to 25% of the total masses excavated.

In the Maurienne-Ambin Base Tunnel, the materials gneiss, shale, mica schist and sandstone are present, and a total of 10 215 000 tonnes aggregates and 4 873 000 m3 concrete were produced

Other specifications

Some 90% of the 72km route will be through the mountains.

Boring will take place from 17 points and it will take a total of five-and-a-half years to complete construction, with up to another three years to equip the tunnel with ventilation and safety measures, and carry out testing.

The base tunnel through the Alps is to be bored at an altitude of 570–750m above sea level, with a maximum gradient of 12%, a much easier climb for trains than the 30% through the current Mont Cenis tunnel.

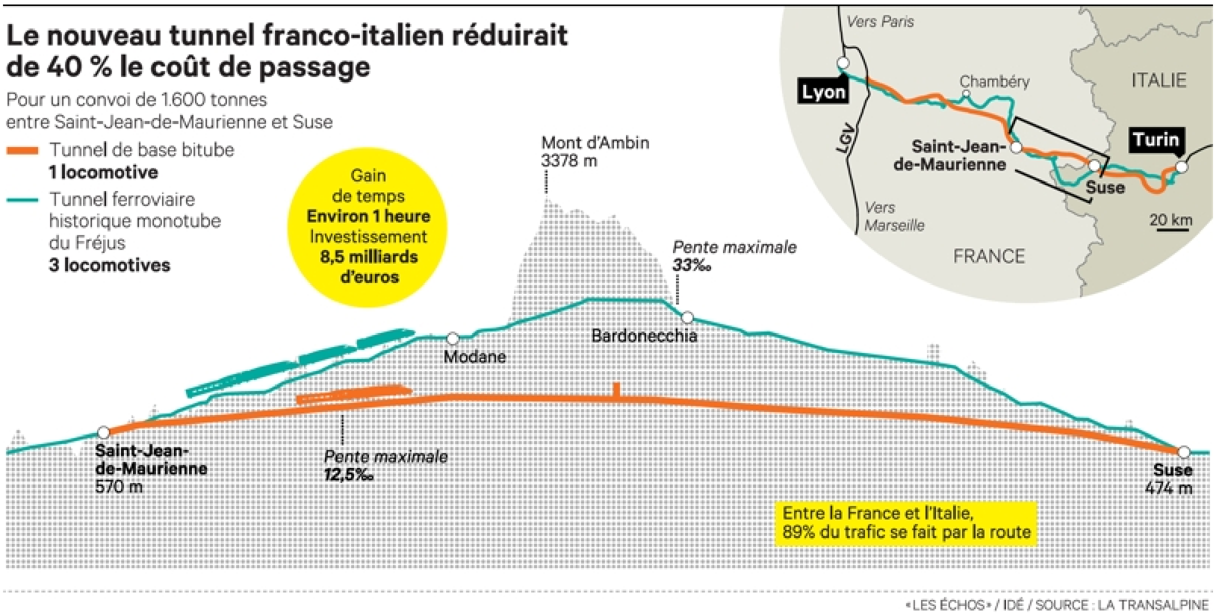


Figure 18: Profile of the tunnel *[76]*.

A18 Gotthard Base Tunnel

General information

Owner	Alp Transit Gotthard, Swiss Federal Railways (SBB).
Length	57 km
Start of the construction	1999
End of the construction	2016
Volume masses	28 million tonnes
Diameter	8,8-9,5 m
Total production of aggregates for concrete	9 million tonnes

June 1st 2016, the world's longest railway tunnel, the Gotthard Base Tunnel in Switzerland opened. The tunnel consists of two 57 km long parallel tunnels with a diameter between 8,8-9,5 meters [44] [77].

Driving method

Large parts of the tunnel were excavated with TBMs, but the drill&blast method was also employed in some sections.

Four tunnel boring machines excavated almost 75% of the Gotthard Basel Tunnel, with blasting used for the remaining 25%. The choice of tunnelling method depended not only on the expected rock conditions, but also on development opportunities, environmental conditions and economic realities. The length of the route and the planned overall construction period also played a role. Tunnel boring machine: A tunnel boring machine with a drilling head diameter of up to 9.5 m and driving equipment is approximately 450 m in length. A single tunnel boring machine costs about CHF 30 million. These machines are particularly suitable for longer routes, as the procurement and

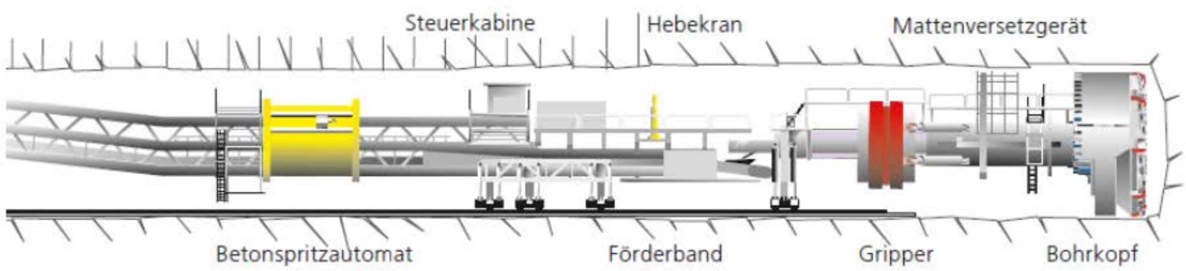


Figure 19: Tunnel Boring Machine TBM *[78]*.

Characteristics and use of the material

In Figure 20, the storage area at the Ertsfeld-part of the tunnel is shown. This large storage was a necessity due to the operating time regulations [44]. 90 % of the material transport was provided by conveyor belts, train or on water, which are considered as environmentally friendly transportation methods [77].

Figure 20: Storage area at Ertsfeld.

More than 90% of excavated material was recycled to produce concrete mixes for the tunnel lining, as landfill for a shallow water zone in the Uri lake basin (nature reserve and swimming area), to create a lake in Sedrun and to backfill material extraction areas below Faido and in Buzza di Biasca.

The exact geological conditions inside a mountain range are difficult to predict. Tunnelling comprises the latest exploration techniques and test bores supported by forecasts from experienced geologists in order to keep risks to a minimum.

The 57 km Gotthard Base Tunnel traverses three main mountain ranges (the Aare Massif, Gotthard Massif and Pennine gneiss zone) and two intermediate areas with diverse rock strata, ranging from hard granite to partly crushed sediment. The two intermediate areas constituted a major challenge. Geologists suspected a 'floating rock mass' in the Piora Basin, a water-saturated, sugar-like dolomite that is under high pressure with risk of leakage. However, preliminary boreholes showed dry conditions at tunnel level. As a result, the miners encountered no problems when boring through the Piora Basin in autumn 2008. The Tavetsch intermediate massif was the second critical formation. Geologists expected to find rock layers created through strong pressure in this area, which led to plans for an additional intermediate heading. People, materials and machines were able to reach the tunnel construction site and the multifunction station in the mountain via a 1 km horizontal access tunnel and two 800 metre shafts. Blasting work was carried out at the bottom of the shaft in both tunnel bores at the north and south ends. As the high mountain overlay and strong pressure threatened to deform the tunnel bores, a special reinforcement structure was necessary. The engineers developed a novel, innovative concept with flexible steel arches that pushed together under pressure of the rock and thus prevented deformation of the finished structure.

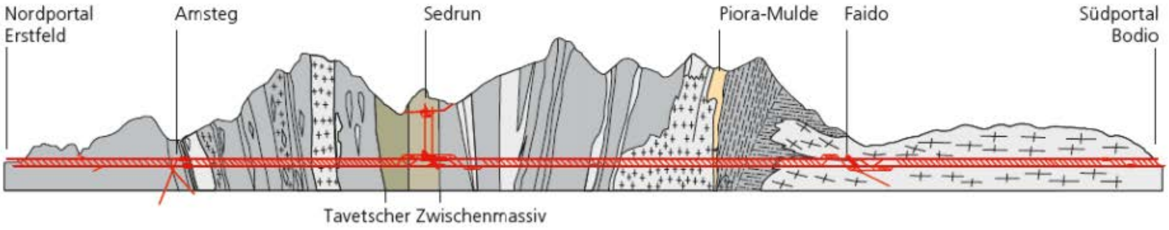


Figure 21: Section of the geological structure of the mountain *[78].*

Technical innovations

According to Thalmann et al. [43], the project led to several innovations in the tunnelling and material industries. It contributed to the development of superplasticizers for concretes with high contents of mica, and it demonstrated the possibility to produce concrete with 100 % crushed aggregate. The project also accelerated technical improvements when it comes to grain rounding (hurricane) and sand-sizing devices. Finally, a method to remove mica from the aggregate was established. The 0/1 mm fraction of the sand was washed with water and collectors in a flotation cell. The phyllosilicates adhere to the collector and segregate to the surface where the foam is evacuated by overflow. This method reduced the content of mica by more than 50 % in the 0/1 mm fraction [43]. For the Sedrun section of the tunnel, muscovite gneisses were found, which were reduced by minimal flotation from 40 % to below 20 % [44].

