BILAGOR

Bilaga A: LCC-modellen och manual för användning[1]

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Bilaga A: LCC-modellen och manual för användning[2]

A1. Allmänt

Den här modellen beräknar livscykelkostnaden för en teoretisk tunnel med avseende på underhållskostnaden för de ingående bergförstärkningarna.

Modellen tar hänsyn till ett flertal olika typer av bergförstärkningar/underhållsåtgärder, tunnelns dimensioner, livslängd och kalkylerad ränta. Resultatet av analysen åskådliggörs med hjälp av diagram som visar dels de ingående delarnas bidrag till totalkostnaden dels totalkostnadens utveckling över tiden. Även kvarvarande underhållskostnad redovisas.

Modellen kan användas för att jämföra olika förstärkningsalternativ och är ett stöd vid val av förstärkningsåtgärd om den totala livskostnaden för tunnelns underhåll är ett kriterium för valet.

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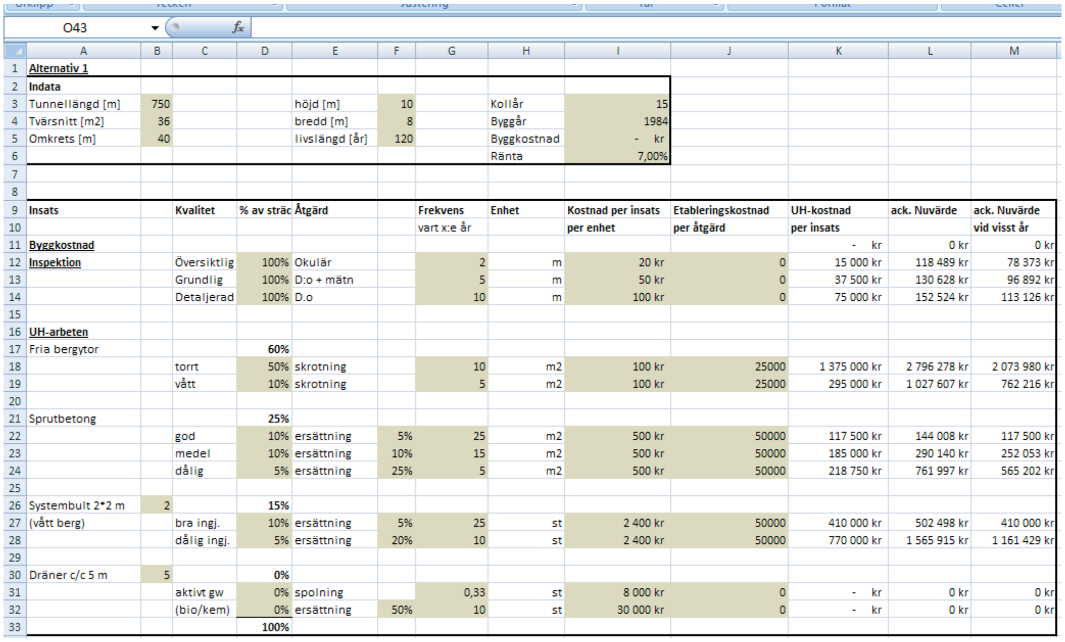
[1] Avsnittet författat av Sebastian Almfeldt

[2] Avsnittet författat av Sebastian Almfeldt

A2. Beskrivning av modellens beståndsdelar

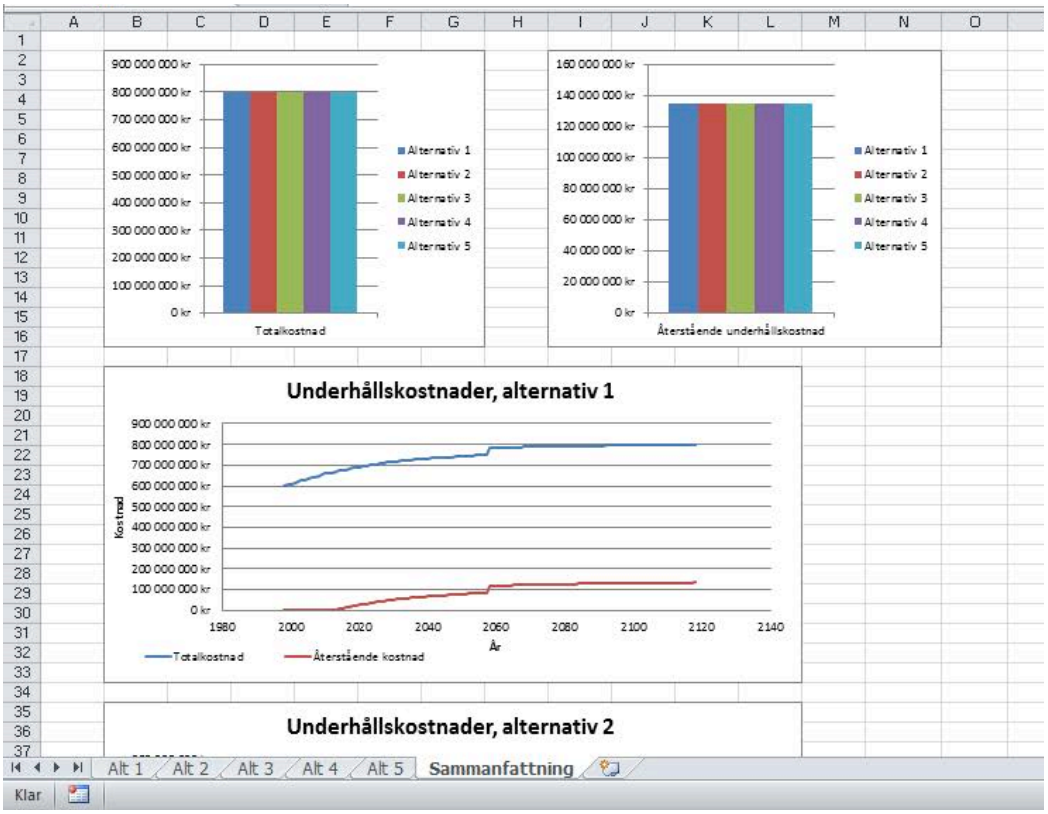
Excelarket som utgör modellen består av sex arbetsblad. I de första fem bladen anges de ingångsparametrar som modellen använder för att beräkna livscykelkostnaden för projektet, se *Figur 1*. Varje blad motsvarar en alternativ konstruktion där blad 1 är grundalternativet som de övriga fyra alternativen ställs emot vid jämförelsen.

Jämförelsen sker i den sista fliken, ”*Sammanställning*”, se *Figur 2*. Sammanställningsfliken innehåller jämförelsedata mellan de fem alternativen och presenterar kostnaden för varje enskild förstärknings- och underhållsåtgärd samt dess återstående kostnad.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**Alternativ 1**												
2	**Indata**												
3	Tunnellängd [m]	750			höjd [m]	10		Kollår	15				
4	Tvärsnitt [m2]	36			bredd [m]	8		Byggår	1984				
5	Omkrets [m]	40			livslängd [år]	120		Byggkostnad	- kr				
6								Ränta	7,00%				
7													
8													
9	**Insats**		**Kvalitet**	**% av sträc**	**Åtgärd**		**Frekvens**	**Enhet**	**Kostnad per insats**	**Etableringskostnad**	**UH-kostnad**	**ack. Nuvärde**	**ack. Nuvärde**
10							vart x:e år		**per enhet**	**per åtgärd**	**per insats**		**vid visst år**
11	**Byggkostnad**										- kr	0 kr	0 kr
12	**Inspektion**		Översiktlig	100%	Okulär		2	m	20 kr	0	15 000 kr	118 489 kr	78 373 kr
13			Grundlig	100%	D:o + mätn		5	m	50 kr	0	37 500 kr	130 628 kr	96 892 kr
14			Detaljerad	100%	D.o		10	m	100 kr	0	75 000 kr	152 524 kr	113 126 kr
15													
16	**UH-arbeten**												
17	Fria bergytor			**60%**									
18			torrt	50%	skrotning		10	m2	100 kr	25000	1 375 000 kr	2 796 278 kr	2 073 980 kr
19			vått	10%	skrotning		5	m2	100 kr	25000	295 000 kr	1 027 607 kr	762 216 kr
20													
21	Sprutbetong			**25%**									
22			god	10%	ersättning	5%	25	m2	500 kr	50000	117 500 kr	144 008 kr	117 500 kr
23			medel	10%	ersättning	10%	15	m2	500 kr	50000	185 000 kr	290 140 kr	252 053 kr
24			dålig	5%	ersättning	25%	5	m2	500 kr	50000	218 750 kr	761 997 kr	565 202 kr
25													
26	Systembult 2*2 m	2		**15%**									
27	(vått berg)		bra ingj.	10%	ersättning	5%	25	st	2 400 kr	50000	410 000 kr	502 498 kr	410 000 kr
28			dålig ingj.	5%	ersättning	20%	10	st	2 400 kr	50000	770 000 kr	1 565 915 kr	1 161 429 kr
29													
30	Dräner c/c 5 m	5		**0%**									
31			aktivt gw	0%	spolning		0,33	st	8 000 kr	0	- kr	0 kr	0 kr
32			(bio/kem)	0%	ersättning	50%	10	st	30 000 kr	0	- kr	0 kr	0 kr
33				**100%**									

Figur 1: En av alternativflikarna.



Figur 2: Sammanställning som visar resultatet av livscykelkostnadsanalysen.

A3. Alternativflikarna

I alternativfliken anges de data som behövs för att göra analysen. För varje alternativ anges tunnelns geometriska egenskaper tillsammans med livslängd, ränta och eventuell byggkostnad, se ***Figur 3***. Det är viktigt att varje alternativ som används får rätt indata för just den tunneln. T.ex. kan de geometriska egenskaperna vara samma för alla alternativ, men byggkostnaden kan skilja sig åt.

Byggkostnaden kan uteslutas om enbart underhållskostnaden ska beräknas.

A4. Parameterhuvud för ett alternativ

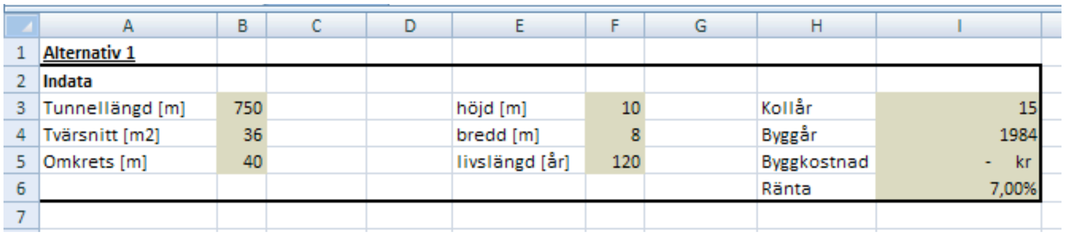
I parameterhuvudet anges tunnelns geometriska egenskaper, livslängd, ränta och eventuell byggkostnad. Tunnellängd, tvärsnittsarea, omkrets, volym, höjd och bredd används för att beräkna kostnaden för de förstärkningar som anges i ”*Förstärknings- och underhållsdata*”.

Livslängden är tunnelns livslängd och det är efter så många år som totalkostanden beräknas.

Byggår kan anges som ett faktiskt årtal för att enklare kunna relatera den ackumulerade underhållskostanden till ett visst år.

Kollår ger möjlighet att hur stor del av underhållskostnaden som kvarstår från det angivna året.

Räntan är den kalkylerade räntan (och inflation) som anses gälla under hela tunnelns livslängd.

