R-08-117

Rock fill in a KBS-3 repository

Rock material for filling of shafts and ramps in a KBS-3V repository in the closure phase

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Abstract

The content of large blocks in blasted rock makes it impossible to fill and compact the material effectively unless those larger than about 500 mm are removed. TBM muck gives flat chips, that are usually not longer than a couple of decimeters, and serves better as backfill. The granulometrical composition of both types can be more suitable for effective compaction by crushing, which is hence a preferable process. Use of unsorted, unprocessed blasted rock can only be accepted if the density and physical properties, like self-compaction, are not important. Crushing of blasted rock and TBM muck for backfilling can be made in one or two steps depending on the required gradation.

Placement of rock fill is best made by use of tractors with blades that push the material forwards over already placed and compacted material. The dry density of well graded rock fill effectively compacted by very heavy vibratory rollers can be as high as 2,400 kg/m^3. For road compaction by ordinary vibratory rollers common dry density values are in the interval 2,050 to 2,200 kg m^3. Blasted rock dumped and moved on site by tractors can get an average dry density of 1,600–1,800 kg/m^3 without compaction. Crushed, blasted rock and TBM muck placed by tractors in horizontal layers and compacted by 5–10 t vibrating rollers in the lower part of the rooms, and moved by tractors to form inclined layers compacted by vibrating plates in the upper part, would get a dry density of 1,900–2,000 kg/m^3.

Flushing water over the rock fill in conjunction with the compaction work gives more effective densification than dry compaction. Based on recorded settlement of Norwegian rock fill dams constructed with water flushing it is estimated that the self-compaction of a 5 m high backfill of crushed rock or TBM muck causes a settlement of the top of the backfill of about 8 mm while a 200 m high shaft fill would undergo compression by more than half a meter. Repeated, strong earthquakes may cause an increase by 100%. Earthquakes can not cause liquefaction of densely compacted rock fill.

The hydraulic conductivity of normally graded crushed rock is, for achievable densities and without adding fines, about E-5 m/s, while addition of fines can reduce it to E-7 m/s.

The mineralogy is important for minimizing degradation of the buffer clay and canisters. Hence, the content of sulphur-bearing minerals should be low and the amount of carbonates at minimum for avoiding risk of dissolution and formation of larger voids in the backfill. The content of potassium-bearing minerals should not exceed normal values for keeping the rate of conversion of smectite in the buffer to illite low, especially in tunnels and openings close to the deposition area.

Sammanfattning

Innehållet av stora block i sprängmassor gör det omöjligt att effektivt fylla och kompaktera materialet om inte de block som är större än ca 500 mm avlägsnas. TBM-muck ger flata brottstycken som är mindre än ett par decimeter och sådant material fungerar bättre som återfyllning. Båda typers kornstorleksfördelning kan göras lämpligare för effektiv packning genom krossning, som därför är ett lämpligt processteg. Användning av osorterad, obehandlad sprängsten kan bara accepteras om densiteten och de fysikaliska egenskaperna,

t.ex. självkompaktering, inte är viktiga. Krossning av sprängsten och TBM-muck för fyllningsändamål kan göras i ett eller två steg beroende på den önskade kornstorleken.

Anbringande och utbredning av bergmaterial görs bäst med traktor med blad som skjuter fram materialet över redan anbringade och packade lager. Densiteten hos mycket lämpligt graderat material som packas effektivt kan bli så hög som 2 400 kg/m^3. Vid vägbyggnad blir torrdensiteten med användning av vanliga vibrovältar 2 050 till 2 200 kg/m^3. Sprängsten, tippad och traktorutbredd utan packning, kan få en torrdensitet av 1 600–1 800 kg/m^3. Krossad sprängsten och TMB-muck anbringad med traktorer och packad med 5–10 t vibrovältar i undre delen av bergrum och anbringad med traktorer och packad med vibroplatta i den övre delen, kan få en torrdensitet av 1 900–2 000 kg/m^3.

Vattenbegjutning av bergmaterialet i samband med anbringande och packning ger högre densitet än torrkompaktering. På grundval av mätningar av sättningen hos norska dammar byggda med vattenbegjutning kan man bedöma att egenkompressionen hos en 5 m hög tunnelfyllning i ett slutförvar blir ca 8 mm. Motsvarande värde för en 200 m hög schaktfyllning skulle bli ca en halv meter. Upprepade starka jordbävningar kan öka dessa värden med 100 %.

Hydrauliska konduktiviteten hos vanliga sprängstensfyllningar är, för uppnåeliga densiteter utan tillsats av finmaterial, ca E-5 m/s, medan tillsats av finmaterial kan ge en minskning till E-7 m/s.

Mineralogin är viktig för att minimera negativ påverkan på buffertlera och kapslar. Innehållet av svavelhaltiga mineral bör vara lågt och karbonatinnehållet så litet som möjligt för att undvika bildning av hålrum i återfyllningarna. Innehållet av kaliumhaltiga mineral bör inte överstiga normalvärdet för att hålla nere hastigheten hos omvandlingen av smektit till illit i bufferten, särskilt i tunnlar och bergrum nära deponeringsområdet.

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1 Introduction

1.1 Background

SKB has worked out a repository concept, KBS-3V, that implies that the highly radioactive spent fuel is contained in copper-lined iron canisters, which will be placed in large-diameter holes with a spacing of 6–10 m bored from the floor of blasted "deposition" tunnels (Figure 1-1). The canisters will be embedded in very tight smectite clay ("buffer") for minimizing migration of possibly released radionuclides to the surrounding rock and for providing the canisters with a ductile surrounding that can reduce the mechanical impact of earthquakes on the canisters. The deposition tunnels need to be filled with blocks and pellets of clay for fulfilling certain defined criteria concerning their hydraulic and mechanical performance. Other tunnels, rooms, ramps and shafts, all of these being in focus of the present study, may not have to be backfilled to reach the low hydraulic conductivity required for the deposition tunnels and the most shallow parts of them should primarily be backfilled so as to make human intrusion difficult. This can be achieved by use of crushed rock that serves as a mechanical protection with no need for being tight but with a compressibility that is sufficiently low to provide the tunnel roof with some support in case of rock fall. The compression of rock backfills under their own weight or exposed to moderate load from degrading tunnel roofs is therefore an important issue that is treated in the present report. It is related to the porosity and nature of the contacts between neighbouring blocks, which are both dependent on how the filling and compaction is made. This matter is hence also discussed in the report. Figure 1-2 gives a schematic example of how ramps and shafts can be filled. Finer fills of quartz sand etc in certain parts of the tunnels, ramp and shafts are not discussed in this report.

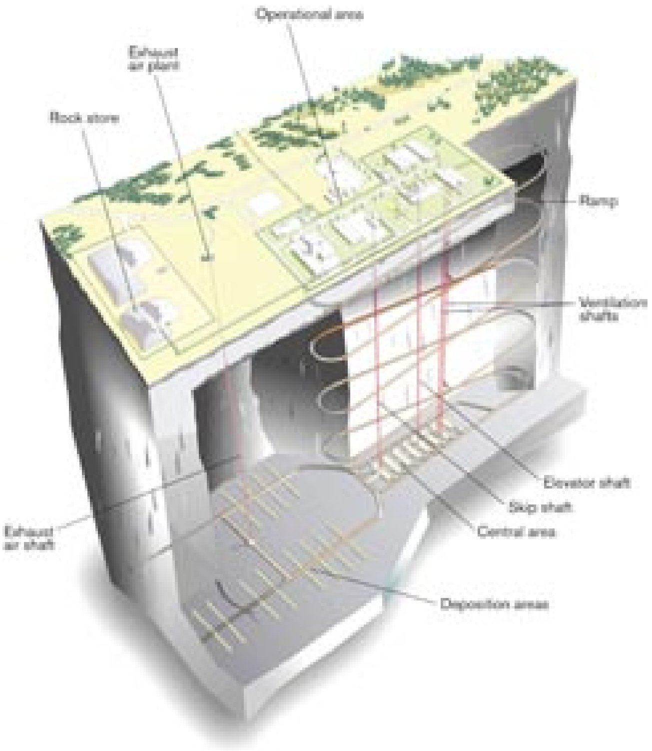

Figure 1-1. *Perspective view of a one-level repository representing the KBS-3V concept. The deposition areas with its deposition tunnel galleries are to the left. The main and transport tunnels connecting the deposition tunnels with the central area, shafts and ramp are in focus in this report /Figure 1-1 I R-07-30/.*