In total, these innovations enhanced the material recovery rate to up to 80 % [43].

Other specifications

The construction process itself was designed to be as environmentally friendly as possible

Air pollution was kept low by transporting materials primarily via conveyor belts, rail and ship.

Residents were protected from dust and noise by temporary topsoil embankments and noise barriers, and restricted operating hours on the construction sites. To prevent the release of dust into the air, non-asphalted construction areas were irrigated and streets and vehicles were cleaned on a regular basis.

Mountain and tunnel water was processed and cooled according to statutory provisions before being reintroduced into rivers. Streams affected by the construction of the tunnel and access routes were diverted and partially upgraded beyond the existing perimeter (e.g. Walenbrunnen stream, Erstfeld/Schattdorf).

As construction work also affects the habitats of flora and fauna, compensatory measures were implemented. Cleared trees were replaced with habitat, streams rehabilitated and riverbank areas renaturalised. Temporary use areas were restored to their original condition.

A19 Linthal 2015 Project

General information

Contractor	Joint Venture: Marti AG, Kraftwerke Linth-Limmern AG & Axpo AG
Depth/high	1800-2500 m above sea level
Start of the construction	2010
End of the construction	2015
Total amount of concrete	250000 m^3
Diameter	8 m

Driving method

Among the methods that were used were both TMB and Drill & Blast.

The heading equipment for a 4 km long inclined shaft at the project power plant Linthal 2015, consisting of a tunnel boring machine with 8 m diameter and a back-up installation of 160 m length, requires extraordinary qualifications from the equipment manufacturer.

Characteristics and use of the material

The excavated material was mainly limestone without any siliceous content, and the amount of mica was negligible. The material was therefore well suited for the production of aggregates.

Crushing and screening plants were established at two locations. One of them was a wet processing plant. To compensate for the low content of fines in the washed manufactured sand, this was mixed with a dry manufactured sand with an easily-controllable fines content. Crushing and screening plant number two was established as a dry processing plant.

The location of the constructions 1800-2500 meters above sea level required careful handling of the resources, and in particular the aggregates as the only access to the principal construction site was by cableway. Therefore, excavated materials were transported to the highest construction site by conveyor belts up to two years in advance.

Other specifications

Linthal 2015 is one of Axpo’s most important expansion projects. A new underground pumped storage plant will pump water from the Limmern Lake up to the Mutt Lake, located 630 metres higher up, and, if needed, use this water to generate electricity.

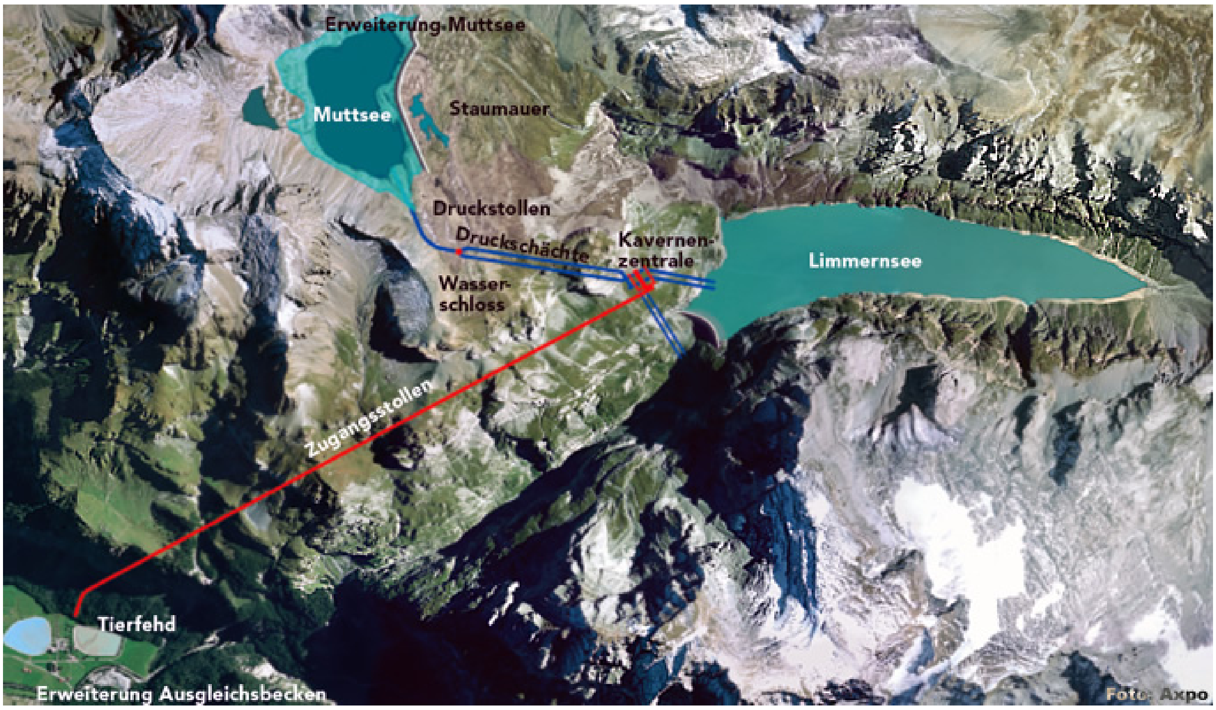


Figure 22: Overview of the project *[79]*.

A20 Koralm Tunnel

General information

Owner	ÖBB Infrastruktur
Length	32,9 km
Start of the construction	2011
End of the construction	2019
Volume masses	8,6 million tonnes

Driving method

The tunnel construction is divided into three main sections: KAT1, KAT2 and KAT3. The KAT1 constitutes the east entrance of the tunnel in Styria and includes a 3.2km open land route, four bridges and a 2.3km tunnel section built by drilling and blasting using the New Austrian Tunnel Method (NATM) or Sequential Excavation Method (SEM). Construction of this section began at the end of 2008 and was completed in October 2013.

Construction of the KAT2, the middle and longest section with an approximate length of 19km, began in January 2011. Two single-track main tubes, namely the North and South tubes, are being built using two 9.9m hard rock Doubleshield TBMs. The tubes will be connected by cross passages every 500m. Scheduled for completion in 2019, the KAT2 section also involves a 900m-long underground emergency station in the central part of the tunnel.

The KAT3 involves widening of the existing 7.6km-long sounding tunnel and building an additional 3.3km of new tunnel for the South Tube. The 12.6km-long North tube will also be drilled using a TBM. Construction on this section began in 2014 and is expected to continue through 2020.

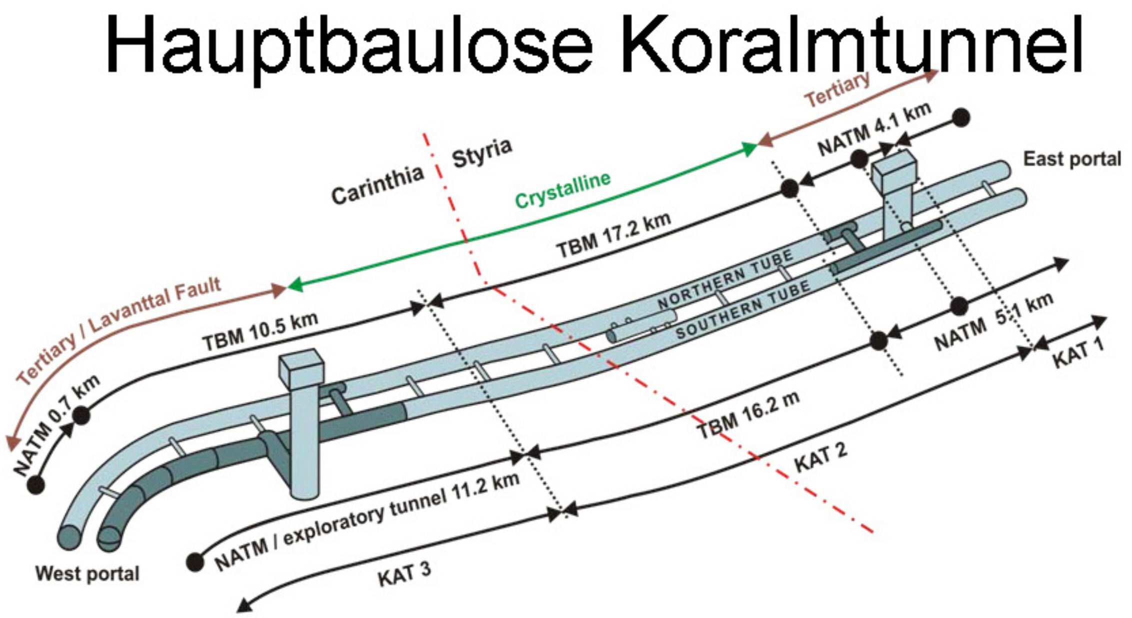


Figure 23: Overview of the tunnel *[80]*.