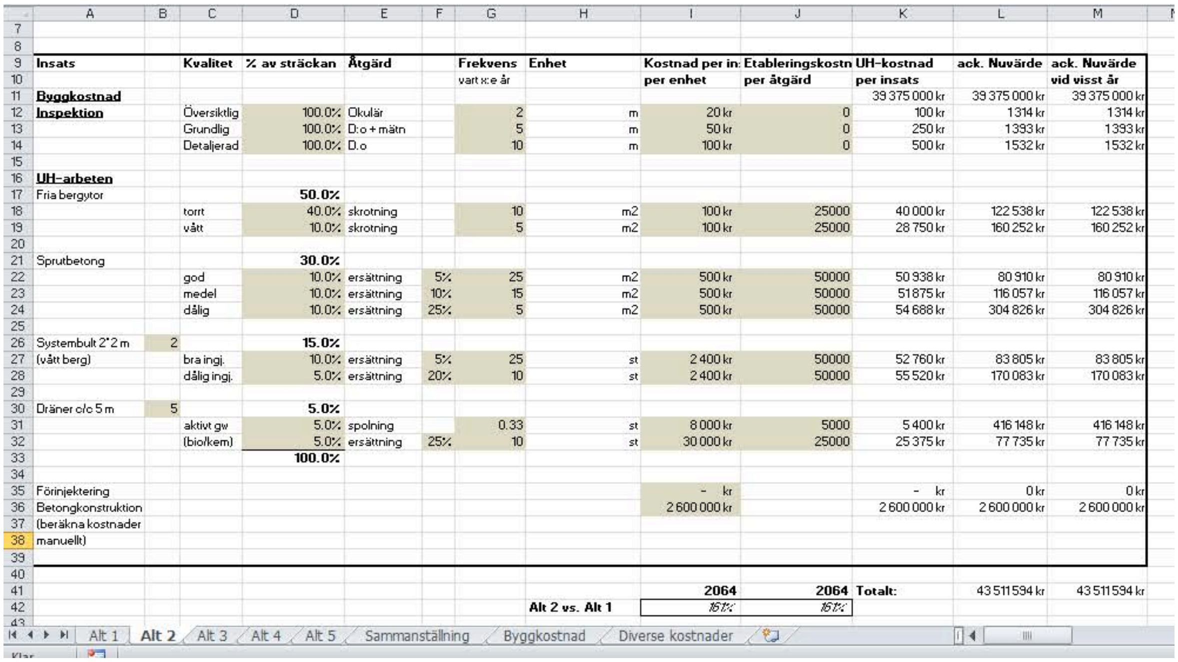


	A	B	C	D	E	F	G	H	I
1	**Alternativ 1**								
2	**Indata**								
3	Tunnellängd [m]	750			höjd [m]	10		Kollår	15
4	Tvärsnitt [m2]	36			bredd [m]	8		Byggår	1984
5	Omkrets [m]	40			livslängd [år]	120		Byggkostnad	- kr
6								Ränta	7,00%
7									

Figur 3: Parameterhuvud för projektet

A5. Förstärknings- och underhållsdata

Under parameterhuvudet finns för varje alternativ ett område där aktuella förstärkningstyper och dess underhållsåtgärder specificeras. I princip anges för varje förstärkningstyp hur mycket av bergytan/massan den täcker, vad den kostar att underhålla per enhet (t.ex. kr/m^2 sprutbetong), underhållsintervall samt eventuell kostnad för att etablera arbetet. I etableringskostnaden får alla initiala fasta kostnader plats som krävs för att påbörja och utföra aktuellt underhålls- eller inspektionsarbete.



	A	B	C	D	E	F	G	H	I	J	K	L	M
7													
8													
9	**Insats**		**Kvalitet**	**% av sträckan**	**Åtgärd**		**Frekvens**	**Enhet**	**Kostnad per in:**	**Etableringskostn**	**UH-kostnad**	**ack. Nuvärde**	**ack. Nuvärde**
10							vart x:e år		**per enhet**	**per åtgärd**	**per insats**		**vid visst år**
11	**Byggkostnad**										39 375 000 kr	39 375 000 kr	39 375 000 kr
12	**Inspektion**		Översiktlig	100.0%	Okulär		2	m	20 kr	0	100 kr	1 314 kr	1 314 kr
13			Grundlig	100.0%	D:o + mätn		5	m	50 kr	0	250 kr	1 393 kr	1 393 kr
14			Detaljerad	100.0%	D.o		10	m	100 kr	0	500 kr	1 532 kr	1 532 kr
15													
16	**UH-arbeten**												
17	Fria bergytor			**50.0%**									
18			torrt	40.0%	skrotning		10	m2	100 kr	25000	40 000 kr	122 538 kr	122 538 kr
19			vått	10.0%	skrotning		5	m2	100 kr	25000	28 750 kr	160 252 kr	160 252 kr
20													
21	Sprutbetong			**30.0%**									
22			god	10.0%	ersättning	5%	25	m2	500 kr	50000	50 938 kr	80 910 kr	80 910 kr
23			medel	10.0%	ersättning	10%	15	m2	500 kr	50000	51 875 kr	116 057 kr	116 057 kr
24			dålig	10.0%	ersättning	25%	5	m2	500 kr	50000	54 688 kr	304 826 kr	304 826 kr
25													
26	Systembult 2*2 m	2		**15.0%**									
27	(vått berg)		bra ingj.	10.0%	ersättning	5%	25	st	2 400 kr	50000	52 760 kr	83 805 kr	83 805 kr
28			dålig ingj.	5.0%	ersättning	20%	10	st	2 400 kr	50000	55 520 kr	170 083 kr	170 083 kr
29													
30	Dräner c/c 5 m	5		**5.0%**									
31			aktivt gw	5.0%	spolning		0.33	st	8 000 kr	5000	5 400 kr	416 148 kr	416 148 kr
32			(bio/kem)	5.0%	ersättning	25%	10	st	30 000 kr	25000	25 375 kr	77 735 kr	77 735 kr
33				**100.0%**									
34													
35	Förinjektering								- kr		- kr	0 kr	0 kr
36	Betongkonstruktion								2 600 000 kr		2 600 000 kr	2 600 000 kr	2 600 000 kr
37	(beräkna kostnader												
38	manuellt)												
39													
40													
41									**2064**	**2064**	**Totalt:**	43 511 594 kr	43 511 594 kr
42								**Alt 2 vs. Alt 1**	*161%*	*161%*			

Figur A4: Förstärknings- och underhållsdata för ett alternativ.

A6. Sammanställningsfliken

I denna flik visas alla olika alternativ mot varandra. Bland annat visas totalkostnadens utveckling i linjediagramsform, samt även återstående underhållskostnad från angivet år.

Totalkostnaden (samt återstående underhållskostnad) för varje enskild komponent visas i procentform ställd mot totala underhållskostnaden.

Här finns även en linjegraf som visar den totala livstidskostandsutvecklingen över tid för alla alternativ var för sig.

Bilaga B: Fotobilaga CBI

B.1 Bolmentunneln

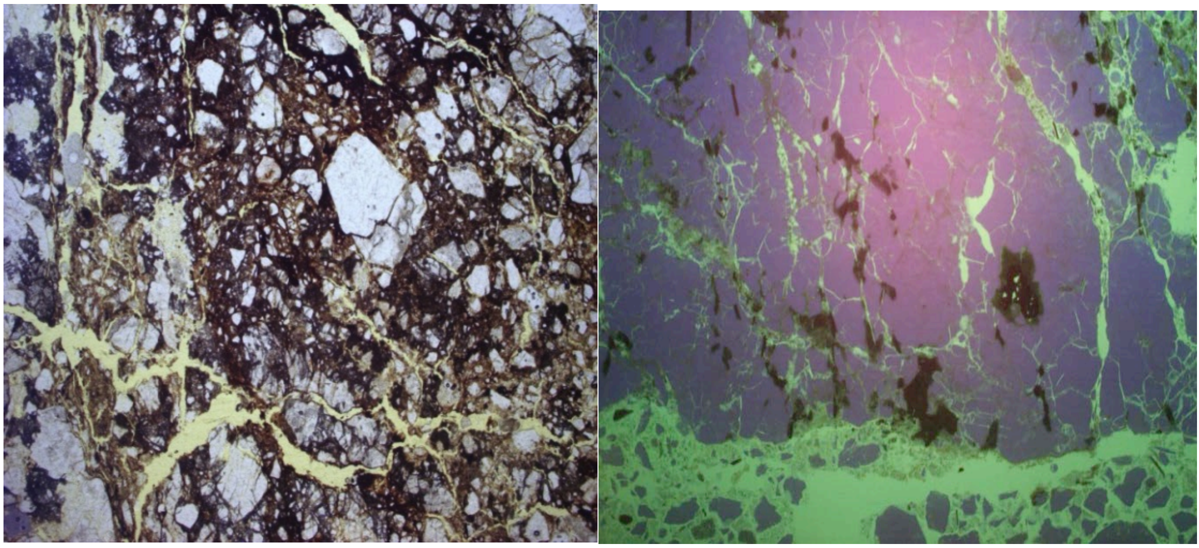
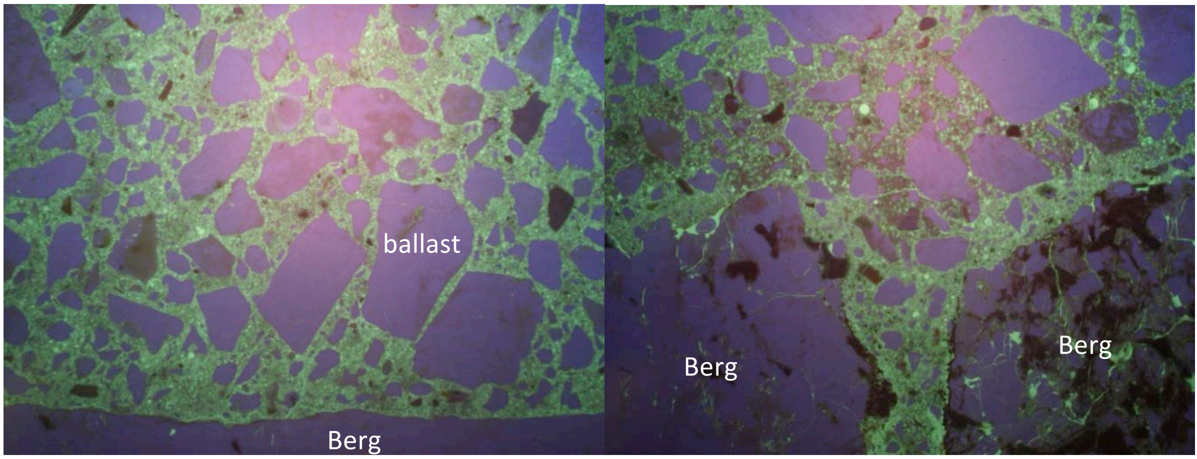


Fig. 2 Tunnslipbilder av sprucket berg.

Bild till vänster. Parallellt ljus. Bild 9 mm. Tektoniskt krossat och fragmenterat berg. Den mörkare massan är ytterst finkornig. Det gula utgör epoxi med fluorescensmedel och markerar sprickor i berget.

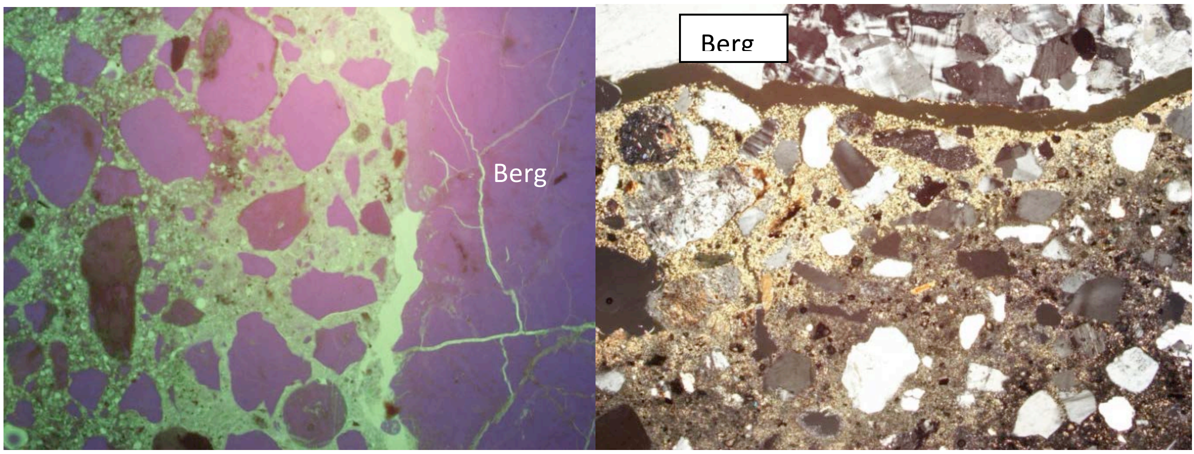
B; Flourescensljus. Bild 9 mm. Ljus gulgrön färg är poröst eller sprickor. Bilden visar kraftigt fragmenterat berg överst och porös betong/cementpasta med spricka underst.



Figur 3 Tunnslipsbilder i UV-ljus.