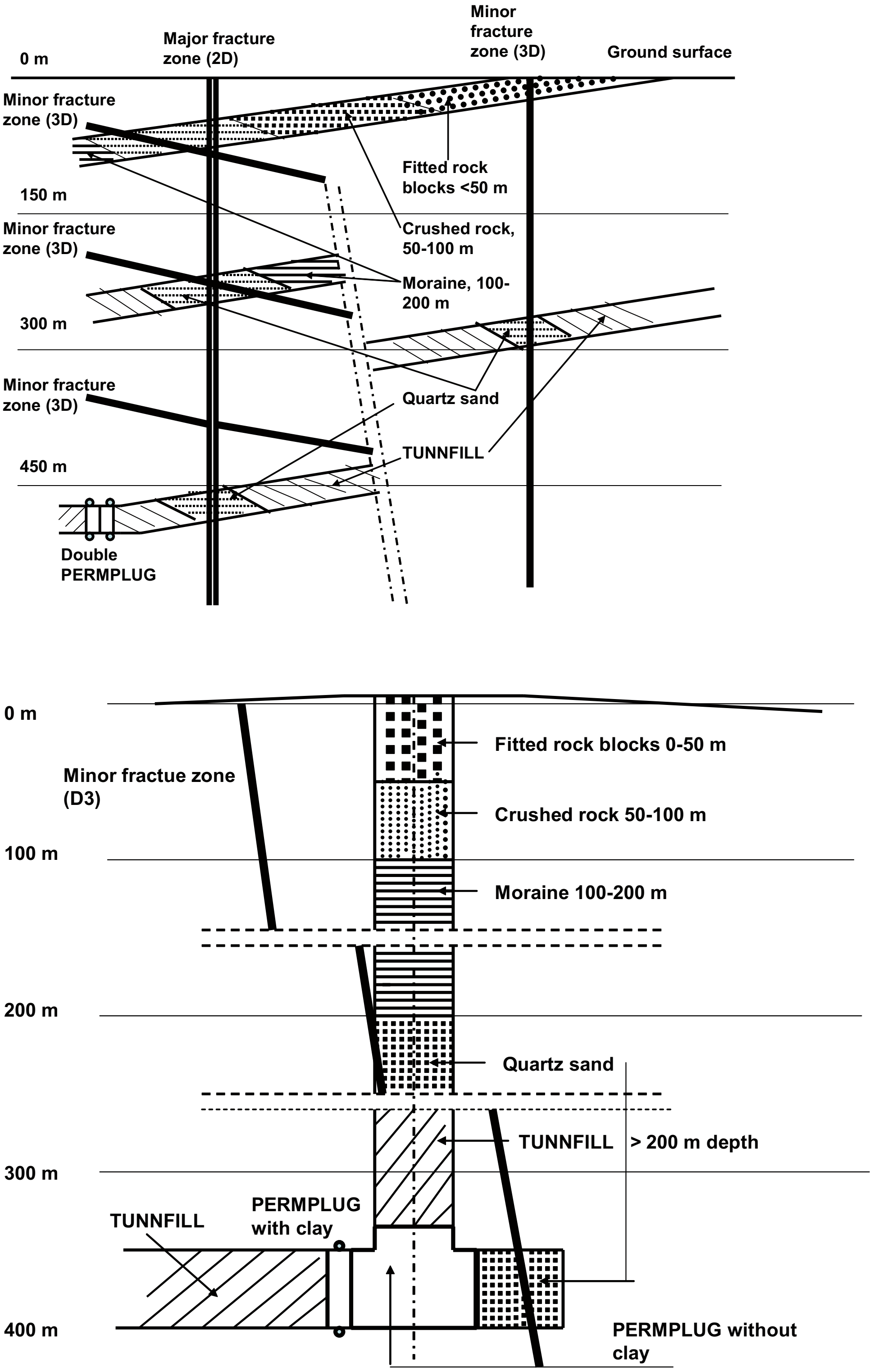

***Figure 1-2.** Example of fills in ramp (upper) and shaft in a KBS-3V repository (dimensions not to scale). Cement-stabilized quartz sand is placed where the ramp is intersected by water-bearing fracture zones. The upper parts may suitably be filled with rock materials as described in the present report.*

Plug seals must be constructed in strategic positions for temporary or long-term separation of different rooms but they will not be treated here. The backfills discussed in this report are proposed to be placed in the transport tunnels, central area, shafts and ramp.

1.2 Scope

The purpose of the present report is to give a condensed overview of the following items, which determine the possibility to fill rooms, shafts and ramp of a KBS-3 repository with rock material:

- Size distribution and shape of rock particles depending on excavation method.
- Density of rock fill; loose layering, moderately compacted, or very effectively compacted.
- Techniques for compaction; dry and wet.
- Compressibility and settlement of rock fill.
- Shear strength of rock fill.
- Hydraulic conductivity of rock fill.
- Petrological composition of rock fill.

In this report compaction is the term for dynamic mechanical agitation for reducing the porosity of fills, while compression stands for reducing the porosity by exerting a static pressure.

1.3 Previous work

Earlier work on backfills of coarse soil and rock material in repositories has been documented in SKB reports /Pusch 1995/ and /Pusch 2002a/. The latter report was based on a recent literature survey and contacts with international expertise.

2 Size and shape of rock fragments

2.1 General

The density, compactability, compressibility, porosity, shear strength and conductivity of a rock fill depend primarily on the grain size distribution and the grain shape, which are defined in the following subchapters.

2.2 Size

The generally accepted grain size classification scheme in soil mechanics is shown in Table 2-1.

2.3 Size distribution

2.3.1 The sorting coefficient

The size distribution /Pusch 2002a/ is often expressed by use of the "sorting coefficient", which is defined as: "Square root of the ratio of d_{75} and d_{25}", where d_{75} is the maximum diameter value of the finer 75% part of the mass, and d_{25} the corresponding value of the finest 25% part of the mass.

Grain size uniformity, *Cu,* is often used for describing gradation of fine-grained soils. It is expressed as the ratio of d_{60} and d_{10}, where d_{60} represents the maximum size of grains of the smallest 60% of the sample, and d_{10} the maximum size of grains of the smallest 10% of the sample.

2.3.2 The Fuller distribution

A soil so composed that smaller particles occupy the voids between larger particles is of "Fuller" type, mathematically expressed as: "Weight percentage of particles with diameter d is equal to $100[(d/D)]^{1/2}$", where d = diameter of a particle och D = max diameter of the entire particle assembly. The curve is a parabola and represents the size distribution that represents the highest possible density, see Figure 2-4 (the lowermost diagram).

Table 2-1. Classification of soil with respect to the particle size /Pusch 2002a/.

Main groups	Grain size, mm	Subgroups	Grain size, mm
Boulder	> 600	Large boulder	> 2,000
Cobble	600–60	Large cobble Small cobble	600–200 200–60
Gravel	60–2	Coarse gravel Medium gravel Fine gravel	60–20 20–6 6–2
Sand	2–0.06	Coarse sand Medium sand Fine sand	2–0.6 0.6–0.2 0.2–0.06
Silt	0.06–0.002	Coarse to fine etc	
Clay	< 0.002		

2.4 Shape

The degree of anisotropy is called the *splintery factor, F*, and expressed as the ratio of the maximum and minimum grain diameters. *F*=1 for spheres and can be up to 1.6 for very oblong particles.

S*phericity S* is expressed as $[(b\mathrm{x}c/a^2)]^{1/3}$, where a=maximum diameter, *b* the diameter measured normally to *a*, and *c* the smallest diameter measured normally to the *a/b* plane (Figure 2-1), /Pusch 2002a/.

The *roundness R* is expressed as the ratio of the sum of *r/R* and *N*, where *r* is the radius of curvature of the edges and *R* the radius of the largest inscribed circle, and *N* the number of edges. *R* is 0.2–0.3 for crushed rock and 0.6–0.8 for well rounded material (esker) /Pusch 2002a/.

2.5 Impact of excavation and processing on the grain size and shape

2.5.1 Blasting

The size of blasted muck naturally depends on the position, spacing and charge of the blastholes and can range from cubic-meter large blocks to very fine silty debris. The shape of larger units is determined by the rock structure and those emanating from granite are hence more spherical than big blocks from blasted gneiss or shales.

The muck represents the whole size spectrum, the details of which primarily depend on the applied blasting technique. The content of large boulders makes it impossible to fill and compact the material effectively and those larger than about 500 mm must be removed and crushed except if the density and physical properties, like self-compaction, are not important. The size distribution of the fragments of blasted rock can not be determined with great accuracy since the geometrical parameters of those larger than about 150 mm can usually not be determined by sieving. Individual measurement is difficult and does not give well defined diameters. Figure 2-2 illustrates the size distribution of fragments of blasted rock investigated for use in road construction. This material contained fragments of up to about 320 mm and indicates a slight deviation from the Fuller curve of the most coarse-grained part. Regulations /AMA Anläggning 07 2007, Vägverket 2008/ specify that the uppermost part of road embankments must consist of grains in the interval 0–90 mm. If the fill is more coarse-grained a shallow layer with this granulometry has to be added. Construction of test roads made of material with 0–320 mm particle size using a 22 ton vibratory roller gave excellent density as manifested by the E-modulus (Ev2) 120 MPa. It required, however, 40 runs. For 10 runs the modulus was about 100 MPa and for 5 runs about 85 MPa /Thorén 2005/.

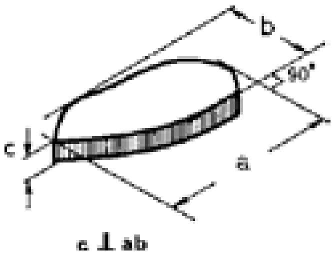

Figure 2-1. Parameters used for definition of grain size /Pusch 2002a/.

Figure 2-2. *Size distribution of road embankment composed of very coarse-grained, blasted rock /Thorén 2005/.*

Figure 2-3 shows another example of the size distribution of fragments in blasted crystalline rock /Sherard and Dunningan 1986/. One notices that the flatter curve of Figure 2-3 represents a median value (50%) of 120 mm while the corresponding value for the curve in Figure 2-2 is about 100 mm. The difference is explained by different blasting techniques and rock structure (anisotropy).

2.5.2 Crushing of blasted rock

Crusion produces fragments of various size, some being too large to be accepted in road and dam construction. They can be removed by a tractor or crane and more systematically by sieving. Two examples of sieved crushed granitic rock are shown in Figure 2-4, which also exhibits a Fuller curve for comparison. They are both of Fuller-type, which means that crushing generally produces a particle size distribution that is suitable for preparing dense backfill provided that the compaction energy is sufficient.