Characteristics and use of the material

The Austrian Railways ÖBB has decided to recycle the excavated material so that it can be used as aggregate in the concrete segments and tunnel linings. The total amount of excavated material is approximately 8,6 million tonnes, and it consists of schistose gneisses and gneisses with inclusions of mica schist, amphibolites and marbles. The average content of mica is 25 %. Concrete of quality C35/45 and C25/30 is produced.

The TBMs have crushers that produce 0/150 mm which is split into the fractions 0/16 mm and 16/150 mm. The 16/150 mm fraction is sent to the processing plant where it is crushed and cubified into the fractions 0/3 mm, 3/8 mm, 8/16 mm and 16/32. The 3/8 mm, 8/16 mm and 16/32 mm fractions are wet sieved, and can be seen in Figure 24. The grading curve for the 0/3 mm fraction is given in Figure 9.

Figure 24: Fractions 3/8 mm, 8/16 mm and 16/32 mm [46].

Other specifications

The Koralm tunnel will be composed of two tunnels running in parallel, each capable of carrying a single railway track, which will be linked together every 500 metres (1,600 ft).

An emergency stopping point at the middle of the tunnel is included in the plans.

A21 Brenner Base Tunnel

General information

Owner	BBT SE
Length tunnel	55 km
Start of the construction	2008
End of the construction	2026
Volume masses excavated	11,1 million m^3
Aggregates for concrete	2,35 million m^3
Diameter of the tunnel	8,1m; two tunnels + exploratory tunnel 5m diameter
Reduction time	From 2 hours to 50 min

Driving method

The driven method used in this project is TBM.

Characteristics and use of the material

Voit and Zimmermann [47] performed concrete mixes with three types of aggregates from the excavation masses. The three aggregate types were quartz phyllite, schist and central gneiss as shown in Figure 25.

Figure 25: Aggregates used in concrete mixes by Voit and Zimmermann *[47]*. (a) quartz phyllite, (b) schist, (c) central gneiss.

Other specifications

A peculiar feature of the Brenner Base Tunnel (BBT) is the exploratory tunnel running from one end to the other. This tunnel lies between the two main tunnels and about 12 m below them and with a diameter of 5 m is noticeably smaller than the main tubes. The excavations currently underway on the exploratory tunnel should provide information on the rock mass and thereby reduce construction costs and times to a minimum. The exploratory tunnel will be essential for drainage when the BBT becomes operational.

Both main tunnels are linked every 333 m by connecting side tunnels. These are safe areas in which passengers can find refuge and reach the other tunnel. From there, a rescue train can bring them to one of the three emergency stations. An access tunnel leads from these underground stations to the open air.

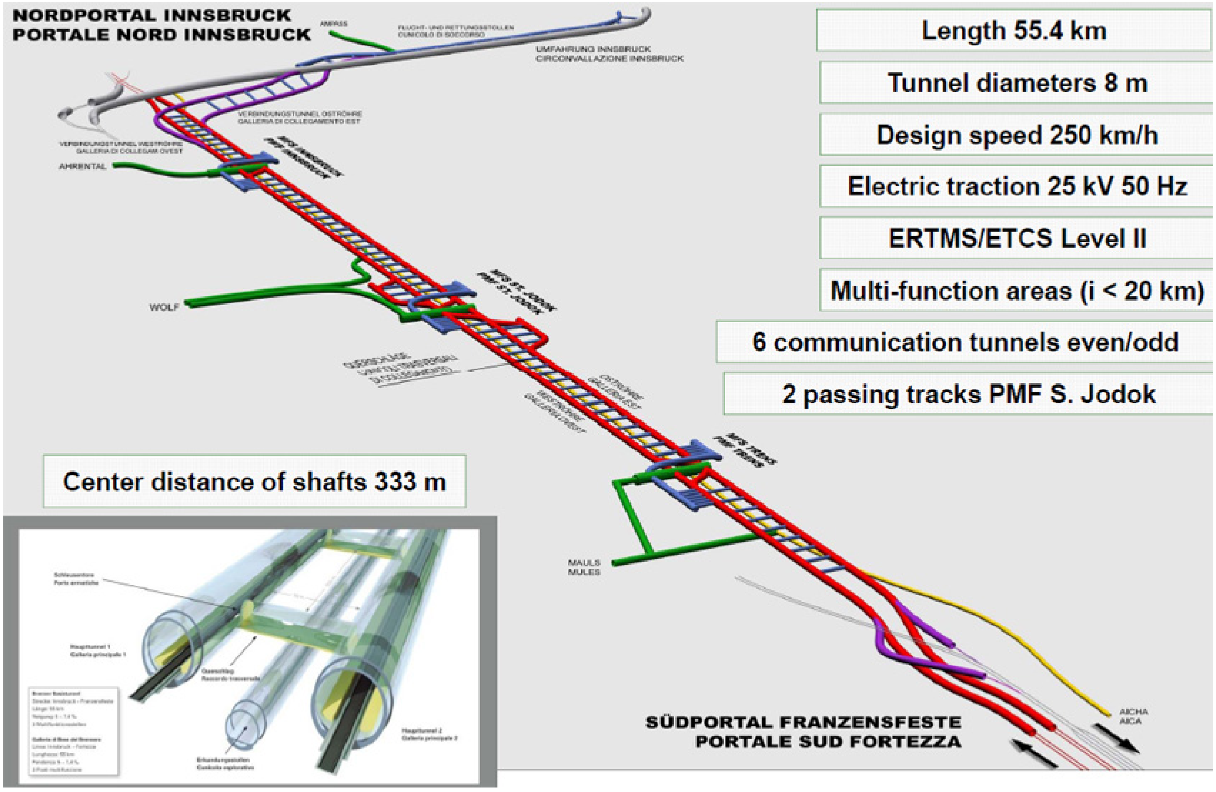


Figure 26 Overview of the tunnel *[81]*.

A22 Follo Line Tunnel (Follobanen)

General information

Owner	Bane NOR
Length tunnel	20 km
Start of the construction	2015
End of the construction	2021
Volume masses	5.6 mill m^3 loose rock
Total production of concrete (3 plants)	500.000 m^3

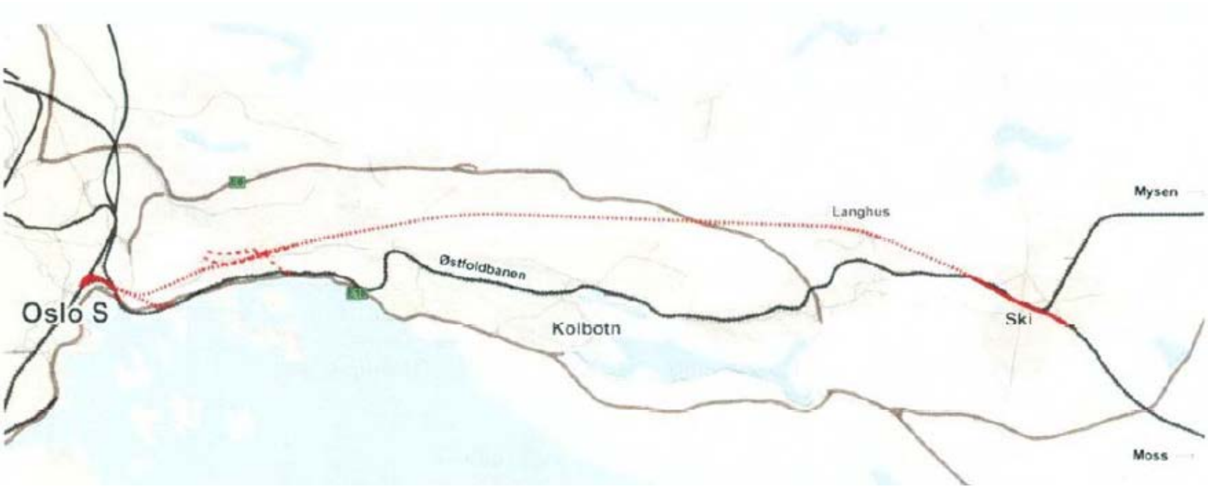


Figure 27: Overview over the Follo line project (Jernbaneverket).