Bilden till vänster visar bra och relativt homogen pasta in mot bra berg. 9 mm

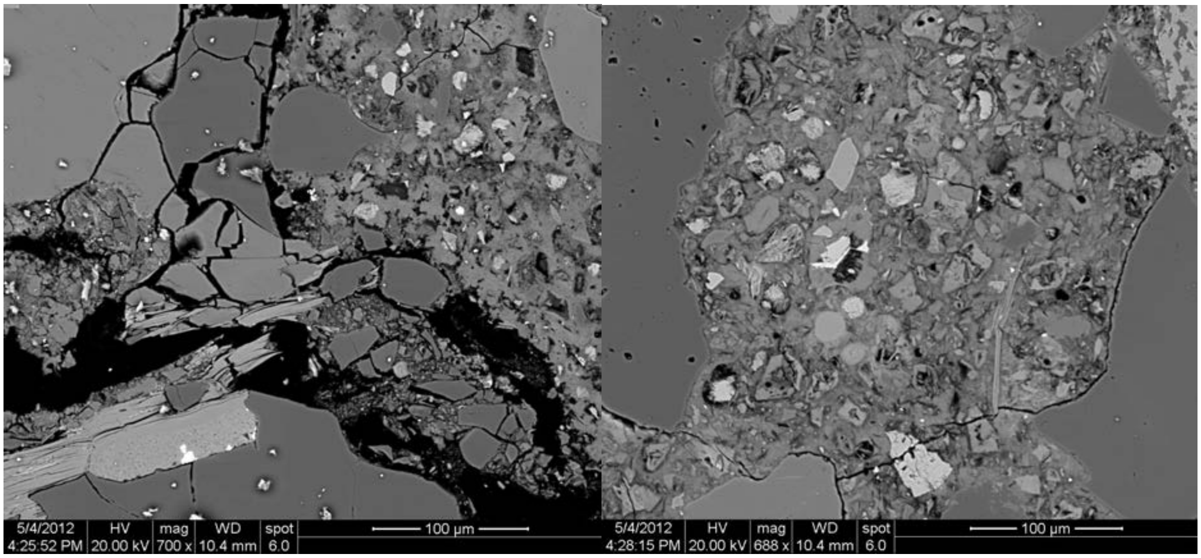
Bilden till höger ser man sprutbetong som trängt in i en större spricka. Det är alltid mindre ballastkorn in mot berget p.g.a. väggeffekten. 4,5 mm



Figur 4.

Bilden till vänster i UV-ljus visar inhomogen pasta in mot sprucket berg.

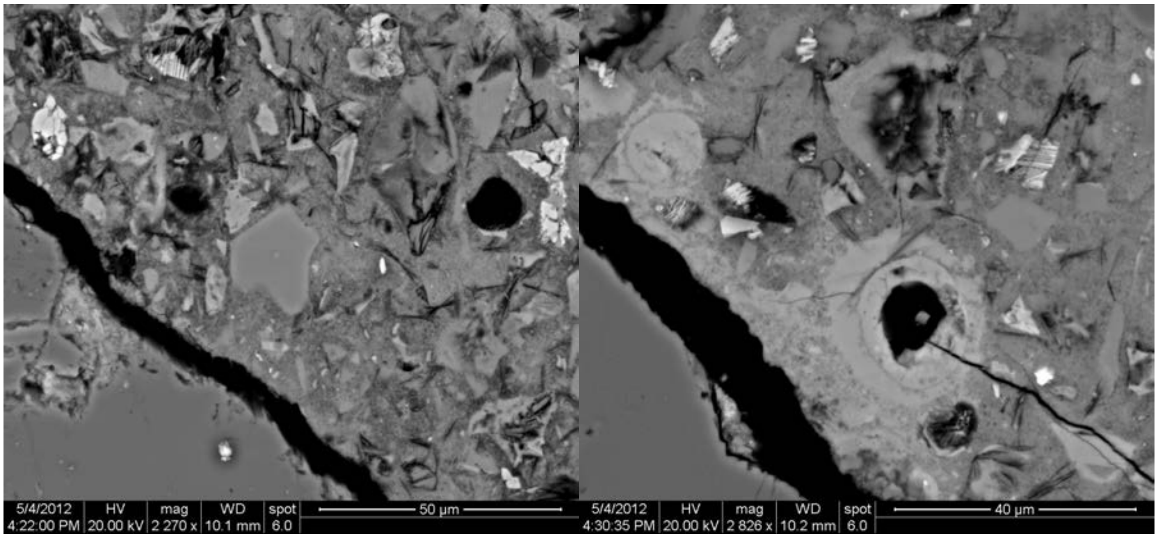
Bilden till höger med korsade polarisatorer visar mikroskopbild med korsade polarisatorer. Den ljusa färgen in mot berg beror på riklig förekomst av portlandit.



Figur 5. SEM planslip.

Bilden till vänster; Sprutbetong mot sprucket berg.

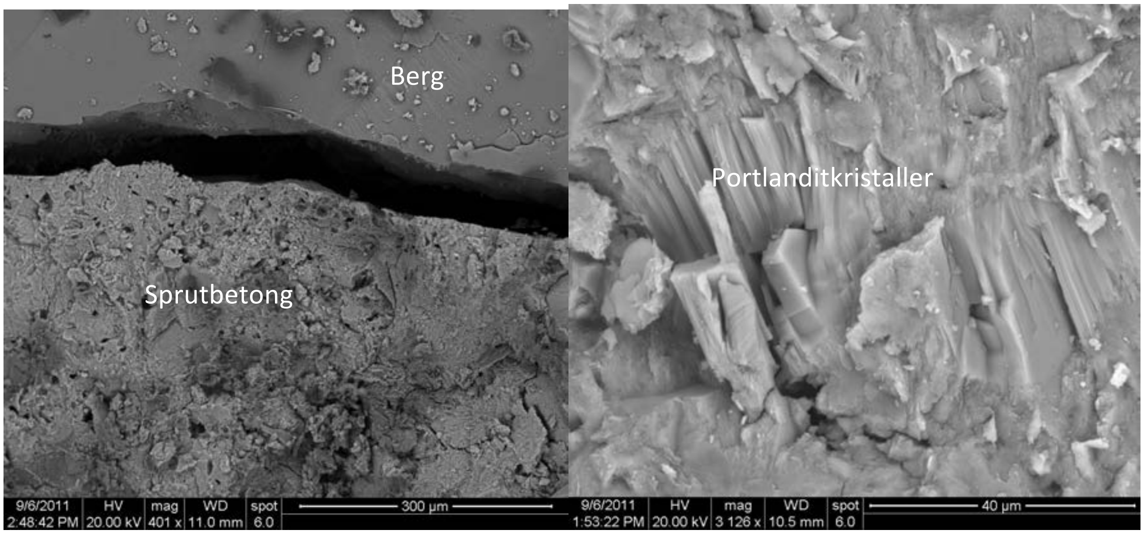
Bilden till höger; sprutbetong 1 cm från bergytan.



Figur 6. SEM planslip.

Bilden till vänster. Relativt homogen pasta in mot berg.

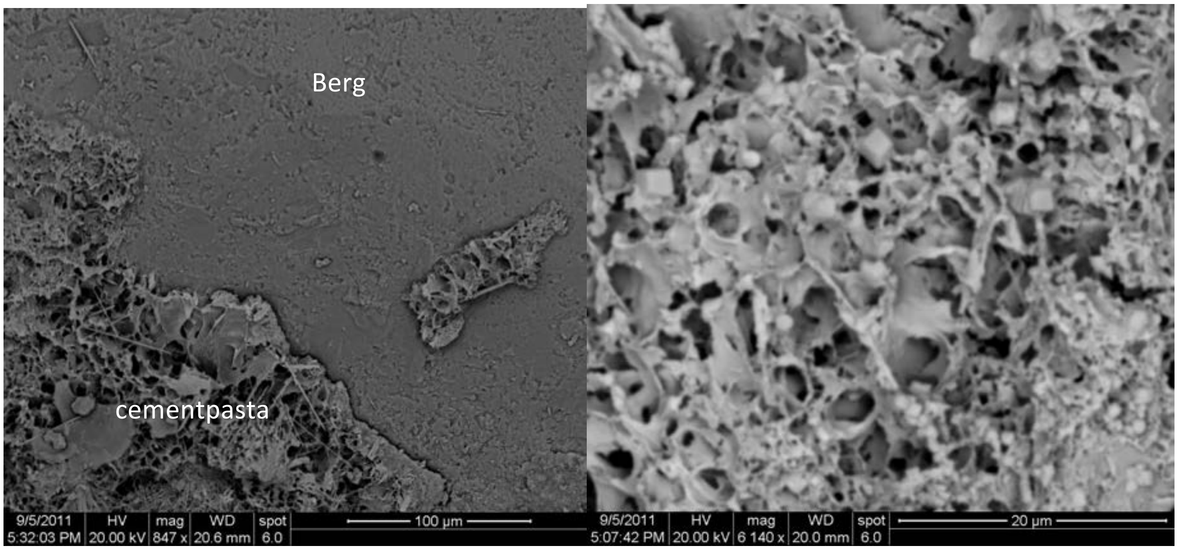
Bilden till höger. Rikligt med portlandit både i hålrum och vid gränsövergången.



Figur 7. SEM brottyta.

Till vänster; något porös cementpasta in mot berg.

Till höger; Portlanditkristaller vid gränsövergång.



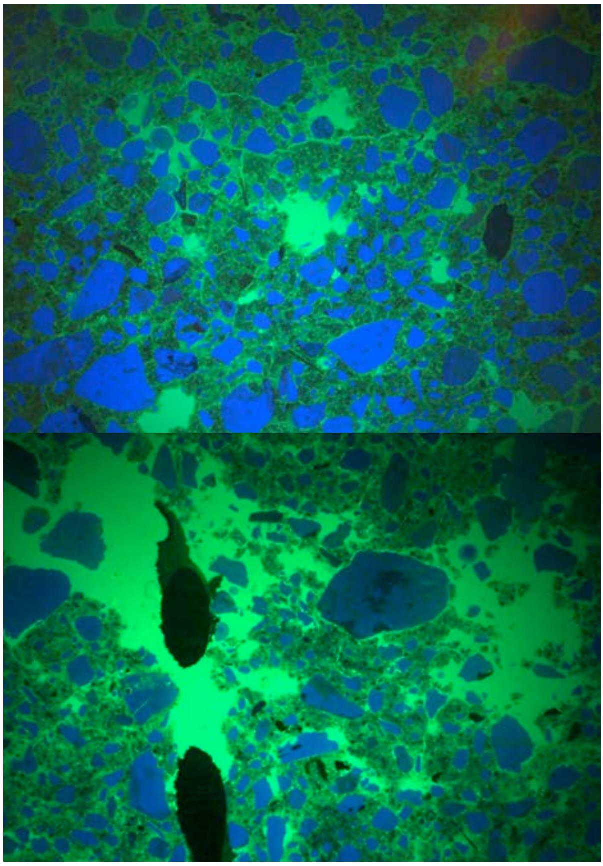
Figur 8.

SEM brottyta.

Till vänster; Cementpasta mot berg. Cementpastan är porös och innehåller rikligt med ettringit och portlandit.

Till höger; samma i större förstoring.

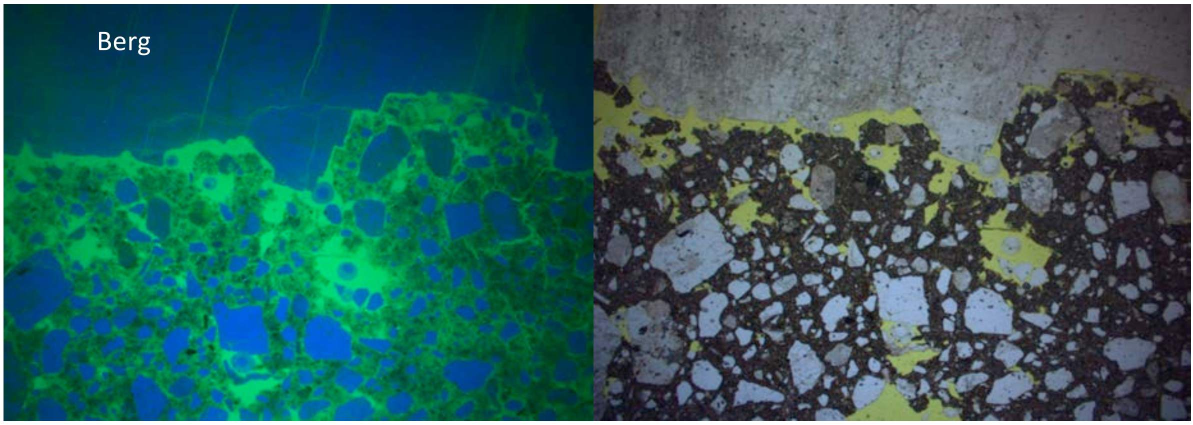
B.2 Lundby tunneln



Figur 9. Tunnslip fluorescensljus.