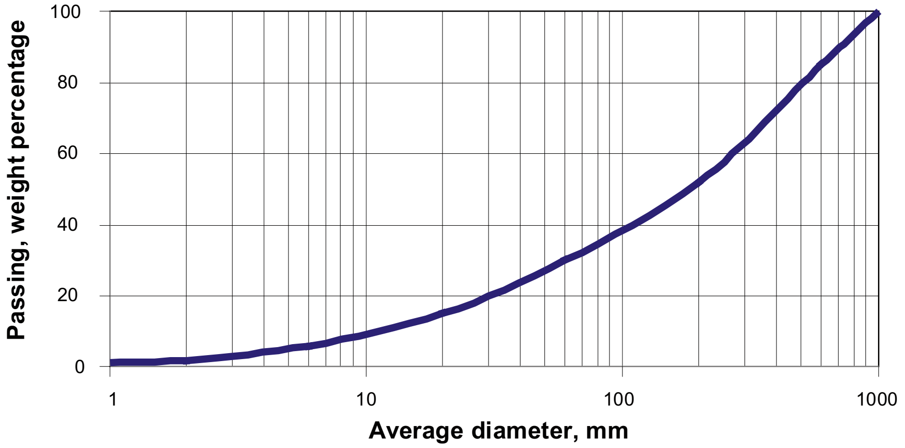

Figure 2-3. *Typical size distribution of blasted rock fill for Norwegian rockfill dams /Sherard and Dunningan 1986/.*

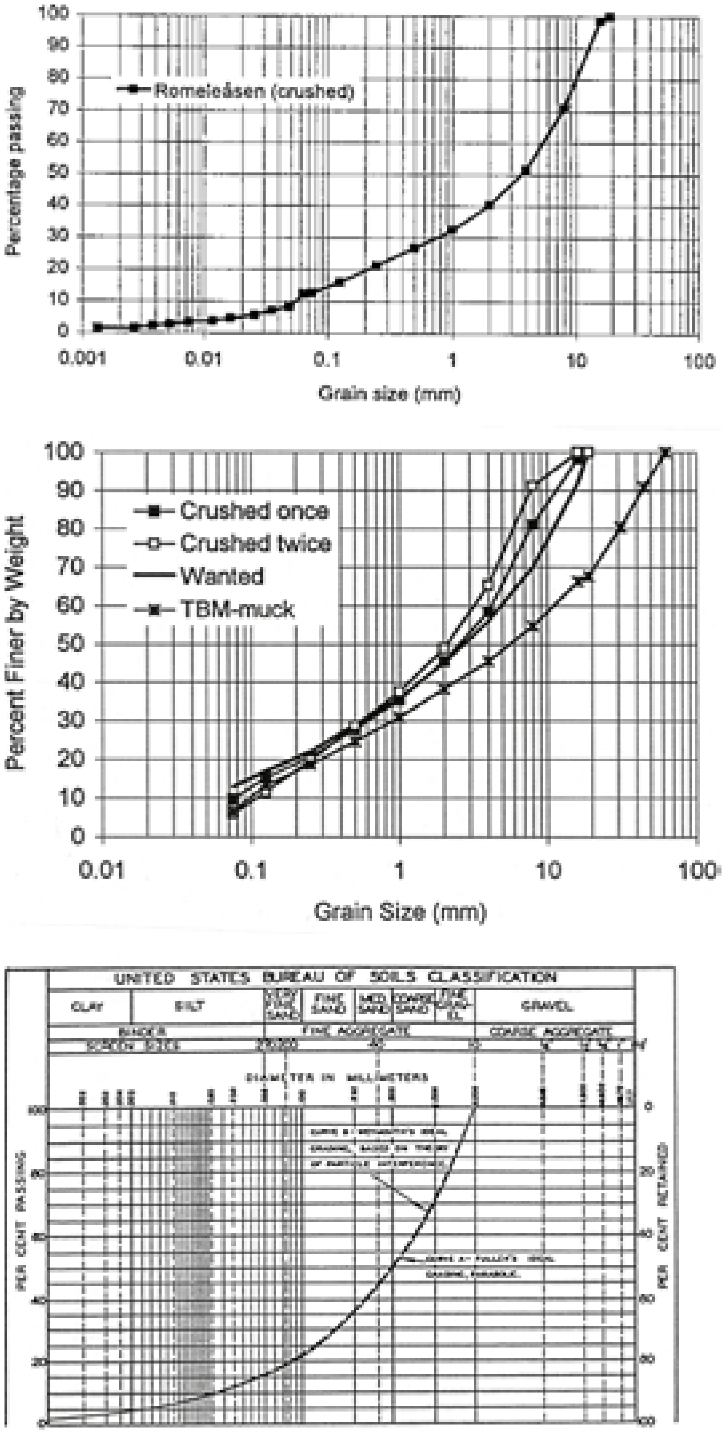

Figure 2-4. Examples of crushed muck of unweathered granitic rock. The diagram in the middle indicates that repeated crushing reduces the size of larger particles rather little, and that as much as 5–10% is finer than 0.1 mm. The curve representing TBM muck is coarser but still contains about 10% smaller than 0.1 mm /Gunnarsson et al. 2002/. The lowermost diagram shows the theoretical Fuller size distribution for comparison /Pusch 2002b/.

2.5.3 Processing of blasted rock

Sieving can be used for removing fragments larger than a specific size (90 mm for the uppermost layer in road embankments) but crushing for removing them is more economic because nearly all the crushed material can be utilized.

Crushing changes the size and shape of the blasted rock and the following empirically derived conclusions concerning its impact on the particle shape have been drawn /cf. Pusch 2000a/:

- The finest and most coarse fractions become most oblong while the intermediate fraction is more isodiametric ("cubical").
- Repeated crushing makes the particles less anisodiametric.
- The "brittleness coefficient, *B*" is a measure of the compressive strength of crushed rock. It is expressed as the difference in the amount of material passing the respective sieve apertures before and after compaction by a defined energy input. The brittleness is nearly a linear function of the splintery factor (for *F*=1.2 *B* is 25, for *F*=1.4 *B* is 35, for *F*=1.6 *B* is 50, etc).

Crushing of rock for production of ballast (aggregate) material can be made in one or two steps depending on the required gradation. Crushing of all the muck material is first made to reduce the grain size to a desired value for which gyratory crushers are suitable. A second crushing round can then be employed if the gradation needs to be changed /Eriksson 2001/.

The granulometry of crushed and ground rock is largely determined by the rock structure and by the sieving and crushing techniques. The grains formed by crushing crystalline rock naturally have a very low roundness while the sphericity factor may vary from nearly unity for massive rock like granite to less than 0.5 for rock with anisotropic structure like gneiss. The fragments are usually rich in fissures and fractures which give them an appreciable porosity and internal specific surface area. The low degree of roundness means that the particles have asperities that break under heavy compaction. This produces much fine debris (Figure 2-5), /Pusch and Yong 2006/. Such debris can cause significant time-dependent settlement of rock fills and effective flushing of water of crushed rock before and in conjunction with placing it is recommended for minimizing delayed compression.

One finds from Figure 2-6 that the hardness of the rock determines the steepness of the slope of the size distribution: the curve of crushed gneiss is very flat and moraine-like while the curve of crushed quartzite, which is very hard, is steep and has almost all particles in a narrow range, i.e. 20–32 mm. The grains contain large numbers of fissures, however, and break at effective compaction.

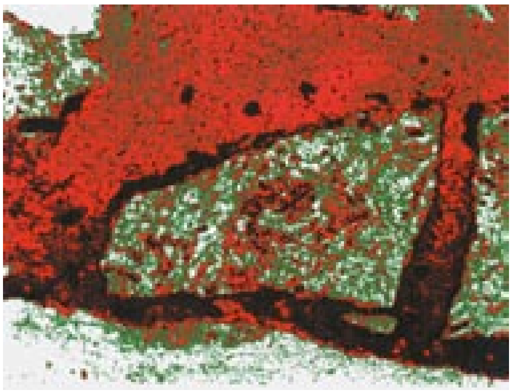

Figure 2-5. *Micrograph of thin section of acrylate-embedded ballast with coatings (black) of fine rock debris on quartz particles in crushed granitic rock. The backfill contains 10% mixed-in clay (red). Magnification 100x /Pusch and Yong 2006/.*

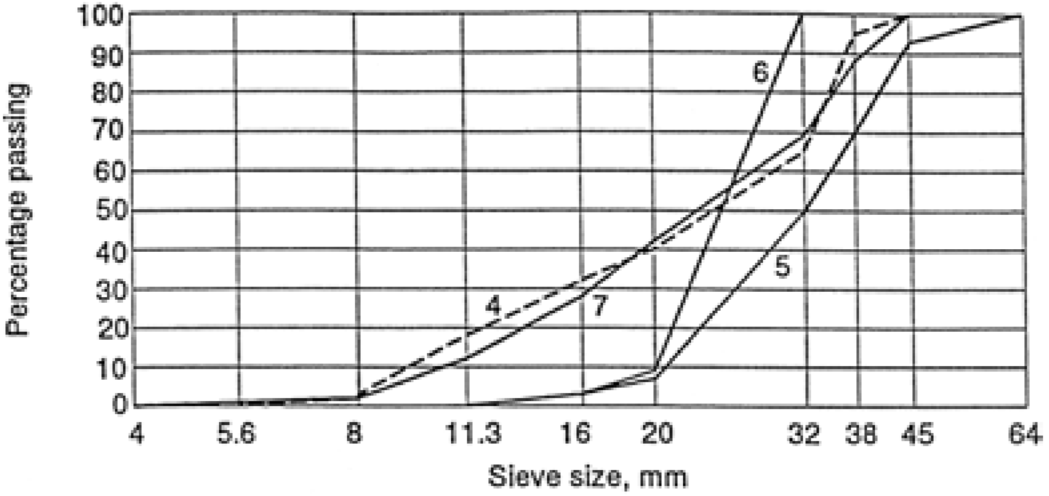

Figure 2-6. *Size distributions of coarse ballasts ("aggregate"). Types 4 and 7 are moraine-like, the firstmentioned being a mixture of well rounded glacial materials while the similar distribution curve 7 was obtained by crushing gneiss. Type 5, which is Fuller-like and similar to the crushed rocks in Figure 1-2, represents crushed fine-grained granite. Type 6 represents crushed quartzite and has almost all particles in a narrow range, i.e. 20–32 mm /Holopainen et al. 1984/.*

2.5.4 Formation and processing of TBM-muck

The cutting heads of tunnel boring machines (TBM) and raise-boring machines are equipped with buttons or discs that are pressed against the rock for fragmentation. This yields breakage in the form of crushing below the cutters and production of dominantly small fragments. TBM:s normally have discs and produce large chips that are platy because of the fracture pattern and the influence of tangential stresses. The impact on the rock and the fragmentation processes have been studied in detail in several contexts and the reason for the anisotropic shape explained, cf. Figure 2-7.