Driving method

Due to the special characteristics of this project, different driving methods have been used in each one of the parts of the project.

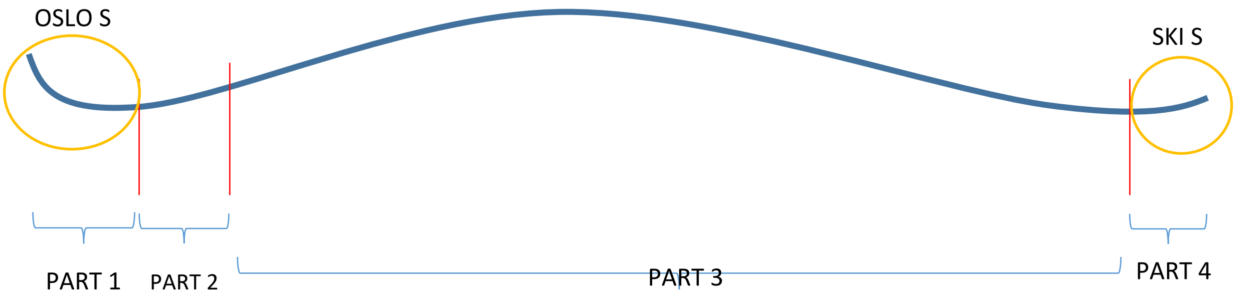


Figure 28: Profile of the tunnel.

PART 1: Concrete tunnel.

In the area of Oslo, the solution applied was a concrete tunnel.

PART 2: Drill & Split

This method is used in order to avoid explosive shacking. The tunnel is going through the city and it is convenient to avoid unnecessary dangers that can affect to the stability of the surroundings.

PART 3: TBM

TBMs are used to excavate long tunnels with a circular cross section.

They use 4 TBM, all of them start in the middle, 2 each direction.

The access from the surface to the tunnel level is done through Drill & Blast

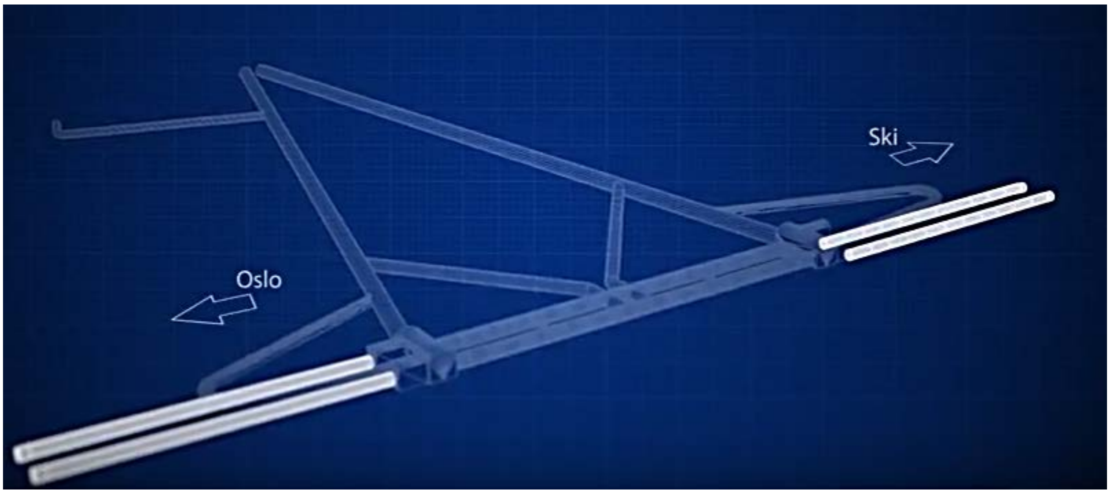


Figure 29: Section of Follobanen start point *[82]*.

PART 4: Cut & Cover

This is a method of tunnel construction where a trench is excavated and roofed over. Strong supporting beams are necessary to avoid the danger of the tunnel collapsing.

The basic steps are:

a. Cut & Blast
b. Concrete tunnel
c. Cover the concrete tunnel with the rock and material obtained from the previous blast.

Geology

The excavated rock material of the project area consist predominantly of Precambrian gneisses. A significant number of intrusives from the Perm period, as well as amphibolite dykes/sills occur. The amphibolite dykes/sills are more prevalent in the project area than the Permian intrusives. Most dykes/sills are a few meters thick, a few thicker than 10 m. Sedimentary shale occur in a very short part in the North toward Oslo Central Station.

The Precambrian gneisses which occur in the project area are divided into the following three main groups; Tonalitic - to granitic gneiss, Quartz-feldspathic gneiss and Biotitic augen gneiss.

Tonalitic- to granitic gneiss is a group of gneisses where the difference in the composition of feldspars is designating the different lithology's. Tonalitic gneiss consists of about 30% quartz, 40% feldspar, 20% biotite, and various accessorial minerals, including chlorite and muscovite. Granitic gneiss contains about 30% quartz, 65% feldspar,5% biotite plus, accessorial minerals. Tonalitic gneiss has a dark color while granitic gneiss is lighter gray. The reason for the color differences lies in the variation in contend of dark micas. Quartz- feldspar rich gneiss is termed supracrustal gneiss because relict sedimentary structures are present. This lithology typically contains 40% quartz, 50% feldspars of different variations. Dark micas (biotite) are the dominating dark mineral, but a number of other minerals occur accessorial. Biotite rich augen gneiss contains 25% quartz, 60% feldspar, 10% biotite and garnet. The lithology is described as homogeneous and grey, with 2-4 cm long eyes of feldspar and in some places with several cm large garnet minerals. The foliation is well developed [50].

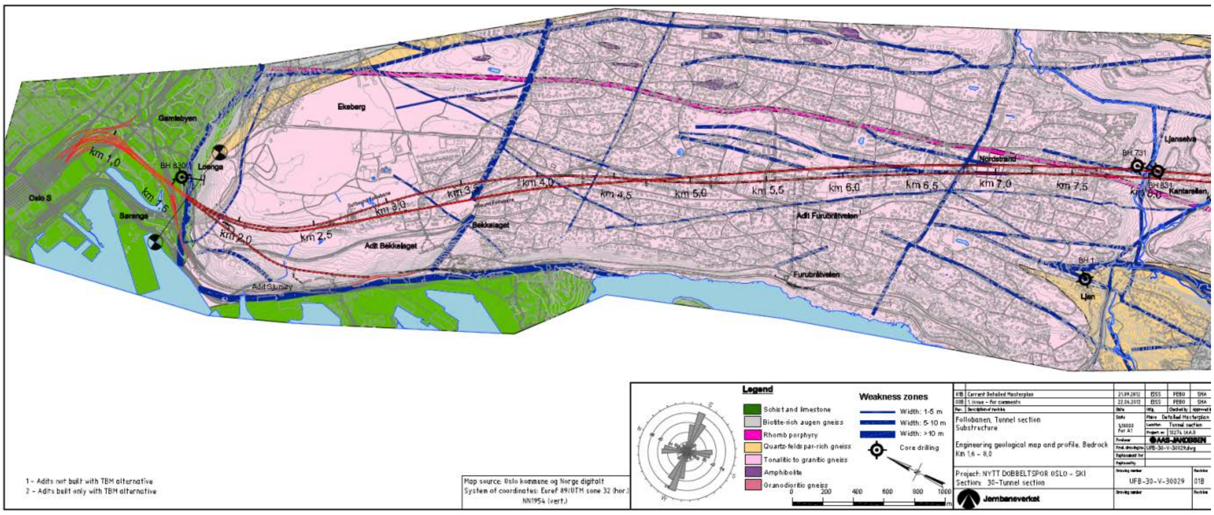


Figure 30: Bedrock map M 1:12500 (example, part one of three), the tunnel goes mainly through gneiss (AAS-Jacobsen).