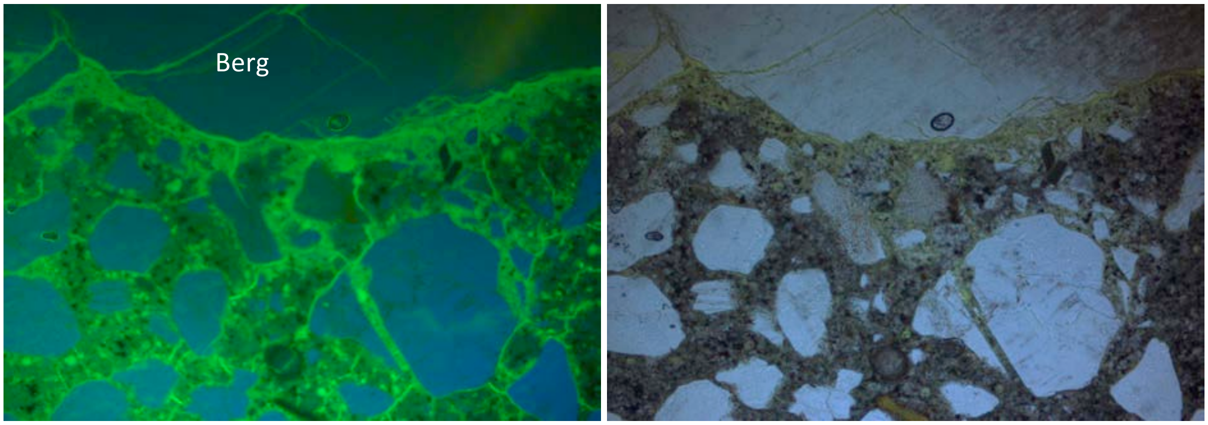
Till vänster inhomogen sprutbetong.

Till höger; Hålrum i sprutbetong. Detta visar en inhomogen sprutning. Bilder 9 mm.



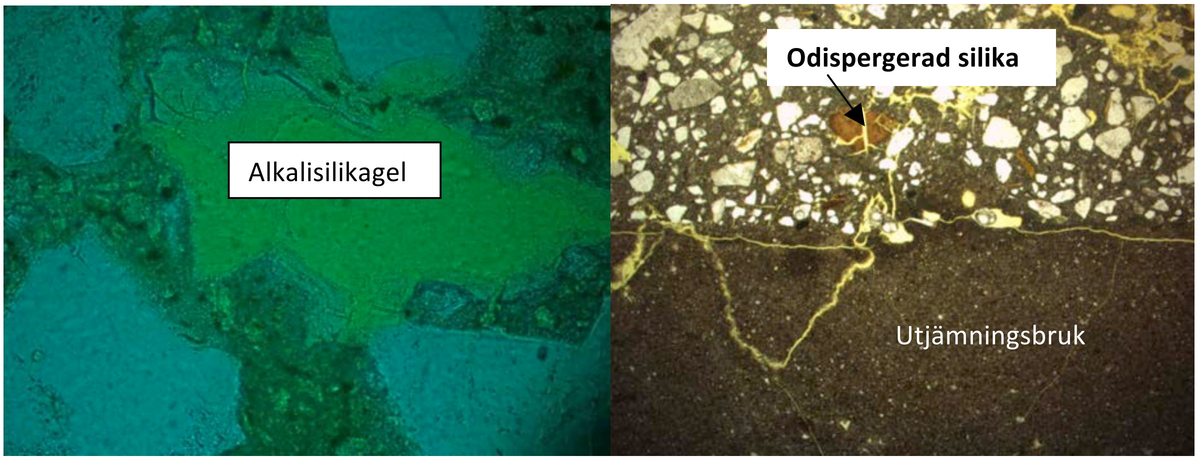
Figur 10. Tunnslip med fluorescensljus och parallellt ljus.

Inhomogenitet och porös övergångszon mellan berg och sprutbetong. Bilder 9 mm.

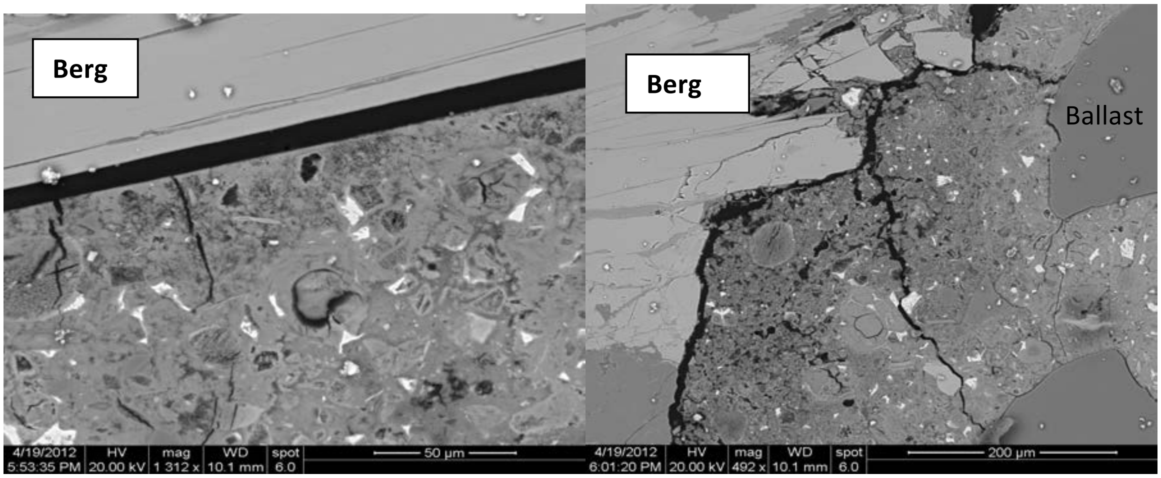


Figur 11. Tunnslip med fluorescensljus och parallellt ljus.

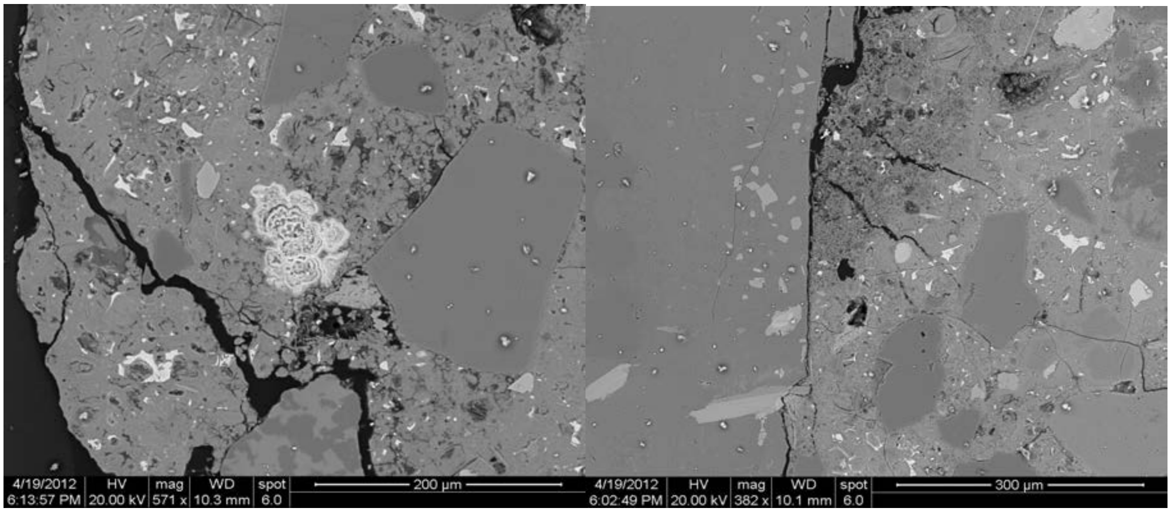
Övergångszonen i större förstoring. Bilder 4,5 mm.



Figur 12. Tunnslipsbilder. Till vänster hålrum med alkalisilikagel. Till höger odisperegerad silika. Den bruna massan är någon slags utjämningsbruk som man sprutat mot. Bild till vänster 2,2 mm och till höger 4,5 mm.

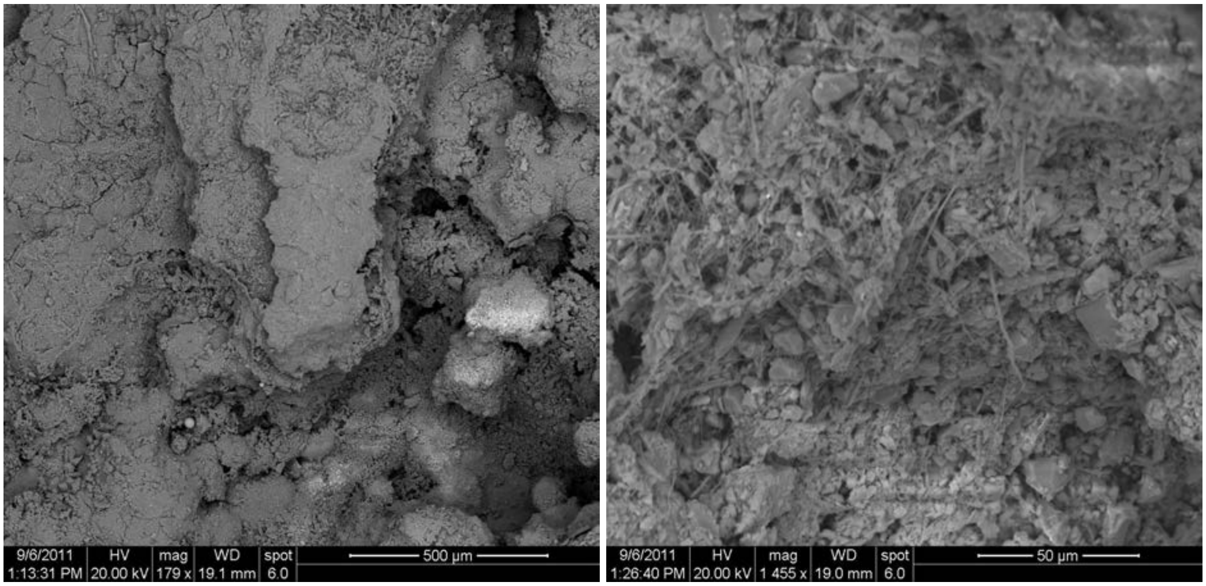


Figur 13. SEM polerprov. Porös övergångszon mot berg.



Figur 14. SEM polerprov.

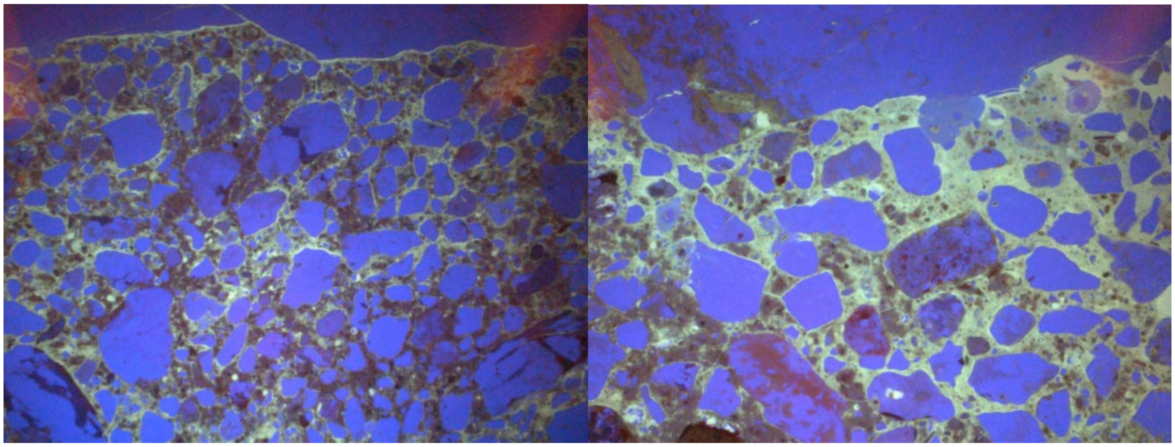
Till vänster; Nära övergångszon. Utfällning av manganoxid. Detta indikerar vattentransport från berg. Till höger variation i porositet vid övergångszon.