The mode of fracturing associated with the indentation of the discs of a TBM head gives much smaller fragments than blasting. The largest chips, which are typically very flat, are usually not longer than a couple of decimeters while smaller fragments are less anisometric. The very high contact pressure between discs and rock causes fine-fracturing to a few centimeters depth, which produces a large amount of relatively fine particles /Lindqvist 1982/. The elongation and flatness of the chips from TBM-drilling makes it necessary to express the size in terms of the ”diameters” *a*, *b* and *c* defined in Figure 2-1. As for blasted and crushed rock, measurements for determining the size distributions are made by use of square mesh and grating (rod) sieves. The former give the size in terms of the *b*-diameter while the latter yield the *c*-diameter. The large diameter *a* of the chips is commonly 1.2 to 2.2 times the intermediate diameter *b*, which is 2–3 times the smallest diameter *c*.

Figure 2-8 shows the typical size distribution of crushed TBM muck, represented by the *b*- and *c*-diameters. Crushing in one step yields Fuller-sized distributions that are hardly further improved by a second crushing round.

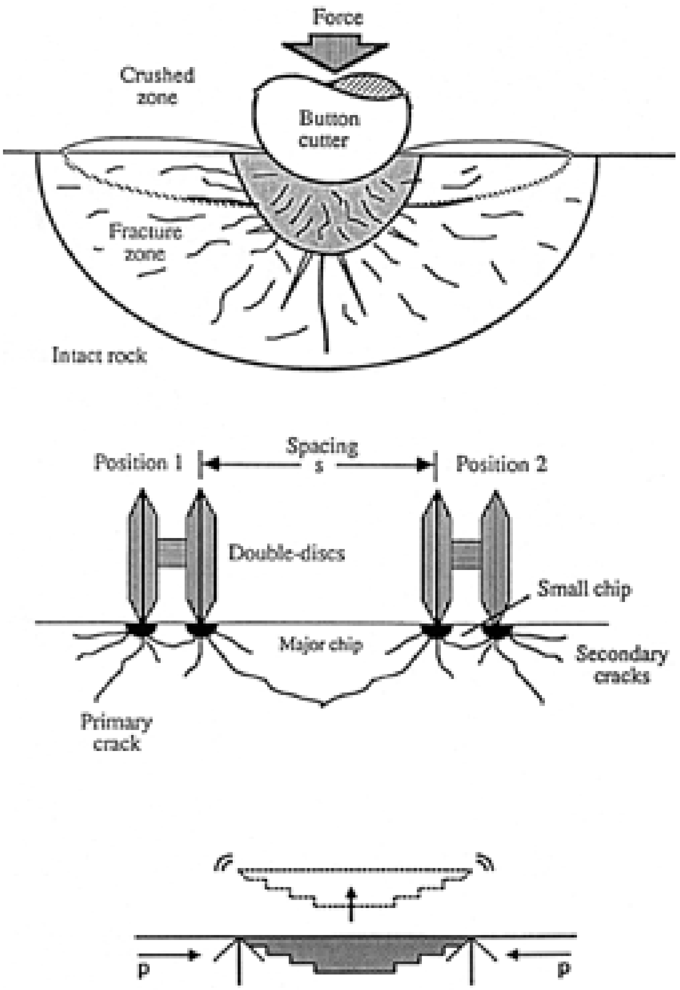

Figure 2-7. Fracturing of brittle rock. Upper: Whittaker's and Frith's model of the impact of button cutters. Central: Guo's model of chip formation. Lower: High tangential stresses release oblong chips /Whittaker et al. 1992/.

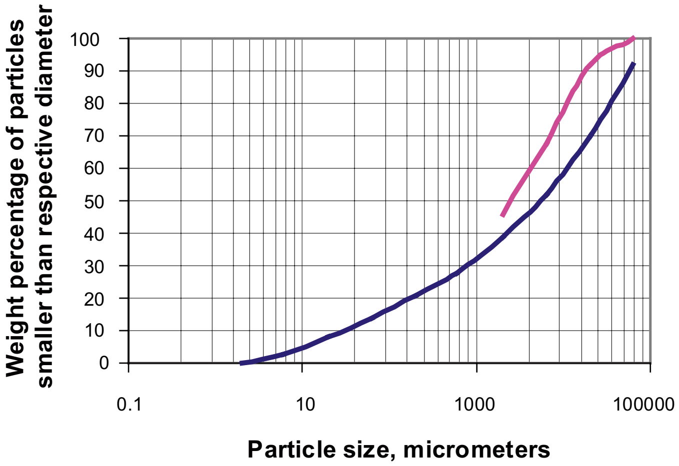

Figure 2-8. Crushed TBM muck. Typical size distribution in terms of c and b diameters. The upper curve represents "c" and the lower "b". Notice the Fuller-type size distribution of the lower curve (cf. Figure 2-4), /Pusch 2002b/.

2.5.5 Adjustment of the size distribution

Applying the principle of Fuller-type size distribution one can artificially compose a suitable mixture of different grain assemblies. This is illustrated by Figure 2-9, which shows the effect of mixing two components of which the finer part (sand) fits in the voids of the coarser ("stone"). The maximum dry density (1,820 kg/m^3) was obtained for a certain mass ratio, i.e. 55% sand.

2.5.6 Trimming of big blocks

As indicated in Figure 1-2 fairly well fitting blocks may be used for sealing the most shallow parts of ramps and shafts. Exact fitting, requiring comprehensive stone cutting work, is unsuitable since it can imply that the block masonry may not stay in contact with settling underlying backfill but remain in the original position by arching effects in shaft, causing significant local open space below it. Some trimming is required, however. Figure 2-10 shows an example of a block masonry structure that may be suitable for sealing ramps and shafts against human intrusion.

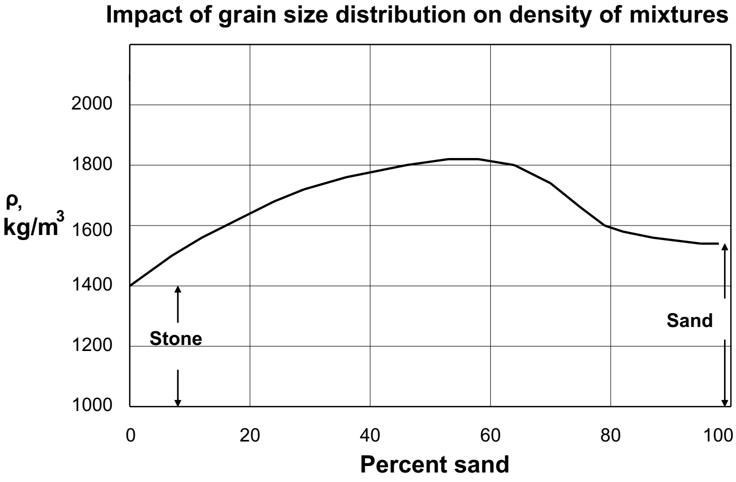

Figure 2-9. *Dry density of mixture of gravel (d=20–60 mm) and sand (d=0.06–2 mm). Curves derived from experimental data (data evaluated from /von Matern 1956/).*

Figure 2-10. *Masonry of granite blocks.*

3 Compaction

3.1 General

Use of rock material has been extensive since the beginning of the 19th century especially in dam and road construction for which crushed and granulometrically well defined rock fragments have been used. Blasted rock without crushing has also been widely used, in particular in landfills for creating new areas for industrial buildings and constructions like wharfs, and for apartment buildings. Large areas have been reclaimed by dumping unprocessed blasted rock containing boulder- and cobble-sized material in estuaries but the problem has been to reduce the settlement of such artificial ground. Ordinary compaction tools can not be used under water, which has required development of special techniques for this purpose. A method for effective compaction of rock fill dumped in water involves use of falling weights consisting of coupled, parallel strong steel bars, like rails. Such weights, which can have a mass from a few to several tens of tons, are dropped from several meters height and effectively compact even very coarse rock fills /Hansbo 1975, 1977/. This technique may be suitable also for compaction of rock fill in repository shafts that become flooded in conjunction with the filling operation.

Blasted rock fill placed and compacted for providing a basis for construction of buildings was long prohibited in Sweden because of the risk of unacceptably large compression of the fill and associated settlement of the houses. Much work was made in this country in the sixties and seventies for minimizing the compression and for understanding of the mechanisms involved in the strain and this has led to acceptance of compacted rock fill by the authorities /Lindblom 1973, Andreasson 1973/.

3.2 Density and porosity of rock fills

Uncompacted fills of coarse-grained soil like rock muck have a dry density of 1,600–1,800 kg/m^3 nearly independently of the grain size distribution, which, however, determines the compactability and the density achieved by compaction. The Fuller distribution naturally yields the highest density. The compactability can be predicted on theoretical grounds but the accuracy is poor since compaction causes crushing of big particles with low degree of roundness like blasted muck. The imposed compaction energy and the grain shape, particularly the sphericity, roundness, and initial degree of fracturing, as well as the mineralogy, play a role. In practice, one has to rely on empirical data illustrated by the examples in Table 3-1, which lists the materials described granulometrically in Figure 2-6. The data refer to laboratory tests using standard Proctor compaction, giving a dry density of about 2,010 kg/m^3 of all the investigated materials.

Table 3-1. Granulometry of coarse rock material defined in Figure 2-6 /Holopainen et al. 1984/.

Material	D_{50}* mm	$C_u=D_{60}/D_{10}$**	Splintery factor, F	Sphericity	Roundness	e_{max}***	e_{min}***
Glacial (4)	25	3.1	1	0.71	0.38	0.70	0.50
Crushed granite (5)	32	1.65	1.17	0.69	0.10	0.94	0.59
Crushed quartzite (6)	25	1.30	1.33	0.64	0.22	0.97	0.53
Blasted gneiss (7)	23	2.6	1.32	0.63	0.18	0.93	0.50

* Median particle diameter, ** Uniformity coefficient, ***void ratio.