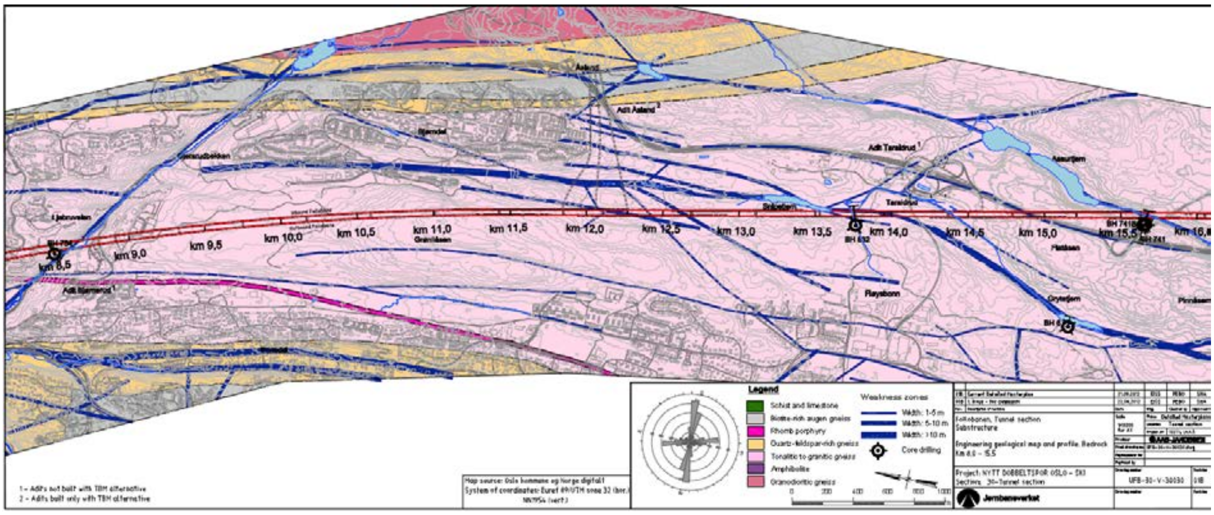


Figure 31: Bedrock map M 1:12500 (example, part two of three), the tunnel goes mainly through gneiss (AAS-Jacobsen).

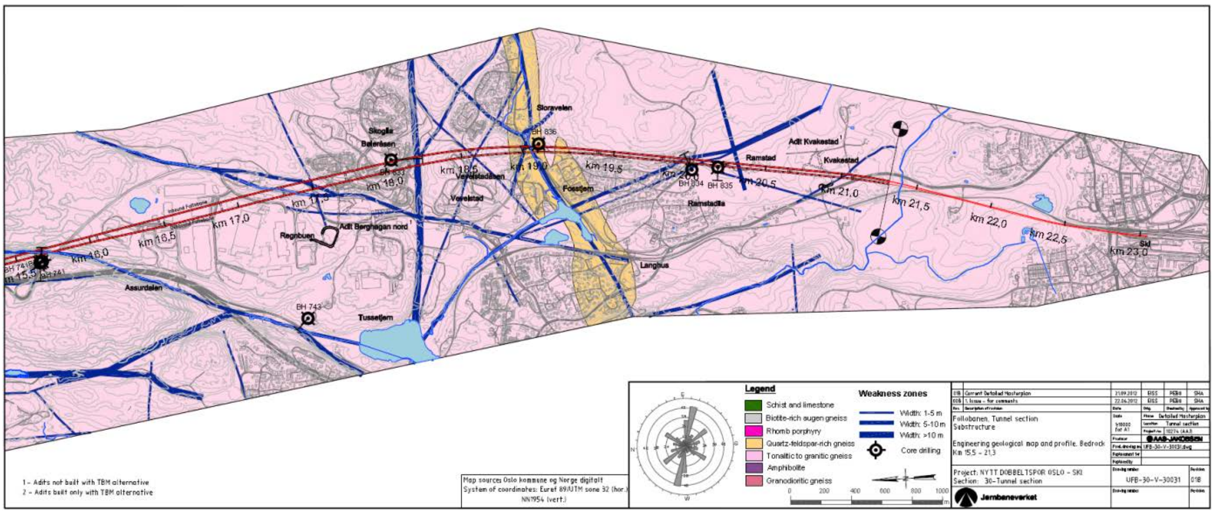


Figure 32: Bedrock map M 1:12500 (example, part three of three), the tunnel goes mainly through gneiss (AAS-Jacobsen).

<u>Characteristics and use of the material</u>

It is part of the project the recycling plan of the material obtained from the tunnelling process.

The material is collected somewhere nearby the tunnel to afterwards be used in the concrete production line or discarded to landfilling, depending on its quality.

The quality of the material is daily checked by the geologists through 3 first fast tests: sieving curve, humidity and geological criteria.

If the results satisfy the standards they will directly be used in the concrete production.

The rest of the test results take longer time, most of the cases they arrive ones the material is already in the production plant.

Most of the material is black gneis, useful material in average.

Even if the quality of the material is valid for the purpose it might not be the size. Therefore, the material goes through a sieving process. The aggregates in between 20-80 mm are used for the concrete production. Thus approximately 40% of the approved material is recycled.

Currently, the plant is using a 50% natural material and 50% crushed sand material proportion in the concrete. Of course, they want to increase the percentage of recycled material.

There is no way to use the material directly coming from the excavation, it has to go through some sorting and sieving first. As well as some tests to ensure the quality.

<u>Other specifications</u>

The tunnels are 1.8m diameter and they are waterproof. To get a water isolated concrete ring they have used a rubber cover all around the ring.

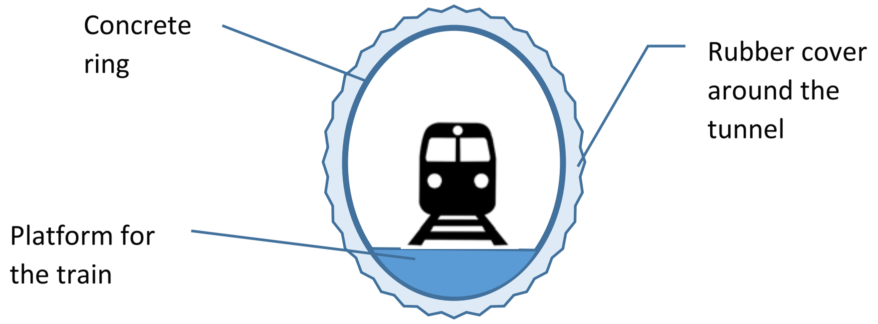


Figure 33: Section of the tunnel.

A23 E6 Fellesprosjektet (Mjøsa)

General information

Owners	Jernbaneverket and Statens Vegvesen
Length tunnel	4,7 km railway tunnel, 3,5 km road tunnel
Start of the construction	2009
End of the construction	2015
Volume rock masses	5,2 million m^3
Mass brought up to Mjøsa and placed on land	33.0

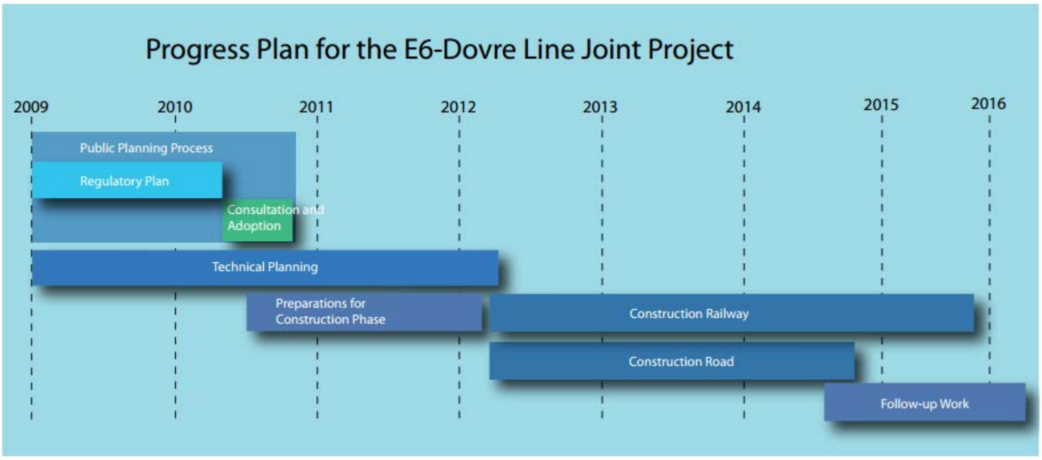


Figure 34: Tasks plan for the project *[83]*.

Characteristics of the road

The E6-Dovre Line Joint Project is a four-lane E6 road and double track railway between Minnesund in the municipality of Eidsvoll and Kleverud in Stange.

The final construction project has been divided into three different sub-projects:

The first section is 6 km long and runs between Langset and Brøhaug. It will include a road tunnel and a rail tunnel, both 600 metres long. The Austrian contractor Alpine Bau GmbH won this contract in May 2012.

The second section is also 6 km long, running between Brøhaug and Strandlykkja. In this section there will be a 2.3 km long road tunnel, and two rail tunnels, 4 km and 150 metres in length. This contract was awarded to JV Veidekke Hochtief ANS in March 2012.

The third section consists of 10 km of the E6 between Strandlykkja and Labbdalen and 5 km of the Dovre Line between Strandlykkja and Kleverud. The E6 will have a 700 metre long tunnel. This contract was won by Hæhre Entreprenør AS in May 2012. The road tunnels will consist of two parallel tubes and the railway tunnels will be of the double track type.