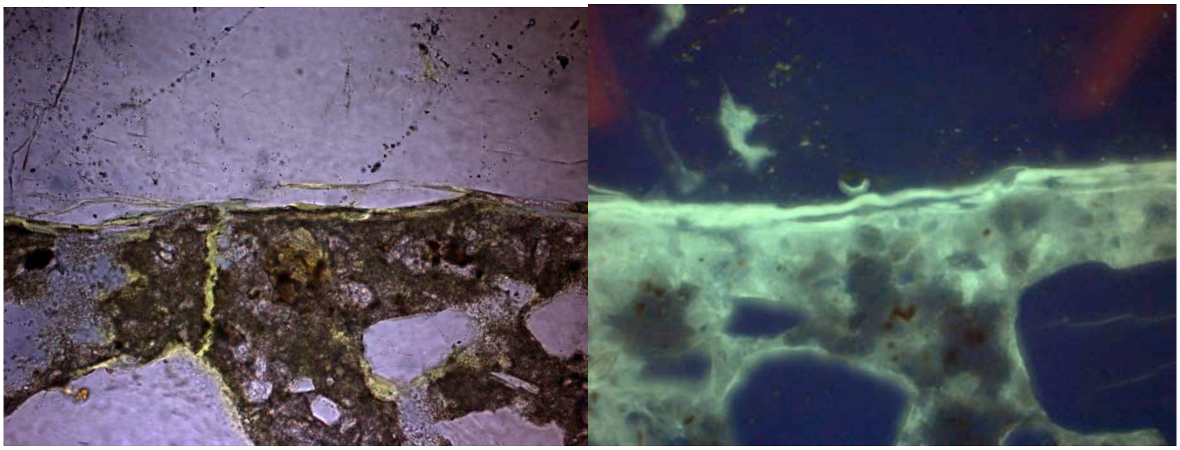
Figur 15. SEM brottyta mot berg.

Porös zon med kristaller av portlandit och ettringit.

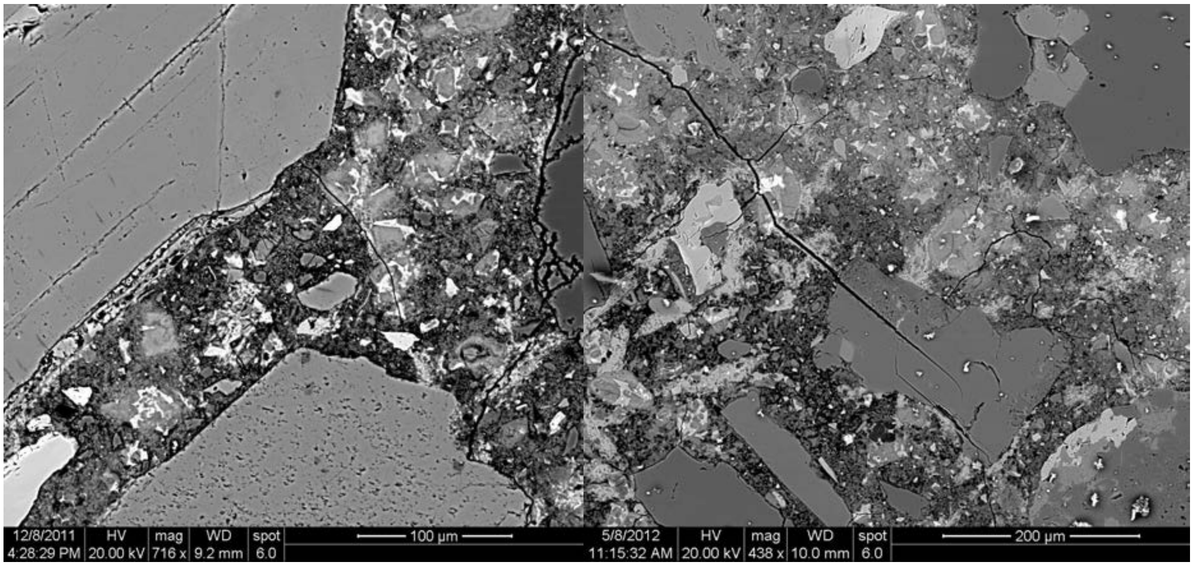
B.3 Shelltunneln



Figur 16. Tunnslipsbilder. UV-ljus. Till vänster. Relativt homogen betong. Bild 9 mm. Till höger visas mera porös betong. Bild 4,5 mm



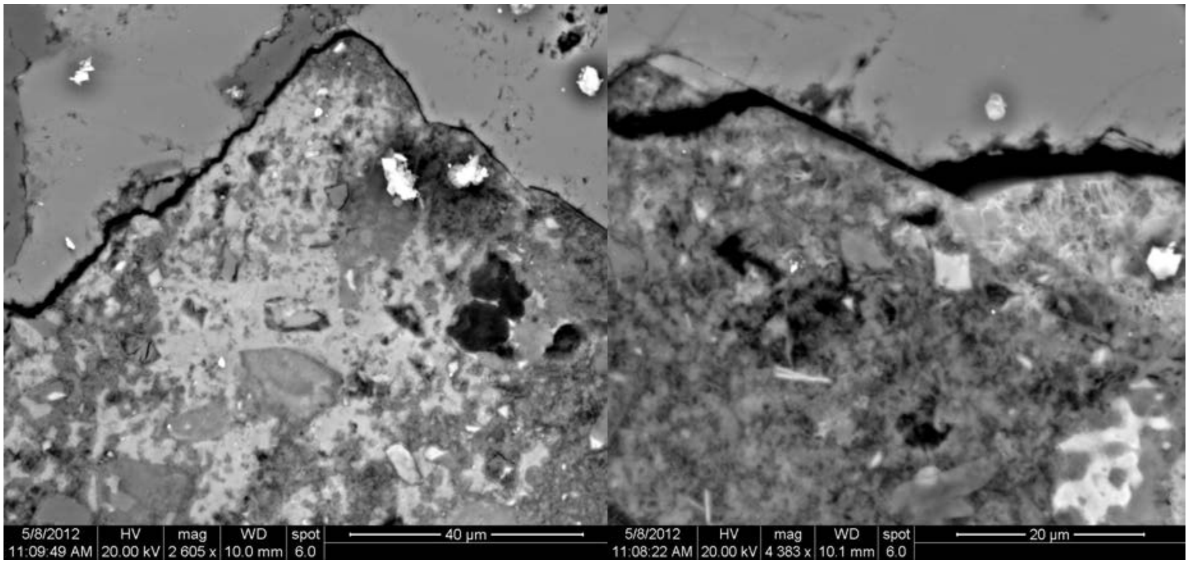
Figur 17. Tunnslipsbilder. Parallellt ljus och UV-ljus. Bild 1,1 mm



Figur 18. SEM polerad yta.

Till vänster kan man se utfällning av portlandit i övergångszonen.

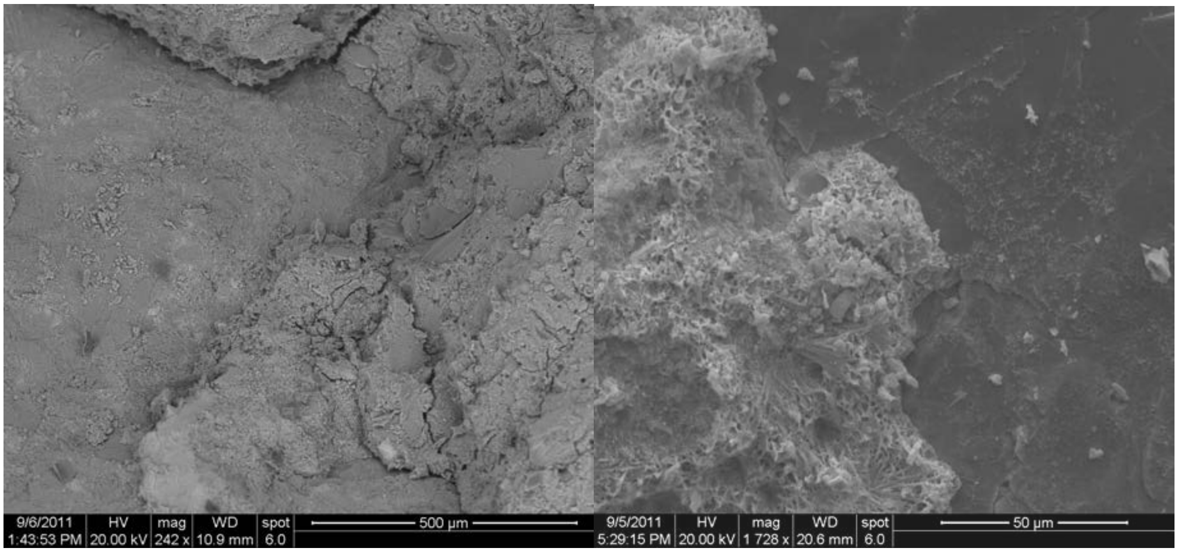
Till höger inne i betongen kan man observera inhomogenitet i cementpastan.



Figur 19. SEM poleryta

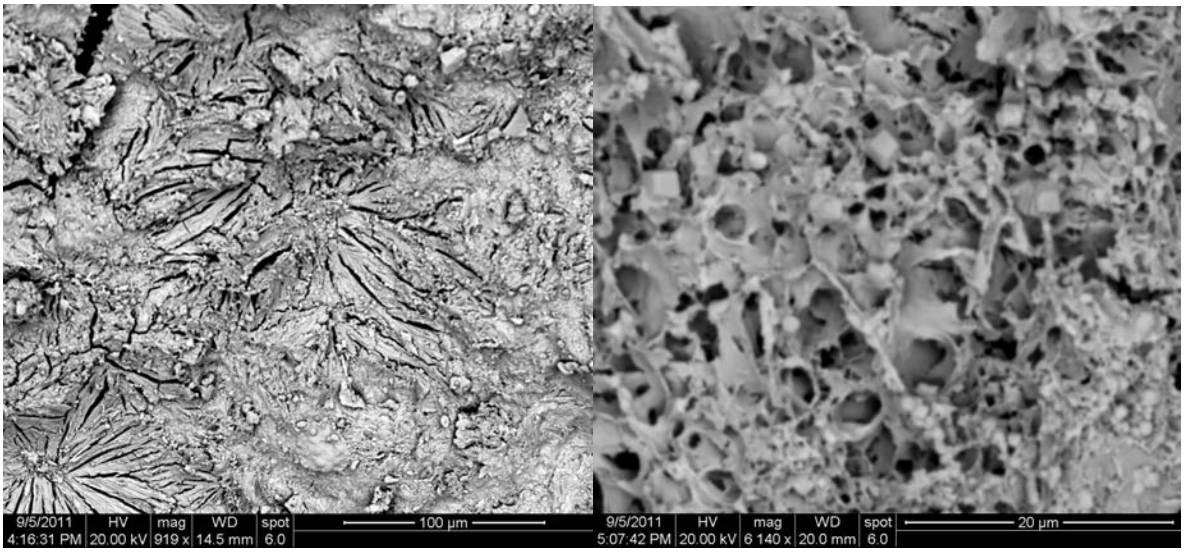
Till vänster massiv utfällning av portlandit.

Till höger ett mera poröst parti



Figur 20. SEM på brottyta.

Cementpasta som en kaka på bergytan. In mot berget är strukturen relativt porös.



Figur 21. SEM på brottyta.

Till vänster syns sekundär utfällning av ettringit.

Till höger syns en porös cementpastestruktur.

Bilaga C: Korrosionsdata KIMAB

Med en förändring av värde N_1, vattentyp, erhålls följande modifierade DIN-norm.

$W_0 = N_1 + N_3 + N_4 + N_5 + N_6 + N_3/N_4$

Vad de olika faktorerna står för framgår av tabellen nedan.

Enhet		**Värde**
Vattentyp		N_1
Flödande		-3
Fuktigt		0
Torrt		+3
$c\,(Cl^-) + 2c\,(SO_4^{2-})$	mol/m^3	N_3
<1		0
1-5		-2
5-25		-4
25-100		-6
100-300		-7
>300		-8
Syrakapacitet till pH 4,3	mol/m^3	N_4
<1		+1
1-2		+2
2-4		+3
4-6		+4
>6		+5
$c(Ca^{2+})$	mol/m^3	N_5
<0,5		-1
0,5-2		0
2-8		+1
>8		+2
pH-värde	mol/m^3	N_6
<5,5		-3
5,5-6,5		-2
6,5-7,0		-1

7,0-7,5	0
>7,5	+1

Utgående från beräknat värde på W_0 kan förväntad korrosionshastighet utläsas ur nedanstående tabell, där de i ursprunglig DIN-norm angivna korrosionshastigheter halverats baserat på resultat från denna undersökning.

W_0	**Medelavfrätning, mm/år**
>0	0,005
-1 till –4	0,01
-5 till –8	0,025
<-8	0,05

Bilaga D: Kemirapport GU

D1. Background

Cement is most common material used in pre-grouting in Scandinavia. During the years of cement grouting the grain size distribution and the used water to cement ratios has been developed in consistency to cope with the demands set on the tunnel ingress of water. In general one can say that the grain size distribution has gone from larger (d_{95}=63 µm) to smaller and smaller (d_{95}=16 or even 12 µm) since the 1960 and 70´s and in the same time using higher and higher water to cement ratios, giving more easy flowing grouts. Over the last decades much effort and resources have been put to understand the limitations of the penetrability of the cement routs due to the grains. To gain strength and rapid increase in the early strength the suspension should be easily mixed with a lot of different chemicals (superplasticers, accelerators, retarders etc) which have entered the market and frequently used in projects. A proper understanding of cement quality changes over the long term with all these different cements and water content together with chemicals is yet to be established. However, tunnels have been built since 1950 or earlier with pre-grouting as a method and the tunnels still meet the requirements but needs maintenance.