The following major conclusions can be drawn from this and similar studies:

- Non-spherical grains and grains with a low degree of roundness, i.e. with rough surfaces, give lower bulk densities than spherical ones for any given grain size distribution, and require stronger compaction effort for reaching a given density.
- One finds that similarly sized grain assemblages of spherical and well rounded material (No. 4) and blasted rock (No. 7) in Table 2 had quite different void ratios before compaction (e_{max}) and after compaction (e_{min}), i.e e_{max}=0.70 and e_{max}=0.93, respectively, while they were equally porous after effective compaction, i.e. e_{min}=0.50. The obvious reduction of the *e*-value of crushed quartzite (No. 6) by compaction is explained by breakage of the grains, yielding numerous finer fragments and the same porosity and density as for the spherical, well rounded grains of glacial material.
- The splintery factor is a better measure of the anisotropy of platy grains than the sphericity. Blasting and crushing of granite do not yield significantly anisotropic fragments and their size is therefore usually taken as the square-mesh size. Hence, *a*, *b*, and *c* are approximated to be equal.
- For the same density there is nearly no difference in the smallest void size, while the largest void size is very different. The glacial, rounded particles move into stable positions with smaller particle spacing than the particles from crushed rock.

3.3 Placement and compaction methods

3.3.1 Road construction

General rules and recommendations for selecting a suitable granulometry of crushed rock for construction of road embankments are given in /AMA Anläggning 07 2007, Vägverket 2008/. Placement and distribution of rock fill is best made by use of tractors with blades that push the material forwards over already placed and compacted material to form 0.3–0.6 m thick layers for subsequent compaction by vibratory rollers. The density of well graded, Fuller-type coarse material, effectively compacted by very heavy vibratory rollers can be as high as 2,400 kg/m^3 /Smith 1968, Forsblad 2000/. For road embankments compacted by ordinary vibratory rollers (5–10 t) common density values are in the interval 2,050 to 2,200 kg/m^3. For the void ratio e=0.4, i.e. significantly lower than of the materials described in Table 2, the density is 2,210 kg/m^3, for e=0.5 it is 2,130 kg/m^3, and for e=0.6 the density is 2,060 kg/m^3. The latter corresponds roughly to the materials in Table 2. As for any rock fill the rules in road construction suggest that the material should be Fuller-graded since it implies the highest number of particle contacts for minimizing settlement of the embankments. The maximum particle diameter should be 30–40 mm and compaction made by use of vibrating single-rollers with line-loads and layer thicknesses according to Table 3-2.

Table 3-2. Most effective line-load for different layer thicknesses (max. particle size 36 mm), /Forsblad 2000/.

Line-load, kN/m	Maximum layer thickness, m	Weight of vibratory roller, t
15	0.2	6
25	0.3	10
30	0.4	15
45	0.6	20

Experience from road and airfield construction works shows that optimal results (technico/economical) are obtained by selecting rollers according to Table 3. The maximum cobble or boulder size should be 2/3 of the layer thickness, which can be up to 0.6 m if subsequent compaction is made by a 20 t vibratory roller /Forsblad 2000/. If only 10 t rollers are available the layer thickness should not exceed 0.3 m and the maximum diameter hence not be larger than 200 mm (Table 3-2). These principles are followed in road construction while bigger boulders are allowed in dam construction.

3.3.2 Dam construction

Thicker layers and larger boulders are accepted in earth dam construction than in road building and 0–500 mm is a commonly used size interval /Bernell 1958, Vattenfall 1988, Gustafsson and Wanhainen 1982/. Acceptable compaction of dam fills, yielding dry densities of around 2,000 kg/m^3, is reported to be achievable by using vibrating single-rollers with 6 t weight (1.0 m), 10 t (1.5 m), and 15 t (2.0 m) /Höeg et al. 1996/. They provide line-loads of 30 kN/m, 45 kN/m and 60 kN/m, respectively. Flushing water over the rock fill in conjunction with the compaction work gives more effective densification than dry compaction. This is partly caused by removal of fines that prevent larger cobbles and boulders to come in close contact, but predominantly by releasing stresses at the contacts between adjacent blocks. Thus, the rock at these contacts is fine-fractured by high stresses in the placement phase and wetting develops breakage and slip by which the big objects move and come closer.

3.3.3 Backfilling of tunnels and underground rooms

General

As for road and dam construction the best way of moving rock fill in rooms, drifts and tunnels is to use tractors with blades since the various rock fragments thereby undergo abrasion and are forced into dense layering. The uppermost part of the backfill in a tunnel cannot be placed and compacted in horizontal layers but requires placement in inclined layers compacted by crane-held vibrator plates or ramming tools. Still, there will be a gap at the roof that has to be filled with dense, expansive clay for maintaining contact between the backfill and the roof (Figure 3-1).

The ealier mentioned criterion that the maximum diameter of cobbles and boulders should not exceed 2/3 of the layer thickness applies also in backfilling of tunnels. Since TBM muck commonly has all particles smaller than about 200 mm it should be placeable without crushing but such processing is still recommended for reaching a more suitable gradation and a high density.

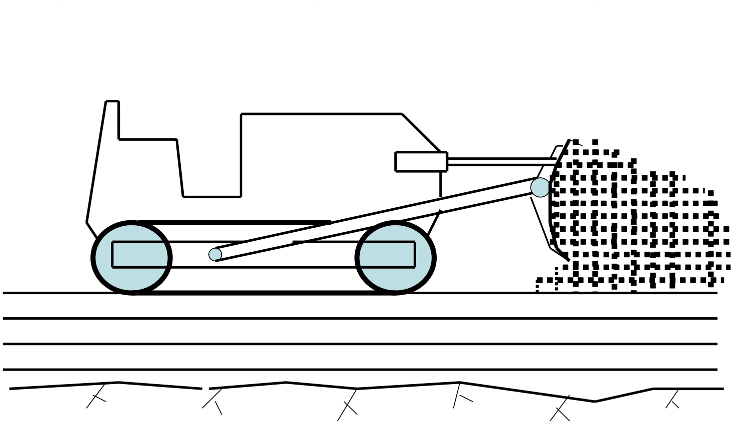

Figure 3-1. *The most effective way of placing rock fill to become dense is by using tractors (bulldozers) with blades. The layers are smoothened and compacted by vibratory rollers /Forsblad 2000/.*

In simpler backfilling operations with no need of reaching a high density it would be possible to place all the rock fill in inclined layers by tractors as indicated in the upper part of Figure 3-2 and combine this with compaction as indicated in the lower part of this figure.

Rammers are effective compacting tools that can give higher densities than vibrating rollers and they may be used for effective compaction of horizontal or inclined layers if they are held by a crane like the ones used for manoeuvering the vibrating plate in Figure 3-2. The German "Frosch" compactor driven by a combustion engine was earlier frequently used in the construction of German highways and further developed versions may serve well for compaction of crushed rock. The original was a 1 t machine that jumped up and forwards in 0.5 m steps and effectively compacted rock with smaller size than about 50 mm. Bigger versions should be suitable for even coarser stone material.

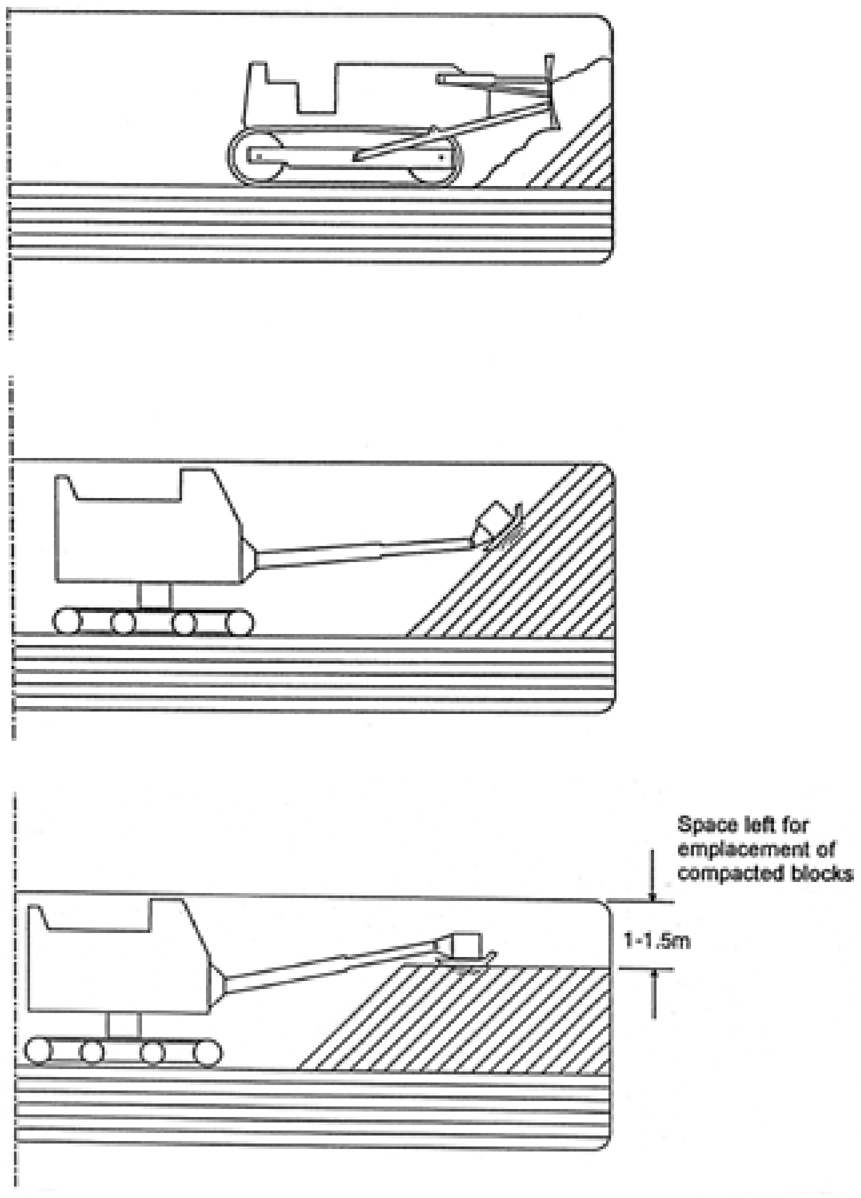

Figure 3-2. *Techniques for placement of backfills. Upper: Pushing in the backfill in the upper part of the room to form inclined layers. Central: Layer-wise compaction of the upper part of the backfill. Lower: Vibrating plates used for compacting the upper part leaving a gap for placing dense clay blocks or blowing in clay pellets /Gunnarsson et al. 2002/.*

Experience from SKB experiments

Backfilling experiments have been performed in SKB's projects in the "Prototype Repository Project" and the "Backfill and Plug Test" at Äspö. They involved placement of rock debris from tunnel boring (TBM-muck) with and without compaction. Some tests were made with material that had been stockpiled without further treatment while crushed muck was used in certain other tests. The crushed material was sieved to yield a maximum grain size of 20 mm, and 90% smaller than 8 mm, 50% smaller than 2 mm, 25% smaller than 0.4 mm and 10% smaller than 0.1 mm /Börgesson et al. 1996/. Proctor compaction (89%) of this material gave a dry density of 2,100 to 2,300 kg/m^3.