Use of the material

One important reason for this is that the material taken from the construction of the road will be used in building the railway, thus achieving a good material balance in the project.

The project has a mass excess of stone of 1.1 million m^3. Out of this quantity, 1 million m^3 is stored norther in Dovrebanen and 100.000 are stored in Eidsvoll. The first quantity will be used on the construction of the E6 in the area Kolomoen-Hamar and the smaller quantity will be used between Venjar and Minnesund, in Dovrebanen.

3-400.000 m^3 from Eidsvoll and norther are already used in the construction of a future double track and many of these material comes from the southern part of the project.

- The material coming from Dovrebanen (620.000 m^3 aprox.) are transported to fill in Mjøsa the construction of the Dovrebane line.
- The total amount of rock mass in the project is around 5 million m^3
- The aggregates for the concrete production have been crushed in the project in different sizes, unless the ballast.
- A big quantity of this material (800.000 m^3 approximately) has gone to the construction of 21 km of the E6.

So the conclusion is that all the material is properly placed and the profit will be reused on new roads and rail projects.

Other specifications

- The E6 road and the Dovre railway line are very close, so it is planned to expand them at the same time.

A24 Melkøya

General information

Owner	Statoil ASA
Contractor	AF Gruppen
Start of the construction	2002
End of the construction	2007
Volume mountain production	2,5 million m^3

Characteristics of the projects

The project involved fabricating a plant in order to bring the natural gas from the fields to land via subsea pipeline for liquefaction and export.

AF divided the work in 4 phases:

Civil construction 1: Preparation of the site (2002-2003)

They created the land and infrastructure in Melkøya. The methods they used included blasting and doing flatwork in the construction area:

- The total amount of rock mass and breakwater blocks and filling was approximately 2,5 million fm^3.
- They created a 900m long dock to protect the infrastructure from the waves and currents. It had a volume of about 0,7 million am^3, using stones in between 1,5-35 tn.
- They built a 1500 m tunnel
- Construction of the dock for processing barge (18.000 m^2 pile cells)
- Establishment of temporary facilities and infrastructure of roads, water, power, telecommunications and sewage (5.000 m road)

Product Jetty (2003-2005):

Construction of product for receiving and LNG vessels turnkey. Jetty head length is 120 m and is covered with 7 fenders (each 36 m^2). The quay passes 3,500 m steel piles with associated concrete work and 12 mooring points with "quick release hooks" and monitoring systems and 2 access bridges. The snow melting system, electrical work and corrosion protection are included in the work.

Civil construction 2&3 (2003-2006):

The project is a general contract for construction work. The scope includes ground work, piping and cable channels, roads and parking lots, more isolated buildings, foundations for mechanical devices and modules, pipe racks for gas pipes packages, finishing work and landscaping. Nearly 90% of the scope of work will be completed in autumn 2004.

The amounts in the contract are:

- About 50,000 m^3 concrete foundations and pipe racks.
- 20.000 m^3 concrete for 9 building
- Approximately 13,000 m tubes, with diameters up to 2.200 mm
- Approximately 7,000 m of cable channels
- Approximately 12,000 m^2 betongbelegning

Civil 4 - Civil Works (2006-2007):

Continuation of civil works working for Statoil at Melkøya.

Figure 35: Overview of the construction *[84]*.

Characteristics and use of the material

The material they excavated in the tunnel was used afterward in the constructions.

A25 Gevingåsen tunnel

General information

Owner	Bane NOR
Contactor	Mika / Implenia
Length tunnel	4.400 m
Start of the construction	Spring 2009
End of the construction	Autumn 2010
Volume masses	350.000 m^3

Driving method

The driving method they used was Drill & Blast.

It was thoroughly investigated in the planning phase. TBM was not chosen because it meant significantly higher costs and longer construction. TBM would have been suitable for longer and less tunnels.

A brief explanation of how Drill & Blast method work follows:

- **Grouting**: 21-24 meter long drilled holes around the tunnels section. Concrete mass is pumped into the holes under high pressure. The cracks are sealed thereby in the mountains where the tunnel will be blasted, so that groundwater does not leak into.

- **Drilling and charging**: It drilled approximately 5 meter long hole being charged with explosives. Drilling and charging take place simultaneously with the same machine. There are arms going in and charging holes gradually, while new ones are being drilled.

- **Blasting**: to reduce the chattering of the surface divided each burst into many small bursts. They fired in rapid succession (5-6 milliseconds between each). The ointments adjusted according to the environment and the mountain nature.

- **Charging**: the blasted mountain masses are loaded onto dump trucks and transported to a storage area outside the tunnel area. Here the material is transferred to masses trucks before they are transported to the delivery point.

- **Scaling and securing**: resolved mountain pigged down with a large hydraulic hammer. To avoid bad conditions, it is necessary to secure the roof and walls with bolts, shotcrete or reinforcement arcs. Afterwards, the geological conditions of the mountain have to be checked, in case of necessary safeguards.

Characteristics material and reuse of it.

The soil conditions in Gevingåsen between Hell and Hommelvik were not really good.

The material was transported to Værnes to reuse it there.

Figure 36: Gevigåsen Tunnel profile *[85]*.

<u>Other specifications</u>

SINTEF considered various options for water and frost protection in the tunnel.

The challenge has been that water can freeze behind water restrictor and the research has been to find out what happens with the systems in the fuel tank.

One of the four emergency exits in railway tunnel is designed so that even Hell-tunnel on the E6 can take advantage of the possible escape routes.

New EU requirements for tunnel safety is safeguarded for the new tunnel. An emergency exit for every thousand meters is only one of several measures that contribute to increased safety.

A26 Strindheimtunnelen

General information

Owner	Statens Vegvesen
Contractor	Skanska, NCC
Length tunnel	2.500 m, four lane road
Start of the construction	2010
End of the construction	2014
Volume masses	387.000 m^3 bedrock and 696.600 m^3 of loose rock

Driving method

Construction and method were selected by competitive bidding dialogue. The project was so demanding that some entrepreneurs proposed offers together. At the end was NCC who got the project.

In order to "tame" quick clay it was chosen a method of steel tube that connects between them which was hardly used anywhere in the world earlier. In total there were 329 modules with a diameter of 60cm and attached impact drill, driven through quick clay layer and two meters into the bedrock before being filled with concrete. This formed a 100 m long, 25 m wide and 25 m deep dense and very rigid pipes connexion.150.000 m^3 clay and 16.000 m^3 of stone were removed before the work on the concrete tunnel could start.

Characteristics and use of the material

About 600.000 m^3 of tunnel material was transported to build an artificial island and a new harbour in Grilstad, Ranheim.

Figure 37: Overview of Grilstad Marina *[86]*.

Other specifications

A church has to be demolished in the way and 5 houses were moved from Lower Møllenberg and temporarily stored to be moved back again afterwards.

The top of some of the pipes connected are kept visible above ground level, and is part of the decoration of the road system around the tunnel.

The deepest part of the tunnel is 15 m below the sea level.

Figure 38: Overview of the Strindheim tunnel (Statens Vegvesen).

A27 2.1. Austrian S10

<u>General information</u>

Client	Asfinag Bau Management GmbH
Contractor	Porr Bau GmbH
Length tunnel	22 km
Start of the construction	2010
End of the construction	2015
Volume masses	4.000.000 m^3

<u>Driving method</u>

The tunnel excavation materials in this project were produced by drilling and blasting.

<u>Characteristics and use of the material</u>

A share of the tunnel excavation materials was used in load bearing layers in the pavement structures on the project. While the total surplus volume in the initial was calculated to 4 000 000 m^3, 10 % of this volume was judged to be suitable for use as bearing course material. After careful sorting and quality assessment of the materials, the project succeeded in using a total of 400 000 m^3 excavation material as aggregates for the pavement structure.

<u>Other specifications</u>

This project comprises the construction of six bridge structures, two passages, the construction of an underpass and a gallery, the construction of two tunnels using the bored tunnel construction method as well as earthworks and road construction works for a 4.5 km long construction section.

Figure 39 Pictures of the construction *[87]*.

A28 E39 Rådal Svegatjern

General information

Owner	Statens Vegvesen
Contractor	Veidekke Entreprenør AS
Length tunnel	16,25 km
Start of the construction	2015
End of the construction	2022
Volume masses	1.800.000 m^3

The project is divided into four contracts: K10 (Veidekke), K11 (Implenia), the extension of the bridge and K20 (electrical and control).

In this case, K10 takes the area from Svegartjørn in the south to Fana road in the north.

Then, K10 is divided into three production lines as well: the tunnel from Hamre, the tunnel from Endelausmarka / Svegatjørn and the approaching areas in Endelausmarka/ Svegatjørn.