This report is part II of the study of durability of grouted cement. The first part was a literature and laboratory study of fabricated cement grout. The outcome was that if the pH of the pore water in the cement is above 12 it is stable. It was also shown that the pH is mainly governed by the leaching of portlandite and as long portlandite is present the pH is above 12 and hence stable. However is should be noted that the kinetics of cement paste is complex and a more thorough study of other components than portlandite is needed to fully understand the long term effects of cement paste. This report brings up tests of the real cement grout that was grouted in two tunnels, some 50 and 10 years ago. The study focuses on the presence of portlandite and the appearance of the cement grout when portlandite is absent or not.

D2. Aims and purposes for the project

- Show the difference in quality of cement grout in natural fractures
- With chemical analysis show how the portlandite affects the cement quality
- To analyse the difference in quality when grouting with high versus low water to cement ratio.

D3. Delimitations

The report will not answer for how long time a cement grout is durable. This requires a kinetic modeling based on experimentally determined time dependent dissolution of several components of different substances as well as how new substances are developed. This is very complex problem and need much longer and elaborative experimental and modeling studies.

One possible reason for giving a poor quality of the cement can probably be described with the Taylor dispersion. The Taylor dispersion is a local process that occurs close to the fracture surface when the grout is flowing in the fractures. This dispersion it thought to dilute the grout during for some circumstances. This analysis has been able to be done besides a likely occasion of this process is found in one borehole.

D4. Method

The cement grout samples from two tunnels have been studied. The Telia tunnel, constructed in the early 1970 and the Lundby tunnel constructed in late 1990, both located in Gothenburg.

Samples were collected using core drilling in parts of the tunnel walls where knowledge of the grouting was known. The amount of core drilling was limited and only one core from each tunnel was able to retrieve traces of cement in the fractures.

D5. The Lundby tunnel

The rock is a gneissic/granitic crystalline rock with pegmatite and amphibolite slabs. The tunnel was built in 1998 and is double tube traffic tunnel, 2 km long with an area of 88 and 92 m^2 respectively. The permitted ingress of water is very low. Not more than 2.5 l/min and 100 m was the general target but for some places 0.5 l/min per 100 m where the rock was covered with clays and settle-sensitive buildings. Allot of effort was put in to the grouting, with around 61 boreholes yielding a c- distance at the tip of the borehole of only some 1,0 m for the most strict sealing class. The grouting started with cement with a water to cement ratio (WCR) of 3,0 (a very viscous suspension) for the first 20 m and after 30 minutes without reaching a pressure the WCR was lowered to 2,0, and again if the pressure has not increased within 30 minutes the WCR was lowered to 1,0. After grouting the boreholes, all boreholes were plugged with a WCR of 0,35 or lower. This concept is traditionally called "tjocka på". The cement type was "injekteringscement" which is not as finegrained as today more commonly used INJ30. It was sulphate resistant aluminiate cement developed around 1985 by Cementa. Post grouting was also used frequently along the tunnel. The grout used was cement and TACCS (Polyurethane).

D6. Telia tunnel

The rock type is the same as Lundby tunnel with granites and gneiss. Some few pegmatite dykes and amphibolites are found. The construction started in 1970 and ended in 1972. It was pre-grouted with cement but type is unknown to the author but with additions of Intraplast-A, an organic compound that expands. However from some relation blue prints from the excavation shows extensive grouting in parts of the tunnel with boreholes spreading far out from the tunnel profile as well with a large overlap between the grouting fans. During the 80´s large efforts of post-grouting was conducted, both with cement and polyutrethanes. In the latest post-grouting, in 2008 was conducted with silica sol. It is also from this post-grouting project where one of the rock cores could be utilized for this durability study. For further information of the latest post grouting and background material see (Janson, et. al, 2010).

In two tunnels nearby, GRYAB sewage tunnel and Gothenburg energy was built in early 1970 and early 1980 respectively. The cement used was denoted as rapid hardening Limhamn cement with 1%

Intraplast for the GRYAB tunnel and Portland cement denoted SH cement for the Gothenburg energy tunnel. Both cement types are according to today's knowledge denoted as SH cement which has a rapid hardening property but not sulphate resistant according to today's standard. The performance for both of the tunnels was that the water cement ratio was changed due to the grouttake. For the GRYAB tunnel the grouting started with a ratio of 3 (easy flowing grout) to gradually thicker grout, down to a ratio 0.5. For the Gothenburg energy tunnel the grouting started with a ratio of 2.0 down to 0.33.

It is likely that in the Telia tunnel a similar approach of the concept of thickening the grout during grouting was performed. The cement grouting in the Telia tunnel was done with addition of Intraplast and then hence possibly the cement type was SH cement (Personal communication with Tommy Ellison, AB Besab). The SH cement is more of course grained type.

D7. Sampling by core drilling

D7.1. Lundby tunnel

Totally four cored drill hole was taken in section 2/179 to 2/159 in the tunnel wall. Two of the cores were shorter with the objective to study the contact between the rock and the shotcrete. These cores are used in another project. Two longer cores, eight to ten meters was drilled where in only one core traces of cement grout could be found, see appendix A for drilling diary.

Samples were taken from the cores. Each fracture surface was visually observed and if a cement-like filling was found on the surface, samples by scratching of a piece from the surface were done. One of the core drillings was done cutting an old cement grouted borehole as well a borehole used for bolting. This was not intended but sine the whole tunnel wall was covered with sprayed concrete it was “luck” that the drilling was cutting this boreholes giving a good opportunity to analyse samples that was not degraded by the ground water. In the table below the 5 samples for further analysis is found.

Table 1. Samples taken from the Lundby tunnel.

		Chainage along the core	
Sample no.	Taken from	Denoted	Working name
L1	KBH1, Box 1	1,2 m grout hole	L1 grout hole
L2	KBH1, Box 1	1,2 m grout hole, outer surface	L2 grout hole outer surface
L3	KBH1, Box 2	6,8 m, bolt hole in pegmatite	L3, bolt hole
L4	KBH4, Box 1	2,4 m, dry-fracturing, clay?	L4, fractured cement
L5	KBH2, Box 2	5,3 m, fracture	L5, grout hole

From the sampling the grouted holes gave cement for certain that could be analysed. The more interesting part of the grouted hole was that around the center of the hole a more porous cement, approximately 1-2 cm thick and more light in colour was found. However, all samples that cement was found was from boreholes and not from the fractures except for sample L4. Sample L4 could not be visually determined between a clay or cement, further analyses was undertaken.

D7.2. Telia tunnel

One rock core drilled in section around 2/980 in the tunnel called “city tunneln” was used for sampling. The core length is 33 m and drilled along the direction of the old pre-grouting holes giving maximum possibility of hitting cement grouted fractures. In at least one fracture with cement grout was found during the actual drilling. The sampling method was the same as for the Lundby tunnel. In table 2 the samples are listed.

Table 2. Samples taken from the Telia tunnel

		Chainage along the core	
Sample no.	Taken from	Denoted	Working name
A	Left fracture surface	Telia_KBH1_10,96m	Cement certain 1
B	Right fracture surface	Telia_KBH1_11,515m	
C	Right fracture surface	Telia_KBH1_27,145m	Cement certain 2
D	Right fracture surface	Telia_KBH1_28,455m	
E	---	Telia_KBH1_29,53m	Filter cake

For the sample E which was not a cement. It has more of paper looking appearance some millimeters thick covering the whole surface plane and easily removed as one piece from the surface. A piece from this sample was taken for further analysis. Later, it was discovered that this must originate from a post-grouting done during 1980 where a mixture of bentonite and talc was tested.

D8. Groundwater analysis

From the water dripping coming from cored boreholes water samples were collected for a ground water analysis. This was done in both as reference test to know the environment the cement been leaching in as well for further analysis to describe degradation of the cement. The report of the ground water chemistry is found Appendix B. The results of the water analysis are presented here since so far it seen as a description of the environment.

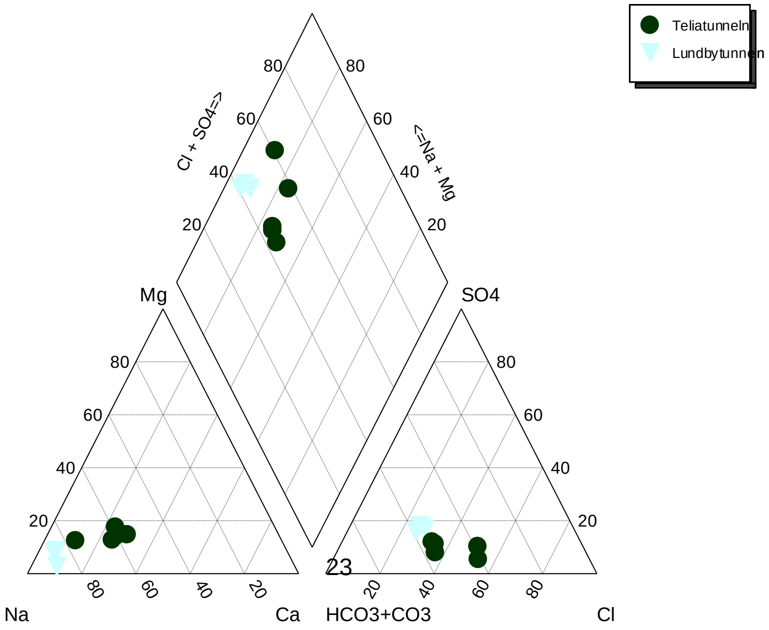


Figure 1. Piper diagram showing the most common ions in the two type waters from Telia and Lundby tunnel.

The Lundby tunnel water shows a higher concentration of sodium (Na). Both waters have a high buffer capacity with alkali. Both of them have a high content of dissolved organic carbon, DOC and indicate that the waters are in contact with the surface. The Telia tunnel shows a high concentration of silica oxide which can indicate dissolution of silica from the cementgrouting or from the grouting with silica sol, see appendix B for further explanations.

D9. Chemical analysis of the samples

When dry cement material comes into contact with water the hydration of solid phases starts immediately. Since cement is composed of calcium silicates such as Ca_3SiO_5, Ca_2SiO_4, sulphates ($CaSO_4$) and aluminates ($Ca_3Al_2O_6$) the resultant products of hydration reactions are portlandite ($Ca(OH)_2$), ettringite ($[Ca_3Al(OH)_6.12H_2O]_2.(SO_4)_3.2H_2O$) minerals along with amorphous C-S-H phases. Portlandite is very soluble in water thus it dissolves quickly according to the following reaction:

$Ca(OH)_2 <=> Ca^{2+} + 2OH^-$

The presence of OH^- ions generates highly alkaline solution in cement matrix. Due to rapid dissolution of the portlandite the pore solution in cement matrix gets saturated with respect to OH^- and Ca^{2+} ions and system reach equilibrium and further dissolution of portlandite stops. Ettringite on the other hand is relatively less soluble in water than portlandite. Formation and stability of ethringite is linked to the presence of $CaSO_4$. As long as $CaSO_4$ is in excess ettringite is stable but when $CaSO_4$ is consumed ettringite slowly converts to monosulphates. Thus this is the reason that in old concrete samples ettringite is seldom detected.

In our previous study we have hypothesized that an important indicator of concrete stability is the presence of portlandite. As long as portlandite is present which provides very high pH in the pore solutions, mineral phases containing silicates etc will be stable. It was shown in our previous report that indeed the pH of the solution played the vital role i.e., as long as pH was > 11 the portlandite ($Ca(OH)_2$) and other phases were stable. However, when pH was < 9.5 the portlandite dissolved. It was also found that concentration of ions such as Na^+, K^+, Mg^{2+}, and Cl^- had negligible effect on the release of Ca^{2+} ions and mineral stability.

Thus, based on previous studies we can safely state the following:

The most important parameter for cement stability is the pH and the presence of portlandite is a good indicator of the degradation process occurring in aged concrete. If the aged concrete shows the presence of portlandite we can safely consider that cement as stable. On the other hand if portlandite is absent from the aged concrete there is risk that pore solution will become acidic which will eventually lead to the dissolution of the other minerals and will generate more open porous concrete structures.

Following analysis were done on the samples

X-ray diffraction (XRD), XRD on all samples in order to find the crystalline cement minerals, such as portlandite and ettringite.

Infrared spectroscopy, IR with diffuse reflectance infrared fourier transformation on all samples with the same purposes including also absorption for detecting C-S-H phases.