The Prototype Repository Project included placement and compaction of virgin and crushed TBM-muck in horizontal and inclined (sloping) layers. Horizontal layers of virgin TBM-muck compacted by a 5 t vibratory roller had a dry density of 2,430 kg/m^3 while crushed muck had a maximum dry density of 2,210 kg/m^3 /Gunnarsson et al. 1996/. Placement of virgin TBM-muck without compaction to form inclined layers gave a dry density of 1,600 to 2,120 kg/m^3 while compaction gave 2,210–2,330 kg/m^3. Crushed rock gave a dry density of 2,140 kg/m^3 of inclined layers.

*The Backfill and Plug Te*st comprised placement and compaction of crushed TBM-muck to form inclined layers /Gunnarsson et al. 2001/. The density was found to range between 2,110 and 2,210 kg/m^3. These experiments included placement of compacted clay blocks on top of the rock-fill.

The experiments indicated that crushed TBM-muck can not be compacted as effectively as virgin muck, which may be related to discontinuities in the grain size distribution or to differences in grain shape.

4 Compressibility

4.1 Mechanisms

Compression of placed and compacted coarse frictional material by an applied load or under its own weight results from the integrated mutual displacement of all the grains. For crushed rock compression is strongly dependent on the porosity as for any other soil but also on mechanical degradation of the grains contacts. They carry high loads and break, undergoing strong fissuring, which causes time-dependent strain, particularly at wetting.

Figure 4-1 illustrates schematically mechanisms that cause compaction of large block assemblies under compression. Masonries of well fitting blocks that can be placed in the uppermost part of shafts and ramps for making human intrusion difficult is shown to the left (A). The compression is very small even at very high pressures. Assemblies of relatively well fitting blocks with wide joints behave in the same way up to a load that starts breaking the blocks (B). Assemblies of poorly ordered blocks (C) undergo large compression even at fairly low loads.

Compression under an external load causes settlement of the fill. Self-compaction is the term for compression under the own weight of the fill.

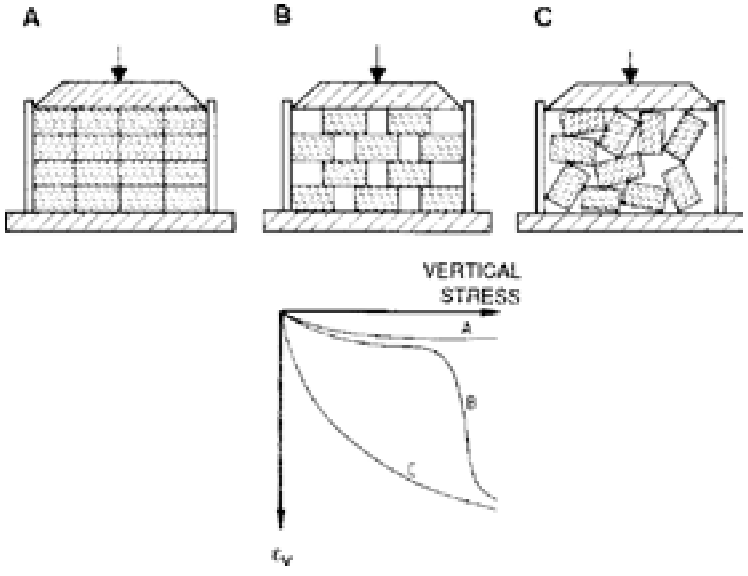

Figure 4-1. *Compression of block configurations /Kjaernsli et al. 1997/.*

4.2 Theory

There is no complete theoretical model for predicting the magnitude and rate of compression. However, "instantaneous" strain can be estimated by use of the expressions described below.

The compressibility of soil is expressed in terms of the oedometer modulus M at one-dimensional compression under lateral confinement /Andreasson 1973/:

$$M=m\sigma_j\{\sigma'/\sigma_j'\}^{(1-\beta)} \tag{4-1}$$

where:

M = oedometer modulus

m = modulus number

β = stress exponent

σ' = effective compressive stress

σ_j' = reference sress, commonly 100 kPa

Integration of the expression $d\varepsilon = d\sigma'/M$ yields the compression ε, *taking C* as a constant:

$$\varepsilon=1/m\beta\{\sigma'/\sigma_j'\}^{\beta}+C \text{ for } \beta \text{ higher or lower than } 0 \tag{4-2}$$

$$\varepsilon=1/m\beta\, ln\{\sigma'/\sigma_j'\}+C \text{ for } \beta=0 \tag{4-3}$$

Typical m and β values are shown in Figure 4-2. These diagrams suggest that relevant m for rock fills is 5E5 and β=1.

Using Eq. 1 for estimating the settlement of backfill in a shaft under an overburden pressure caused by 400 m backfill one obtains ε=0.4%, meaning that a 10 m thick section of crushed rock at 400 m depth would be compressed by 10 cm. This demonstrates that vertical displacements in the shafts of a repository will be significant.

The "instantaneous" strain generated by loading is followed by time-related deformation, i.e. creep. It can be considerable but there is almost no experience except from recording of the settlement of dam crests as described in the subsequent section. The involved mechanisms are similar to those producing creep in other soils, implying that microstructural energy barriers have to be climbed to yield creep. According to rate process theory this means that the compression rate is proportional to log time /Pusch and Yong 2006/. Hence, compression by 1 mm after 1 year grows to 2 mm after 10 years, 3 mm after 100 years etc.

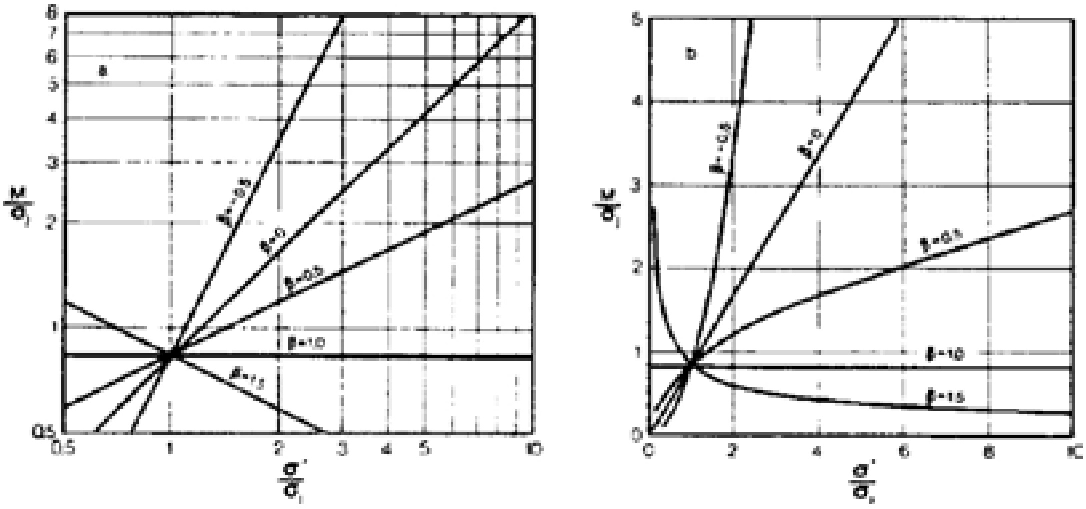

Figure 4-2. *Typical m- and β-values for various soil materials /Pusch 2002a, Andreasson 1973/.*

4.3 Empirical

4.3.1 Measurements of rock fill dam settlement

Rock fills settle under their own weight and dry rock fills can undergo compaction by up to 2%, while for fills flushed with water in the construction phase it may be significantly less than 2% /Höeg at el 1996/. This is illustrated by measurement of Norwegian rock fill dams of which more recently constructed ones with water-flushing show a settlement of the crown, expressed in percent of the total dam height, of 0.17%, while the corresponding ratio for older dams constructed without flushing is about 1.7%. The rock material in the inner shoulder part of these dams had a particle size ranging between 0 and 400 mm and was placed in 0.6 m layers subsequently compacted by 15 t vibratory rollers (8 passes). For the outer shoulder part the size ranged between 0 and 800 mm placed in 1.6 m layers and compaction was made by 15 t vibratory rollers (6 passes).

Using the value ε=0.15% for estimating the compression of a 5 m high backfill of crushed rock or TBM muck in a repository tunnel would yield a settlement of the top of the backfill of about 8 mm after several decades. There will hence be a gap of this magnitude between the roof and the backfill placed in a tunnel.

4.3.2 Experimental

Compression tests of differently compacted crushed granite rockfill have been reported in the literature and Figure 4-3 illustrates the very significant effect of the applied compaction energy on the compressibility of such material /Brauns et al. 1980/. The tests were made on granite material and showed that the compression of material that had been compacted 4.5 times more effectively than implied by (laboratory) Proctor technique was only about 20% of the Proctor-compacted material. If the energy was only about 12% of the Proctor-produced energy the compression was about 4 times larger than for the Proctor-compacted material.