Driving method

The driving method used is Drill & Blast.

Today there are 5 jumbo drillings with 3 drilling rigs in use and all of them have alternative operation. On Hamre there are 4 backhoe that are in circulation and two drilling rigs. Until now, part of stormwater tunnel has been excavated by the Hammers, but it will run by an excavator with backhoe for loading (versus 350 wheel loader used elsewhere in the tunnel).

Characteristics and use of the material

Tunnel masses are owned by SVV, they determined the consumption and the masses are only used in the line replacement.

The volume masses are transported from Hamre to deposits in Stock Rådalen / Hordnes forest and the handover is the responsibility of one of the constractors. Masses from the south of Skogafjell and Endalausmarka will be used as mass replace in Svegatjørn and Kvernatjørn which has been drained down.

It turns out that the masses in Svegatjørn consisted of more soil and infected areas and the south of Skogafjell of poor mountain.

Figure 40: Cross of Endelausmarka and cross of Rådal (Statens vegvesen).

A29 E39 Romsdalsfjorden crossing

Owner	Statens Vegvesen
Length tunnel	16 km
Start of the construction	Not decided
Volume masses	4.000.000 m^3

An example project highlighting efforts to utilize excvated material is the E39 Romsdalsfjorden crossing. In this upcoming highway project, a fjord will be crossed by a 16 km long twin tube subsea tunnel.

Driving method

This project will create a significant surplus of blasted rock, and during the planning process, the possibilities for commercial utilization of the surplus have been investigated. It is decided that in order to be able to utilize the surplus rock, it is necessary to use conventional drilling and blasting as the construction technique for the tunnels [52].

Characteristics and use of the material

Preliminary investigations show that the rock material from the tunnel is expected to keep sufficient quality for use in the pavement structure, including use in asphalt layers [88]. Material from the tunnel is planned to be used in the road pavement and for shotcrete and possibly other concrete purposes within and in connection with the tunnel. Nonetheless, the fjord crossing is expected to result in a surplus of 3.5-4 million m^3 rock material from the tunnel.

Surplus materials from the project were offered to public and private interests through a public announcement stating that suggested uses would be prioritized by benefit for the society [89]. From this announcement, a total of 35 bidders showed interest, and the project was able to agreements of intent with several bidders.

The NPRA are planning several new fjord crossing projects as part of the Coastal Highway Route E39, and in general, a significant surplus of rock is expected from the highway. In connection to the Coastal Highway Route E39, the NPRA is financing a PhD position at NTNU regarding how lower quality aggregates can be used in road construction.

A30 Ulriken

General information

Owner	Bane NOR
Contractor	Skanska
Length tunnel	7.800 m
Start of the construction	2015
End of the construction	2021
Volume masses	530.000 m^3
Diameter	9,3 m
Saving time	Departures every 10 min instead of 20

It was the first tunnel in Norway operating with TBM.

Driving method

The driving methods used in this project was TBM and Drill & Blast.

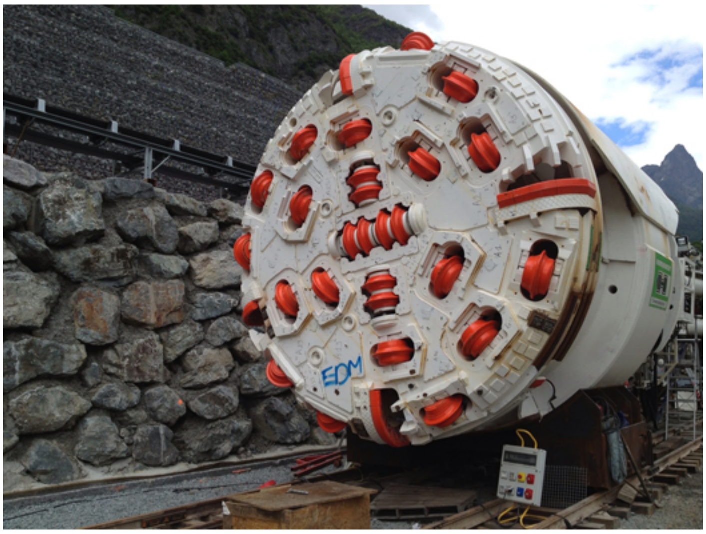


Figure 41: Tunnel Boring Machine *[90]*.

Characteristics and use of the material

The excavated rock material from the drill&blast-part from the tunnel is processed to aggregates. The TBM-masses are deposited, and further use is uncertain.

Other specifications

New Ulriken tunnel provides increased capacity with frequent departures between Arna and Bergen from departing every 20 minutes with the possibility of departures every 10 minutes when the facility is completed.

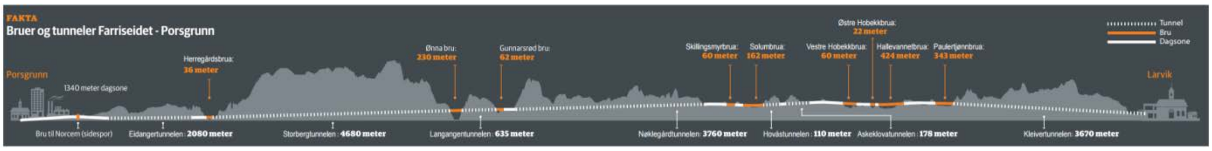
The stretch gets better security with escape possibilities in cross passages every 500 m between the tunnel tubes.

A31 Farriseidet-Porsgrunn

General information

Owner	Bane NOR
Length tunnel	2.200 m
Start of the construction	2012
End of the construction	2018
Volume masses	3.550.000 m^3 loose
Reduction time	From 34 min to 12 min.

There will be 22 km of new double track railway, 7 new tunnels at a total length of 14,5 km and 10 bridges at a total length of 1,5 km.



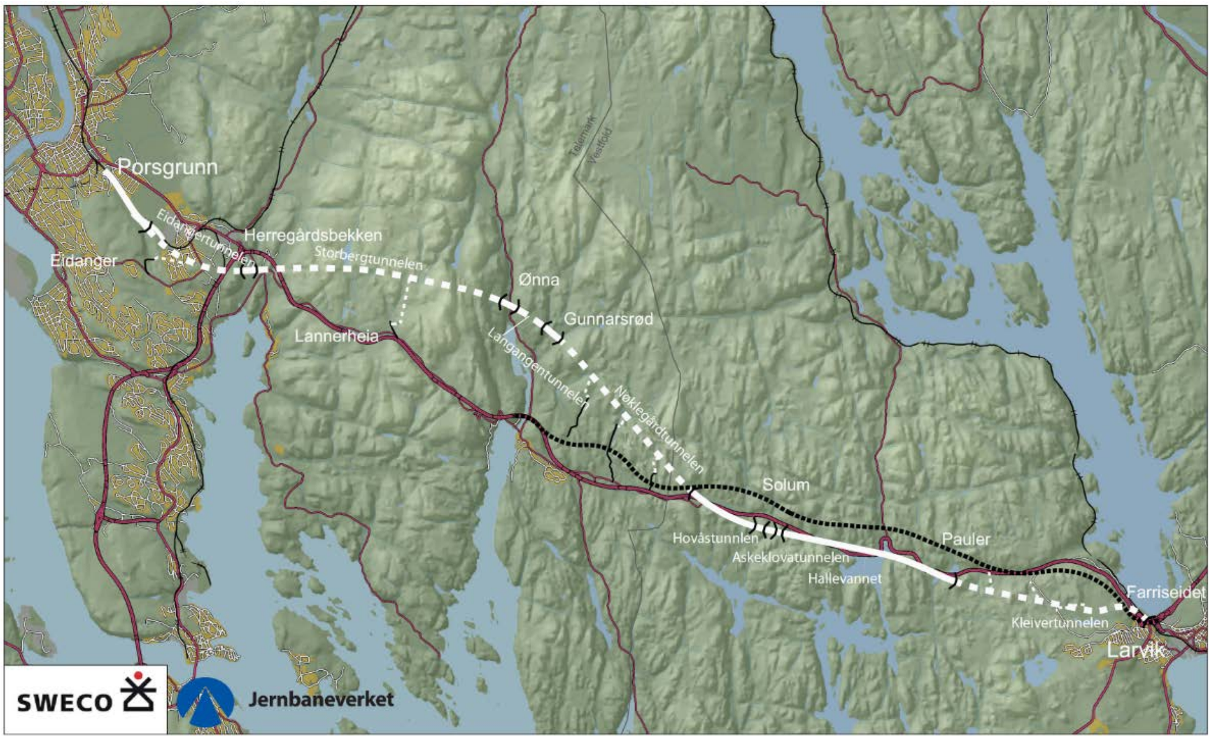


Figure 42: Overview of the project Farriseidet – Porsgrunn.