Scanning electron microscopy (SEM), SEM analysis combined with EDX is done on selected samples to visually show a good and a poor quality of the cement. The structure of the cement will have influence on the sealing effect from the cement. Although this method only provides a "picture" of the surface it still gives indication of how it has been affected by leaching.

D10. Results

All the results from the chemical analysis are shown in appendix C. Here, the most significant results are presented. The results are divided where the first priority is to show weather the sample origins from cement grout or not. When the cement samples are considered as cementitiuos origin the results are divided into good and poor quality of the cement.

D10.1. Samples with cementitious origin

Lundby tunnel

In Lundby tunnel samples L1, L3 and L5 are of cementitious origin i.e., having portlandite as dominant phase along with some ettringite and also alkali and alkaline aluminosilicates. On the other hand in sample L2 there was calcite ($CaCO_3$) along with significant amount of alkali and alkaline aluminosilicates. This sample was the taken from the outer surface of the grouted borehole. The XRD analysis show no trace of portlandite but the sample in itself shows that it was cement from the beginning. The sample L4 was dominant by sand along with alkali aluminosilicates. No portlandite or $CaCO_3$ were found. A typical diagram for sample L1 from the X-ray diffraction is shown in Figure 2 where the peaks shown are the minerals Ettringite and Portlandite.

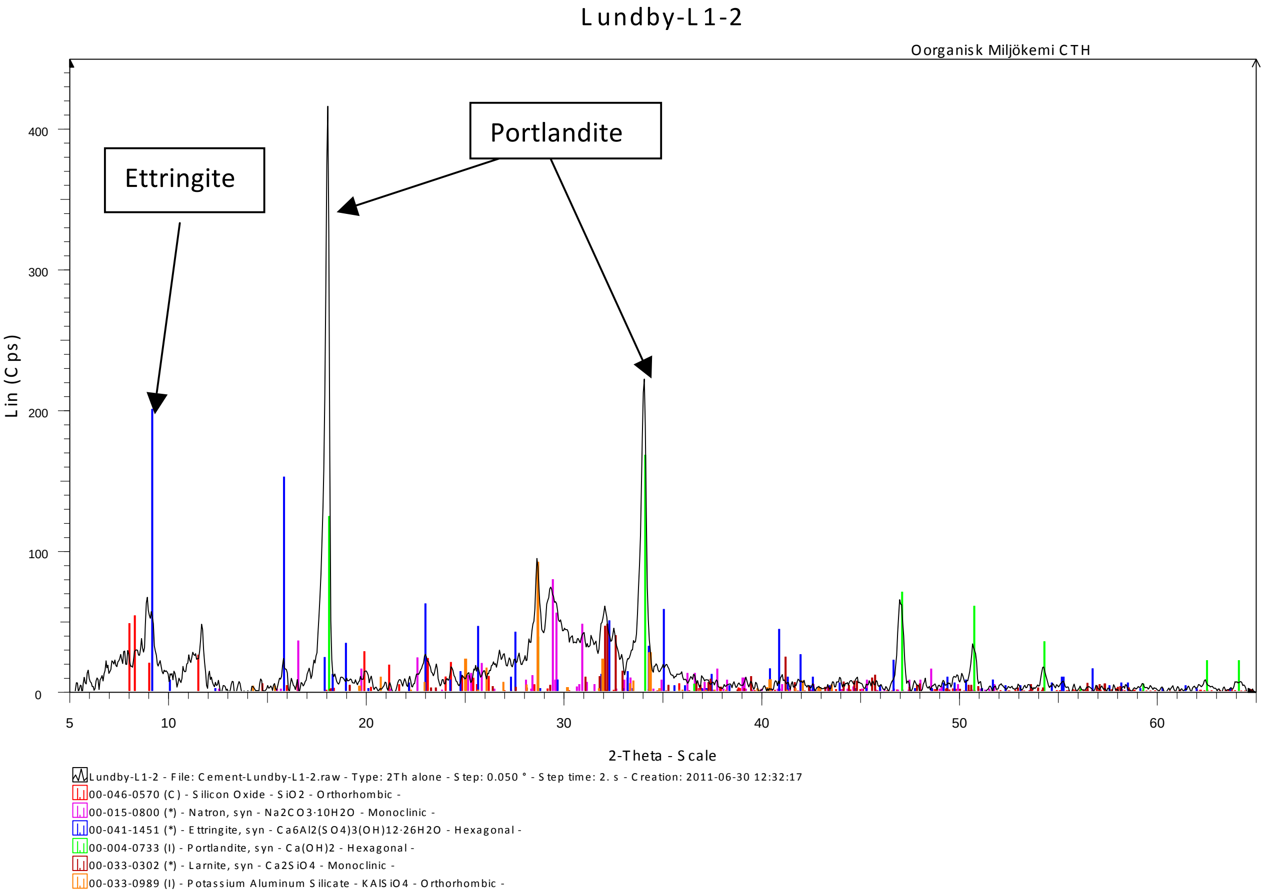


Figure 2: The X-ray diffractogram of Lundby L1. The portlandite ($Ca(OH)_2$) and ettringite mineral phases are marked with arrows.

Figure 3. Photo of the cored grouted borehole where sample L1 and L2 were taken from. It is evident that L2 origins from the grouted borehole.

From the Lundby tunnel following samples originates from cement grout, Table 3.

Table 3. Samples from the Lundby tunnel that originates from cement grout.

Sample L1	Inner core of grouted boreholeplug	Portlandite is found
Sample L2	Outer surface of grouted borehole plug	Portlandite is NOT found instead the sampling indicates grout
Sample L3	Bolt hole, plug.	Portlandite is found. Probably another type of cement used for bolting than for grouting.
Sample L5	Grouted borehole	Portlandite is found

The grouting of the Lundby tunnel was done in 1997-1998, hence the grout around 14 years old and can still be found in the core from the core drilling.

D10.2 Telia tunnel

It is clear from the XRD analysis showed that the samples from Telia tunnel do not contain portlandite nor ettringite. Instead $CaCO_3$ is dominant mineral in samples B, C and D and also present to some extent in the sample A. The XRD of sample C from Telia tunnel is compared with the sample L1 of Lundby tunnel in Figure 4. It is evident from figure that the portlandite phase which is dominant phase in Lundby tunnel sample is absent from the Telia Tunnel sample C and on the other hand calcite phase is the dominant phase in sample C. This indicate that the Telia C sample which most probably was originally the grouted cement has lost portlandite phase due to dissolution and the presence of $CaCO_3$ indicated that the leached solution has been in contact with air. The CO_2 has been dissolved in the highly alkaline solution and $CaCO_3$ phase is formed in considerable amount.

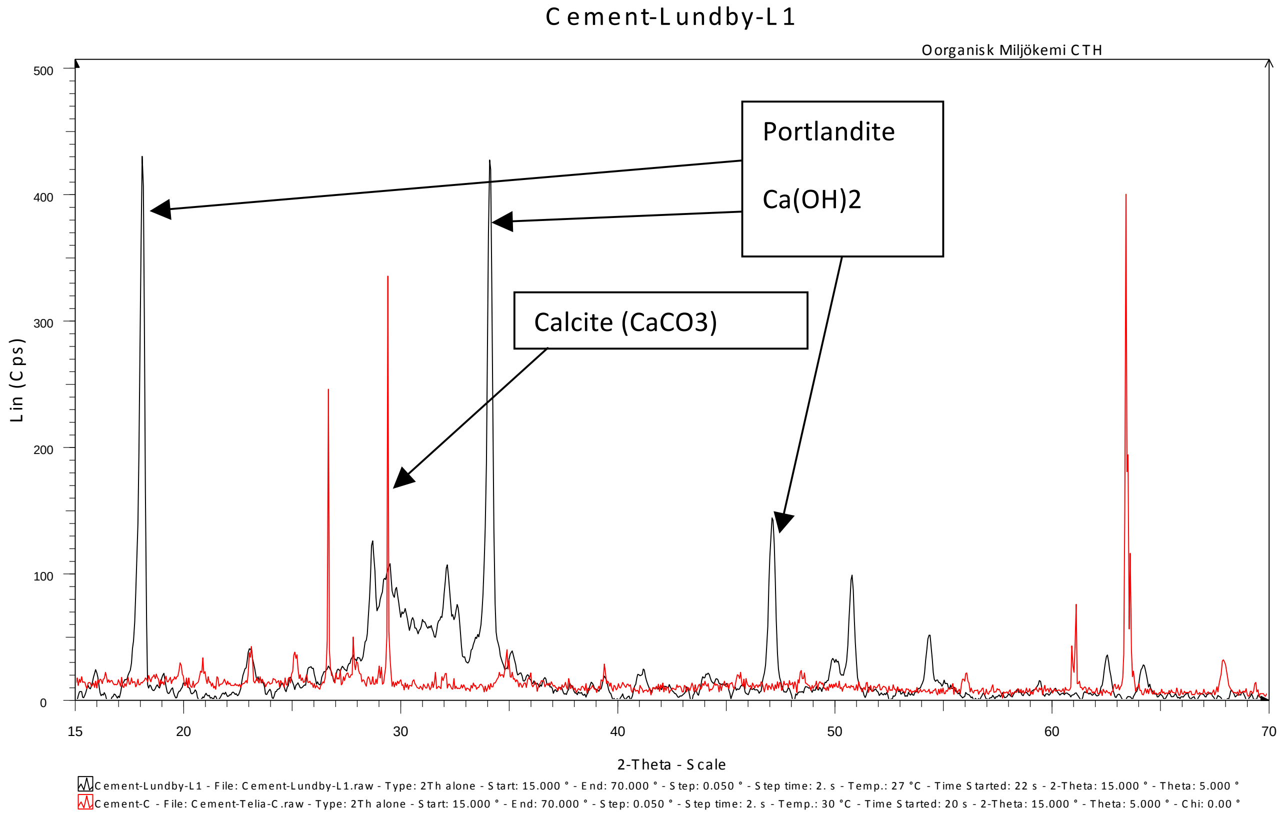


Figure 4. The black color is X-ray diffractogram of Lundby L1 and red one is the x-ray diffractogram of Telia C. One can see that the portlandite is missing from the Telia sample.

From the Telia tunnel following samples originates from cement grout, Table 4.

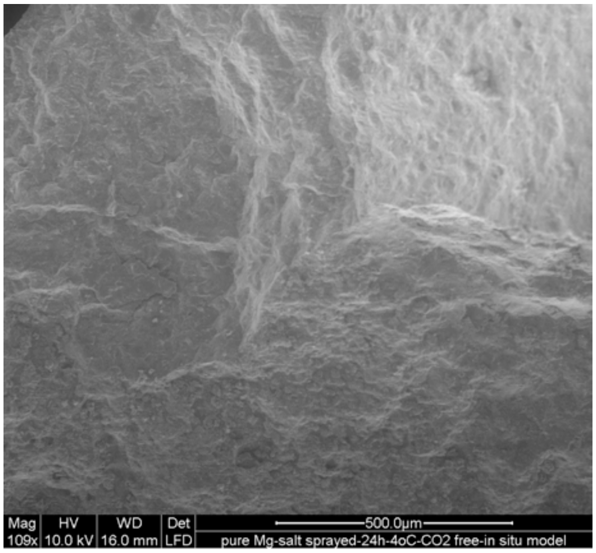
Table 4. Samples from the Telia tunnel that originates from cement grout.

Sample A	Fracture surface	Portlandite is NOT found nor Ettringite in the XRD analysis. In the IR analysis Ettringite is very close to the significance found in this sample. (see appendix C)

The samples that were taken had a very small amount making the analysis difficult. It might also be that these samples have been contaminated from nearby fracture minerals during actual sampling.

D11. Poor versus good quality of cement samples

In the Lundby tunnel all samples analysed that originated from cement showed that portlandite was present, except for sample L2, which was the outer surface of the grouted borehole plug. A SEM picture of the the samples are shown in Figure 5.



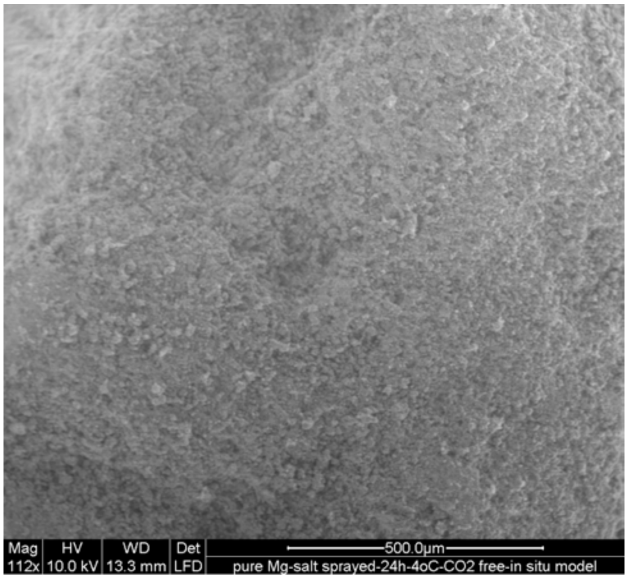


Figure 5. Two SEM-pictures of, left sample L1 and right, sample L2 from the Lundby tunnel.