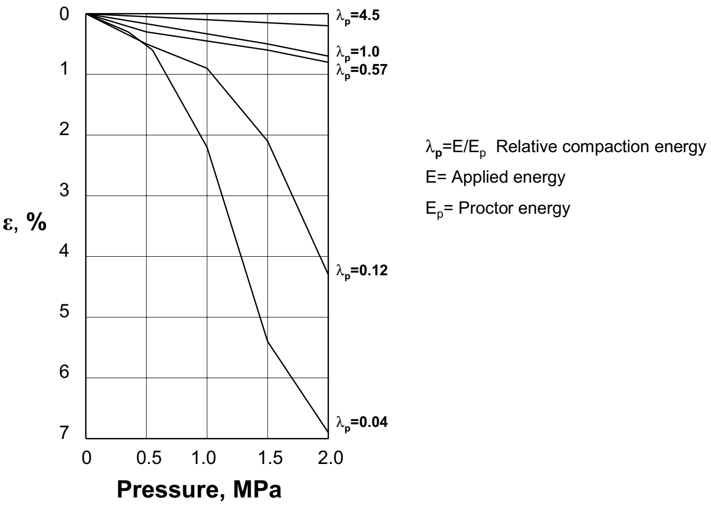

***Figure 4-3.** Compaction effect on the compressibility of crushed rock under uniaxial loading /Brauns et al. 1980/.*

5 Shear strength

Rock fills have high shear strength. They perform as Mohr/Coulomb materials with no cohesion but an angle of internal friction of more than 35°. Loosely layered crushed rock fill behaves as coarse sand for which one can take the friction angle to be about 35°, and compaction increases the angle strongly by the impact of dilation due to interacting asperities of contacting mineral surfaces /Pusch 1994/. For rock fills that have been effectively compacted to a dry density of around 2,000 kg/m^3, the apparent angle of internal friction is hence more than 45° and even up to 60°, giving the compacted mass very high stability. Such a mass can be excavated to form stable vertical slopes.

The absence of “preconsolidation pressure” means that the peak strength of a sheared rock fill mass is not reached until the strain has become substantial. This means that the pressure exerted by such a fill on stiff confining structures, like plugs and rock walls, is high. It can exceed earth pressure at rest /Sutton 1986/ if the fill is compacted close to such structures.

6 Hydraulic conductivity

The hydraulic conductivity of porous media has been subject to numerous studies and modelling attempts assuming non-turbulent flow. In principle, they apply also to rock fills.

6.1 Theoretical considerations

Starting from Darcy's basic flow equation one can express the unit flux q in terms of mass of water flowing perpendicularly through a given area of an isotropic porous medium, as a function of seven characteristic parameters /Kenney et al. 1984/.

$$q = f(i, \gamma, \mu, D_{x,} S, \eta, n) \tag{6-1}$$

where:

i = hydraulic gradient

γ = density of fluid

μ = viscosity of fluid

D_x = representative grain size

S = gradation factor expressing the shape of the grain distribution curve

η = grain shape factor

n = porosity

By means of dimensional analysis the following expression can be derived /Kenney et al. 1984/:

$$q = i(\gamma / \mu)k_0 \tag{6-2}$$

and:

$$K = (\gamma / \mu)k_0 \tag{6-3}$$

where:

K = experimentally determined hydraulic conductivity,

k_0 = "specific permeability" of dimension $(\text{length})^2$ describing the geometry and size of the void network,

k_0 can be expressed as:

$$k_0 = \beta_\alpha \cdot D_a^2 \tag{6-4}$$

where:

β_α = dimensionless factor describing the geometry (but not the size) of the void network

D_α^2 = measure of the cross-sectional area of the average pore channel

Plottings of $\log k_0$ and $\log K$ versus different particle size fractions show that $\log D_5$, which is the percentage of particles representing the 5th percentile of the grain size curve for different grain size distributions, is a key parameter, implying that the few weight percent of the finest material most significantly affect the hydraulic conductivity almost independently of the rest of the grain size distributions (Figure 6-1). Hence, the Fuller law, implying parabolic shape of the grain size curve, would not have to be followed provided that D_5 is sufficiently small, preferably less than 0.005 mm. This is validated by the fact that moraine, which is commonly characterized by an almost straight curve in grain size diagrams of the type shown in Figure 6-2, is low-permeable because of its content of very small grains. However, the finest grains need to be safely confined between bigger grains for avoiding transport by flowing water so Fuller-type granulometry is still desirable.

The diagram in Figure 6-1 indicates that C_u is not a determinant of the bulk hydraulic conductivity but that D_5 has this role. Different α-values in D_α changes the position of the bands but it is concluded that α=5, which corresponds to D_5, is the conductivity-controlling particle size independently of the particle distribution of the rest of the mineral mass provided that the distribution curve is not discontinuous. Taking as an example a Fuller-type material with $D_5 = 0.008$ mm the conductivity would be in the range of E-6 to E-5 m/s, which is on the same order of magnitude as the conductivity of the most fine-grained materials represented in Figure 6-2.

Calculation of the hydraulic conductivity by use of this theory gives data that agree in principle with those obtained from testing of Swedish and Finnish coarse soils, like the mixtures of crushed and ground rock described granulometrically in Figure 6-2. Materials without finely ground rock had a hydraulic conductivity of E-5 m/s, while addition of fines gave conductivities down to E-7 m/s. This is in agreement with the outcome of systematic Canadian studies /Kenney et al. 1984/. The lower diagram in Figure 6-2 shows laboratory (Proctor) compaction curves of the materials from which one concludes that the water content is of substantial importance for reaching a high dry density of coarse materials.The most Fuller-like material (IVO-4) became most dense.

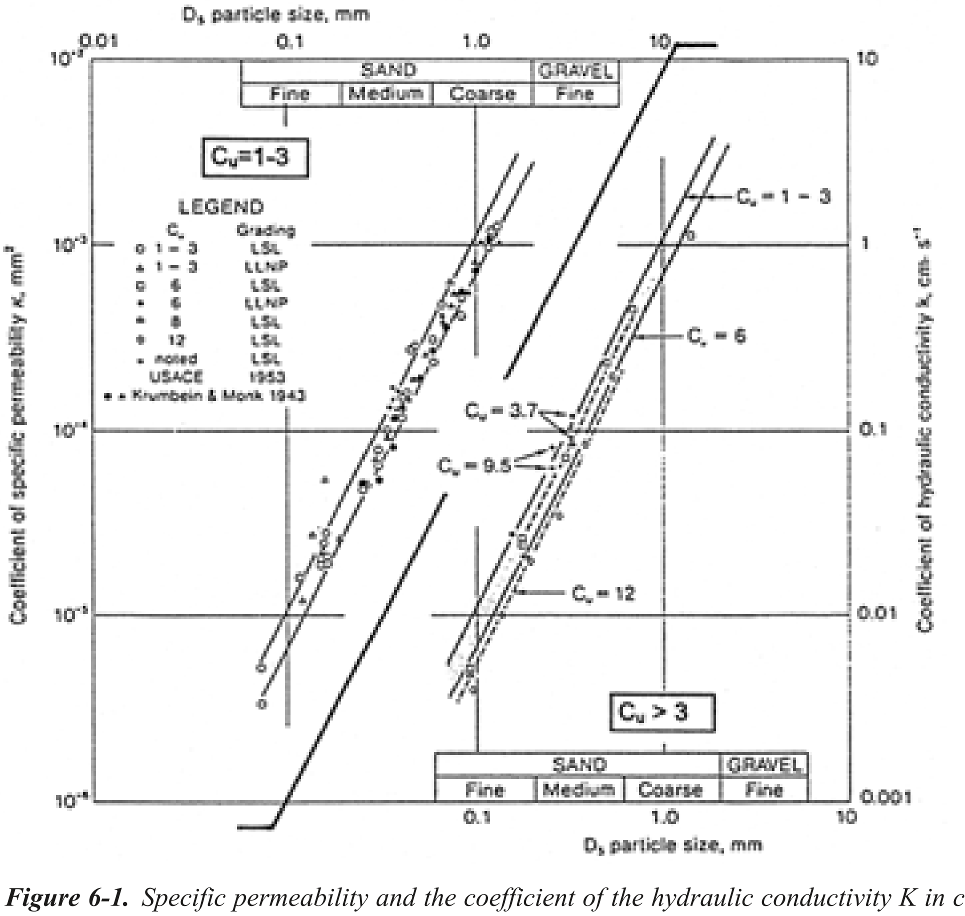

__Figure 6-1.__ Specific permeability and the coefficient of the hydraulic conductivity K in cm/s (K is termed k in the diagram) /Kenney et al. 1984/.