Driving method

The driving method in this case is TBM.

Figure 43: Entrance of one of the tunnels *[90]*.

Characteristics and use of the material

The dominating rock mass in all tunnels except the Eidanger tunnel is the rare plutonic rock mass called Larvikite (Monzonitt). The Larvikite rock mass is mostly coarse grained, with a typical grain size of 1 -2 cm. About 90 % of the Larvikite is made out of the mineral Feldspar, but it also contains small amounts of darker minerals such as amphibole, olivine and biotite. Larvikite is known as a hard and competent rock and has been used as a natural stone for buildings since the 18th century and are even today mined in several quarries around Larvik [64] [65].

The rock mass in the Eiganes tunnel is sedimentary and consists of limestone, clay slate and sandstone that are variously affected by contact metamorphosis. The metamorphosis has made the rock mass hard and massive and can be classified as hornfels. The degree of contact metamorphosis is higher towards the Larvikite in the east. The rock mass is presented in the geological bedrock map, Figure 44.

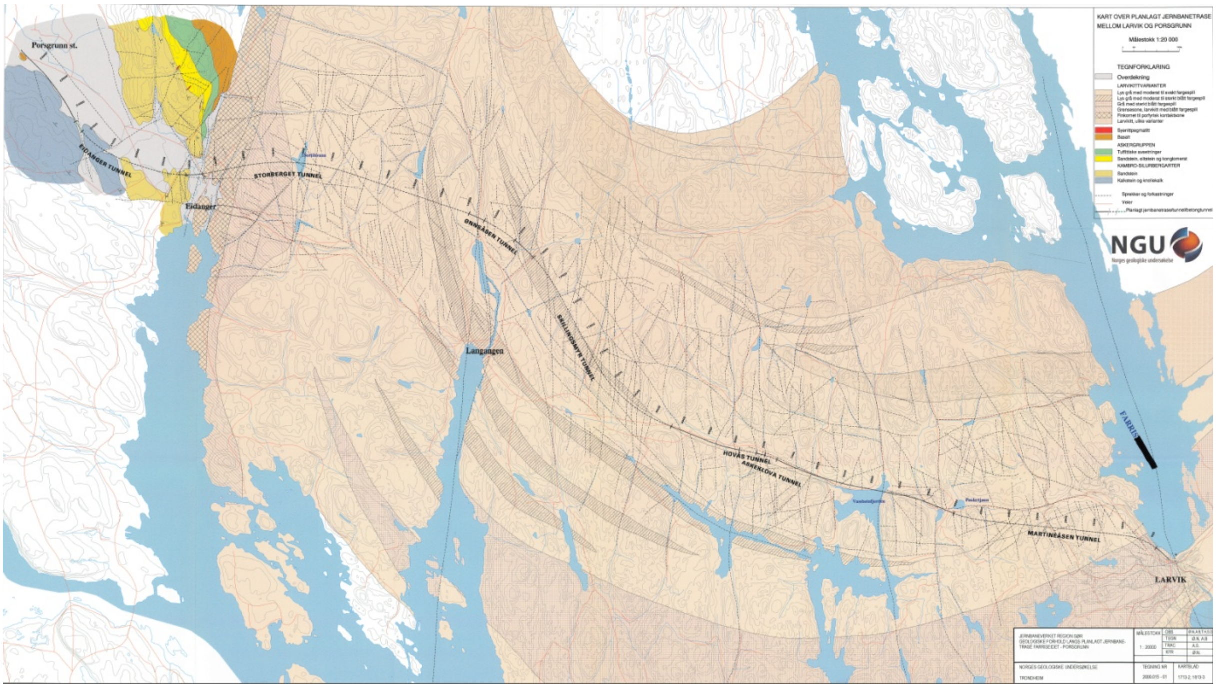


Figure 44: Geological bedrock map over the rock mass in the project.

All of the excavated rock material was at the planning stage considered to be usable as fill material in the line or for leveling of the terrain. It was concluded that if the excavated rock mass were to be used for the superstructure of the railway, crushing and sorting equipment would be necessary. It was also concluded that if the excavated rock materials were to be used as ballast in the superstructure of the railroad the excavated rock material properties had to be tested thoroughly.

The geological characteristics of the construction have been divided into two areas:

- Farriseidet - Telemark border

The total capacity of the rock fills in the plan was 730.000 m3 and had such an overcapacity of approx. 195.000 m^3. This was deliberately planned for since experience shows that you should have a slight overcapacity for the flexibility to handle unforeseen extra masses.

The majority of the overbalance came from the Kleiver tunnel, therefore the landfills' location was preferred to be close to the tunnel, in order to ensure a cost and time effective production during excavation of the tunnel. However the location of the Kleiver tunnel is located in a valuable nature and recreation area which was considered to be an unwanted location for a landfill.

- Telemark border - Porsgrunn

The total amount of excavated rock masses from the stretch Telemark border – Porsgrunn was 2.998.000 m^3. A total of 14 (initially 16) rock fills were placed along the line resulting in a total capacity of 3.770.000 m^3 of loose rock and had such an overcapacity of approx. 770.000 m^3. The excavated rock mass distributed on the separate key locations of the project is presented in Table 17. All the rock fills were located along the line within reasonable transportation distance from each of the excavation sites [66].

Mass balance in the project

The total theoretical overbalance of excavated rock for Farriseidet – Porsgrunn was 3.533.000 m^3 (loose rock mass). Of which the theoretical overbalance of excavated rock for the stretch Farriseidet – Telemark border was 535.000 m^3 (loose) and for Telemark border – Porsgrunn was 2.998.000 m^3 of loose rock mass, the numbers are presented in Table 25. The main alternative in the project for handling of the excavated rock mass was to place the masses in rock fills along the line. (Jernbaneverket, 2008a)

Table 25: Volumes of excavated rock from Farriseidet - Porsgrunn, the volumes are presented in theoretical solid volumes and handled, loose volumes, calculated with a swelling factor of 1.6.

	Volume, solid (m^3)	**Volume, loose (sf. 1.6) (m^3)**
Farriseidet - Telemark border	335.000	535.000
Telemark border - Porsgrunn	1.875.000	2.998.000
Total	**2.110.000**	**3.533.000**

Other specifications

The total theoretical overbalance of excavated rock for Farriseidet – Porsgrunn was 3.533.000 m^3 (loose rock mass). Of which the theoretical overbalance of excavated rock for the stretch Farriseidet – Telemark border was 535.000 m^3 (loose) and for Telemark border – Porsgrunn was 2.998.000 m^3 of loose rock mass. The main alternative in the project for handling of the excavated rock mass was to place the masses in rock fills along the line [66].

A32 Holmestrand-Nykirke

General information

Owner	Bane NOR
Length tunnel	14,3 km new double track railway and 12,3km railway tunnel
Start of the construction	2010
End of the construction	2016
Volume masses	3.300.000 m^3 of excavated rock (loose)

Figure 45: Overview of the line Holm-Nykirke. It is drawn in red, the thicker line in the middle represents the new Holmestrand station.

Driving method

The driving method used was TBM.

Characteristics and use of the material

For the line between Holm and Holmestrand the dominating rock mass is the Ringerik sandstone, rockmasses that belongs to the Asker group; Schiffer, sandstone and conglomerate and rock masses that belongs to the B1-formation; Basaltic lava flows intervened with layers of red silt- and sandstone, tuff, agglomerate and lava conglomerate. Approximately 11% of the tunnel between Holm and Holmestrand will go through the Ringerik sandstone and about 86% of the tunnel will go through the B1-formation, most likely will the tunnel not come in contact with the Asker group.

For the line between Holmestrand and Nykirke, the dominating rock mass is magmatic basalt and rhomb porphyry of Permian age. The basalt consists of several lava streams that are assumed to have a thickness of 5-10 m. between the lava flows there most likely was a gap of time without lava flows, during this time gap the uppermost layer of the lava eroded and alien material transported through water and air sedimented on top. This period was then followed by a new period with lava streams. The creation process has created sub horizontal layers in the rock mass with a lower strength than the surrounding rock mass.

Both the Basalt and the Rhomb porphyry are strong rockmasses and can be suitable for construction purposes. However the creation process of which the Basalt at Holmestrand-Nykirke was created indicates that weaker layers exists in the rock mass.

KORTREIST STEIN

VEIDEKKE

metso

Statens vegvesen

HORDALAND FYLKESKOMMUNE

NORGES GEOLOGISKE UNDERSØKELSE - NGU -

BERGEN KOMMUNE

Multiconsult

asplan viak

BANE NOR

NTNU

SINTEF

Forskningsrådet

Støttet av Norges forskningsråd