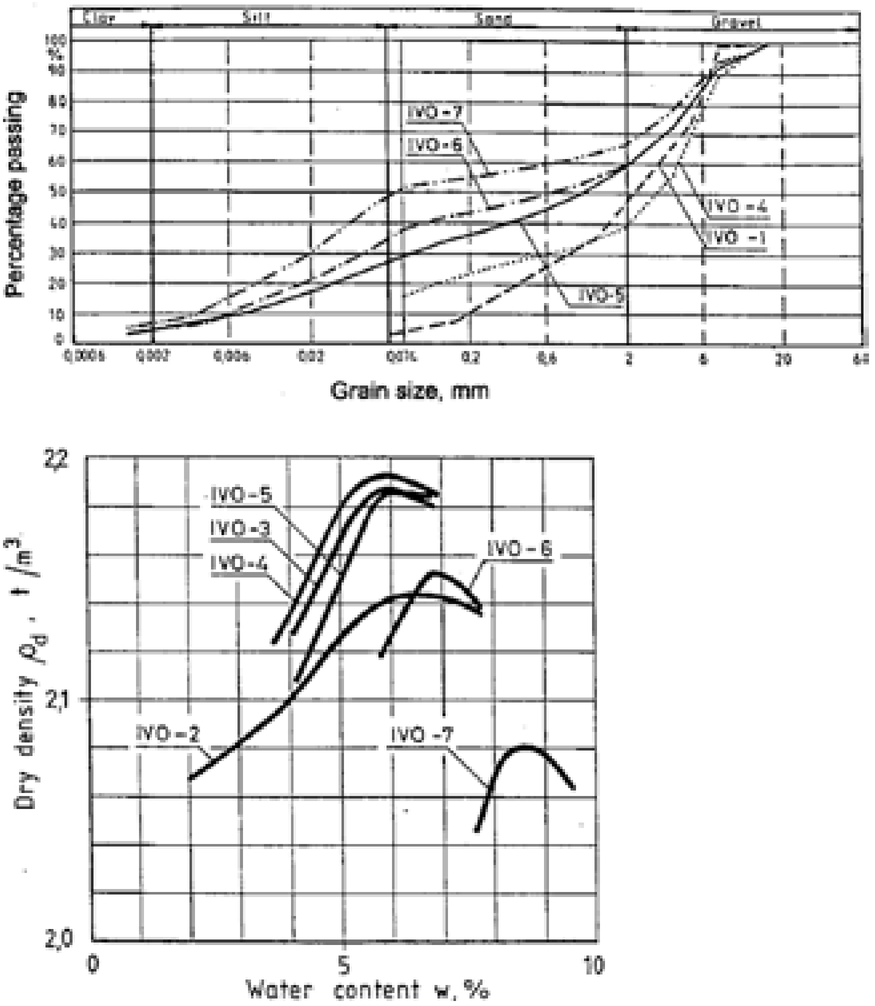

Figure 6-2. Grain size and compaction curves of Finnish mixtures of crushed and ground rock investigated with respect to the hydraulic conductivity /Holopainen et al. 1984/.

The importance of the tail of the size distribution curve has been recognized in the composition of earth dam cores for many years and it was also a major issue in the composition and preparation of the backfills of the Buffer Mass Test (BMT) in the underground research drift in the Stripa mine /Pusch et al. 1985/.

The aforementioned compaction tests made in conjunction with SKB's large-scale field tests included determination of the hydraulic conductivity of crushed TBM rock in the laboratory (cf. Section 3.3.3). The outcome of these tests was that very densely compacted crushed TBM-muck (dry density about 2,300 kg/m^3) can give a hydraulic conductivity as low as 2E-10 m/s, and that such material compacted to a dry density of 2,100 to 2,210 kg/m^3 is characterized by a hydraulic conductivity of 2E-8 to E-7 m/s. All these values are significantly lower than the theoretical model (Figure 6-1) and the Finnish tests provide and their relevance is being further checked.

7 Mineralogy

For backfilling of repositories for highly radioactive waste it is essential to select rock backfill so that it does not degrade of the buffer clay embedding the canisters or the canisters. This means that the content of sulphur-bearing minerals like pyrite should be at minimum for minimizing the risk of canister corrosion, and that the carbonate content should be low enough to avoid significant dissolution and formation of voids. Furthermore, the content of potassium-bearing, easily dissolved minerals like K-feldspars, should not exceed that of granites with common content of microcline and orthoclase (cf. Table 7-1), especially in tunnels and rooms close to the deposition area. This is for eliminating the risk of more rapid conversion of the smectite in the buffer to illite than predicted /Pusch and Yong 2006/.

Table 7-1. Rock-forming minerals as backfill components /Pusch 1993/.

Group	Mineral	Species	Elements	Properties
Silicates (S)	Quartz		Si, O	Excellent (physically and chemically stable, high thermal conductivity)
	Feldspars	Microcline	Si, Al, K, O	Poor (provides potassium to smectite)
		Orthoclase	Si, Al, K, O	Poor (provides potassium to smectite)
		Plagioclase	Si, Al, Na, Ca, O	Good (physically and chemically stable)
	Pyroxene		Si, Fe, Mg, O	Good (physically and chemically stable)
	Amphibole		Si, Al, Fe, Mg, O, OH	Acceptable (physically unstable, chemically stable)
	Mica	Muscovite	Si, Al, K, O, OH	Poor (physically and chemically unstable)
		Biotite	Si, Al, K, Mg, Fe, O, OH	Poor (physically and chemically unstable)
	Epidote		Si, Al, (Fe), Ca, O, OH	Good (physically and chemically stable)
	Chlorite		Si, Al, Mg, Fe, O, OH	Poor (physically unstable)
Oxides (O)	Magnetite		Fe, O	Good (physically and chemically stable)
	Hematite		Fe, O	Good (physically and chemically stable)
Carbonates (C)	Calcite		Ca, O	Poor (physically and chemically unstable)
	Dolomite		Ca, Mg, O	Acceptable (chem. stability)
Sulphates (S)	Gypsum		Ca, S, O	Poor (Gives off sulphur)
	Barite		Ba, S, O	Poor (Gives off sulphur)
Chlorides (Cl)	Halite		Na, Cl	Poor (Dissolves and raises the porewater salinity)
Elements	Graphite		C	Poor (physically unstable)

8 Sensitivity to seismic impact

Liquefaction may be a serious problem for any water-saturated backfill with low density, since seismically induced shearing will cause contraction and development of a porewater overpressure that can reduce the effective pressure to a critically low level – particularly in slopes. For densities exceeding about 1,800 kg/m^3, this is not a problem as long as the seismic events represent lower values on the Richter scale than 6 /Pusch 2000/.

For low-permeable clayey, silty and sandy soils saturated with water loose layering can lead to liquefaction while dense layering of such soils make them insensitive to seismic attack. This is because dilatancy generated by shearing yields porewater suction and associated increase in effective pressure. Not unless the exposure to critical amplitudes and frequency of the vibrations persists there will be expansion and possible approach to a critical density /Sutton 1986/ and unstable conditions. Coarse soils like rock fills have a much higher conductivity and the porewater pressure is not raised to a critical level and the effective pressure not lowered enough to make them stable even at strong and lasting seismic impact.

Strong and repeated earthquakes may, however, cause quick compaction of rock fills that is estimated to be on the same order as the self compaction under static conditions. Using the earlier derived compression under own weight, a 5 m high tunnel backfill in rock that is exposed to seismic events may hence undergo a total compaction of about 15 mm, by which a gap between fill and roof of the same magnitude will be formed. The corresponding compaction of a 200 m rock fill in a shaft would be on the order of one half to one meter, which would cause considerable discontinuities at its upper end. Naturally, several strong earthquakes will produce accumulated compaction and so will convergence of the surrounding rock by creep and glacial loading.

9 Conclusions and suggestions

Backfill of rock material in the ramp, shafts and repository rooms other than deposition tunnels can be processed and placed in different ways for fulfilling different requirements. The most simple function of the rock backfill is to occupy the space with no other requirement than to prevent substantial, ultimate convergence of the surrounding rock and to make intrusion difficult. A more demanding performance is to provide an effective support of the surrounding rock for minimizing convergence of the room and to eliminate intrusion. The most advanced function would be to perform in this way and at the same time also be as tight as the surrounding rock. The respective functions and properties can be provided in the following ways:

i) Simple backfill for preventing substantial ultimate convergence of the room and collapse of the surrounding rock

Unsorted blasted rock dumped in bulk and moved in by use of tractors without compaction can form backfills with an average dry density of 1,600–1,800 kg/m^3. Self-compaction will be significant and cause separation from the tunnel roof of several centimeters and even decimeters. Large local voids are expected in which organic material can be accumulated and develop. The backfill will undergo further, considerable compression if and when insufficient stability of the surrounding rock causes convergence. Even poorly densified rock backfill will make intrusion rather difficult.

ii) Backfill for providing effective support of the surrounding rock for minimizing convergence of the surrounding rock, and to make intrusion difficult

Crushed blasted rock and TBM muck placed by tractors in horizontal layers and compacted by 5–10 t vibrating rollers in the lower part of the rooms, and moved by tractors to form inclined layers compacted by vibrating plates in the upper part, yield an average dry density of 1,900–2,000 kg/m^3. The backfill in 5 m high tunnels will undergo small self-compaction, i.e. about 5–10 mm but be compressed if and when the room begins to converge. In the uppermost 50 m part of ramp and shafts, rock blocks from the stone industry trimmed to fit reasonably but not perfectly well will serve as a very effective obstacle to intrusion.

iii) Backfill for providing effective support of the surrounding rock for minimizing convergence of the room and to make intrusion difficult, and also to make the backfill as impermeable as the surrounding rock

Crushed blasted rock and TBM muck mixed with rock flour to $D_5 < 0.001$ mm and placed by tractors in horizontal layers and compacted by 5–10 t vibrating rollers in the lower part of the rooms, and moved in by tractors to form inclined layers compacted by vibrating plates in the upper part, will yield an average density at water saturation of 2,050–2,200 kg/m^3. The backfill will probably have a hydraulic conductivity in the range of E-8 to E-7 m/s, which is comparable to that of the contacting rock. The backfill will undergo moderate compression if and when the room begins to converge. Self-compaction will be insignificant, i.e. about a few mm. If blocks of highly compacted smectitic clay are placed between the roof of the rooms and the compacted rock fill the roof will be supported sufficiently much to prevent formation of an open gap at the roof. In the uppermost 50 m part of ramp and shafts, rock blocks from the stone industry trimmed to fit reasonably but not perfectly well will serve as a very effective obstacle to intrusion.

iv) Top filling for preventing human intrusion

Filling of fairly well fitted blocks of crystalline rock in the most shallow parts of ramp and shafts. Such fill, which is difficult to remove and investigate by drilling because of slight block movements, will settle slightly when the underlying backfill matures. Good but not perfect fitting of the blocks eliminates arching and risk of open space between this fill and the underlying in conjunction with the settlement. The porosity is very low but the hydraulic conductivity initially high, probably higher than E-5 m/s, before the joints become occupied by migrating fines from the surface. It may ultimately drop to less than E-8 m/s. Preparation of the blocks requires some trimming.

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