Sample L1 and L2 both originates from cement grout since they were taken from the borehole plug. In Figure 5 it seen that sample L1 shows rigid homogenous surface and for sample L2 is a more porous structure. L2 did not show any portlandite in the XRD and IR analysis.

D12. Discussion and conclusions

With the question of how a fresh versus aged cement look like, three samples can be used; Samples L1 and L2 from the Lundby tunnel and sample C from the Telia tunnel.

In two of the samples from the Lundby tunnel portlandite was found as the dominant mineral phase. The SEM pictures showed a rigid surface. The samples were however from the grouted plug in the borehole and in this short time span of about 10 years the small leakages that may have occurred show no effect on the cement. However, the sample of the outer part of the grouted borehole showed a very porous surface with no portlandite. If this caused by dissolution of the cement through diffusion or occurred during the actual grouting is unclear. It is thought that a process called Taylor dispersion can occur and result in a local degradation of the cement. The sample can though be looked upon as a sample where the portlandite is absent resulting in poor quality cement and could even be the result of aging. The reasoning supports the hypothesis that the major mineral phase i.e., portlandite $Ca(OH)_2$ which keeps the pH of concrete up to high values (>11) has been dissolved from these samples.

A SEM picture of a sample containing both the rigid surface in L1 together with more porous surface of L2 is found in Figure 6.

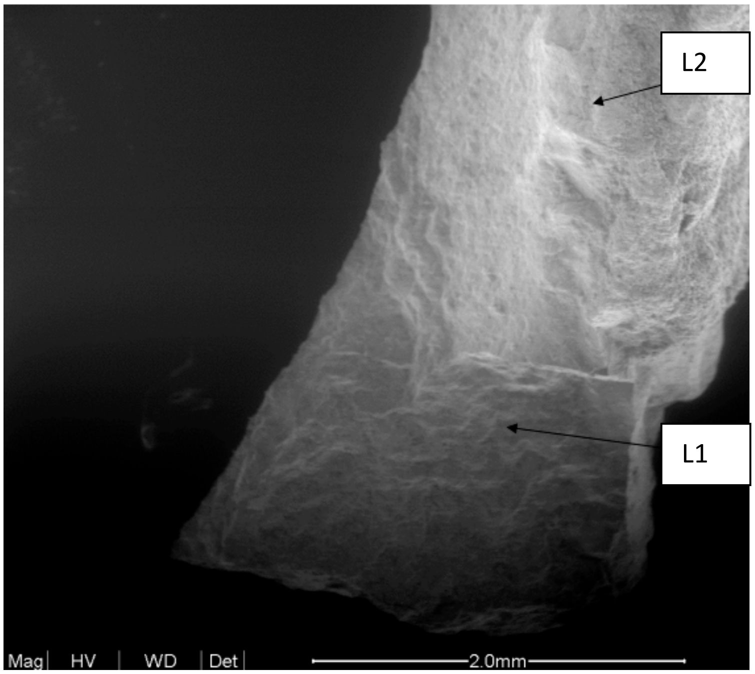


Figure 6. One SEM picture of the grouted borehole plug in the Lundby tunnel containing both L1 and L2 sample.

In the Figure 6 the transition from a rigid surface to a more porous one is evident. A SEM-EDX (Energy-dispersive X-ray spectroscopy) analysis is done as comparison which makes is possible to identify elements on the surface. However, we should keep in mind that for absolute values of the elements present in the surface layers requires very smooth and planar surfaces which these samples are not. EDX analysis of the L1 and L2 sample is shown in Figure 7 below.

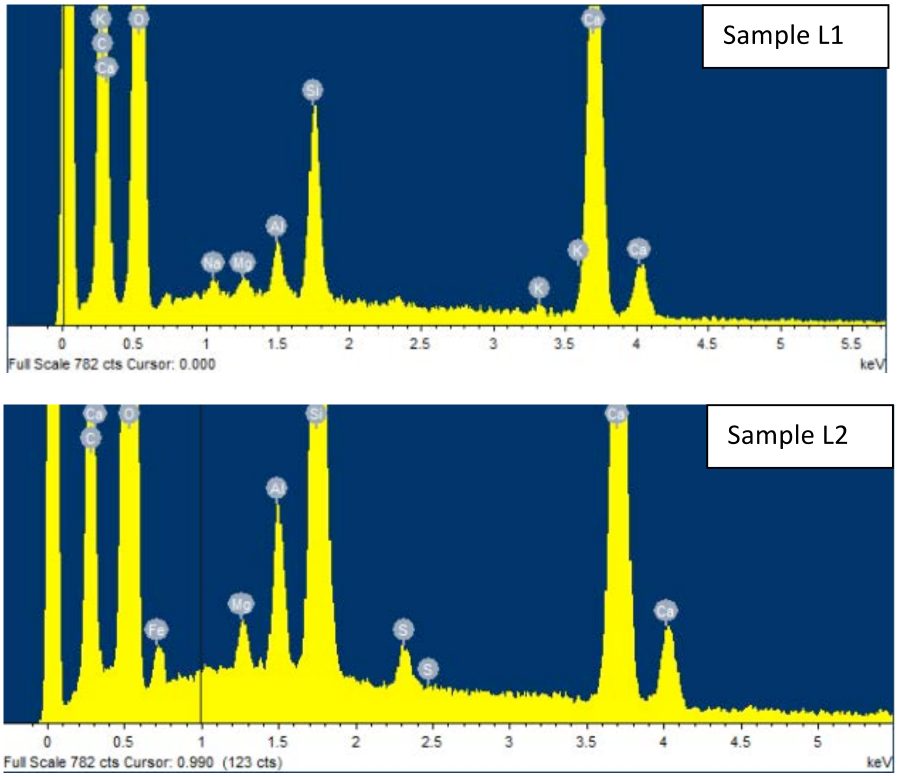


Figure 7. EDX spectrum for sample L1 on top and sample L2 in the bottom.

The EDX showed that elemental composition of two samples is very similar. They contain carbon ©, calcium (Ca), silicon (Si) and several metals like iron (Fe), aluminum (Al) and magnesium (Mg). All are elements are found in cement. The EDX analysis shows also that both samples originate from cement.

For sample C in the Telia tunnel would be an indication of a sample of aged cement in a natural fracture.

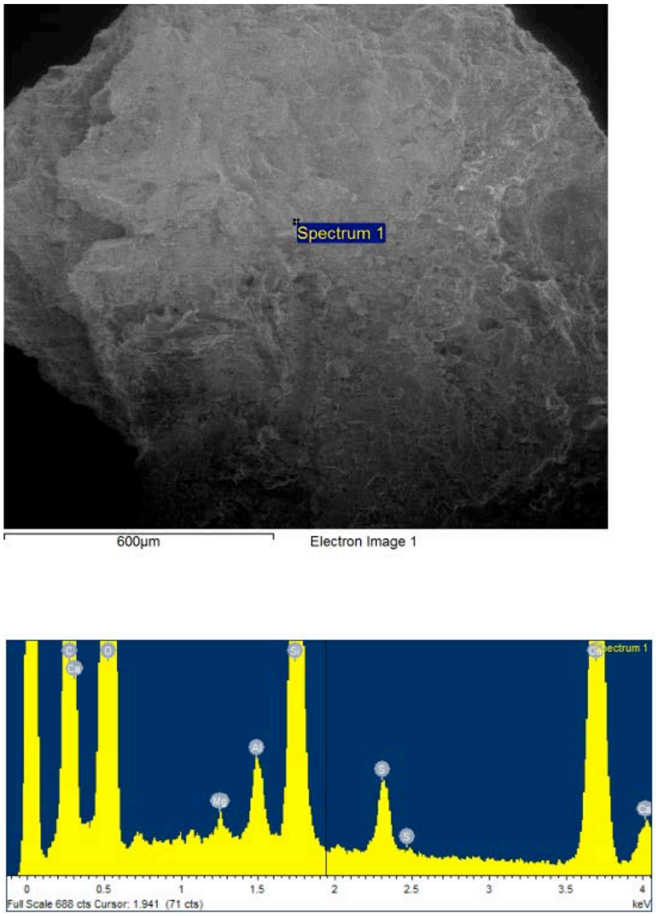


Figure 8. Above; a SEM picture of sample C in the Telia tunnel. Bottom; the combined EDX analysis of the SEM picture above.

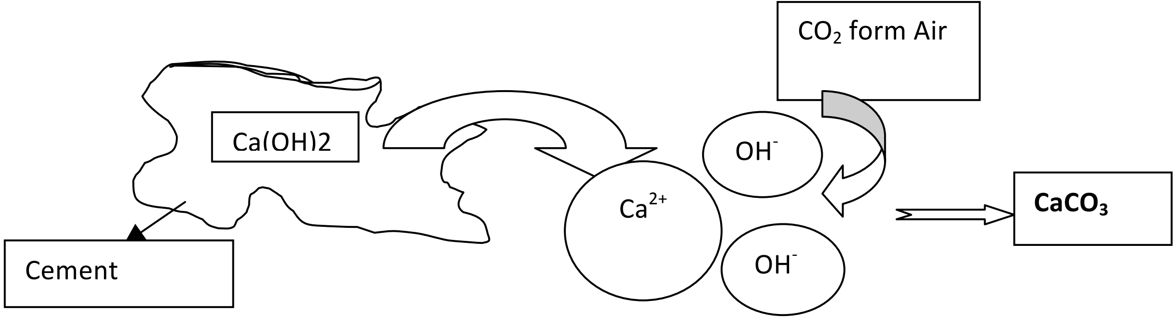
From the analysis of both the SEM picture and the EDX it is concluded that this sample is from cement grout. From the XRD and IR analysis it was shown that it lacks portlandite. The SEM pictures show a slightly porous surface but not as much as for sample L2 in the Lundby tunnel. This is then a sample of naturally aged cement where the only degradation is the flowing water surrounding it.

The chemical analysis of the samples collected from the Lundby tunnel and Telia tunnel conclude the following:

1) The samples from Lundby tunnel conclude that the samples L1, L3 and L5 are definitely like normal concrete as revealed by XRD, IR SEM analysis. The L2 sample has very porous structure and had no portlandite. The sample L2 is taken from outer edge of the hole which means that it might be the case that the release of solution containing Ca^{2+} and OH^- might have reacted with the CO_2 from air and generated $CaCO_3$ which is dominant in this sample.

2) From the samples of the Telia tunnel the X-ray diffraction and IR show that the dominant phase of normal concrete i.e., portlandite is absent from all these samples. The dominant phase in the samples A-D is $CaCO_3$. This means that the $Ca(OH)_2$ has been dissolved from the concrete and material will most probably have pH < 11 in the pore solutions. Consequently due to the further decrease in the pH of pore solution the aluminosilicate minerals and C-S-H amorphous phases will relatively easily be dissolved.

   An observation is that in those samples where portlandite is absent there is $CaCO_3$ present. One scenario is that due to dissolution of portlandite the Ca^{2+} and OH^- ions are released to pore solution and solution acquires the high pH. This high pH will in turn facilitate the absorption of CO_2 from air and make $CaCO_3$. The process is depicted below.



3) The main conclusion from SEM images of normal (L1, L5) cement compared with aged (L2) sample is the aged cement has very porous structure. SEM images support the XRD and IR analysis i.e., L1, L5 are close to normal concrete while L2 is mainly composed of Carbonates.

4) The Telia C has structure in between the normal and aged cement. Even though the portlandite ($Ca(OH)_2$) has dissolved from this cement as shown by XRD and IR it has relatively compact structure.

5) For quantitative estimation of chemical changes from EDX much more work is need.

D13. Modeling

D13.1. Introduction

The major objective of modeling is to understand how pH, amount of dissolved HCO_3^-, CO_3^{2-} SiO_2 (aqueous) and $CaCO_3$ (calcite) may influence the solubility of the portlandite ($Ca(OH)_2$). In the modeling approach saturation indexes (SI) of different minerals are calculated according to the formula given below.

$$SI = \log Q - \log K$$

$$SI = \frac{Q}{K}$$

Here Q is the product of ion activities and K is the equilibrium constant. An unsaturated mineral will have positive SI and an oversaturated mineral will have positive SI. When SI has value 0 it means mineral is in equilibrium with the surrounding solution.

In order to mimic the real water interactions with the grouted material we have used the chemical composition of water samples from Lundby and Telia tunnels as shown in Appendix B.

The experimental results showed that in the aged samples the dominant phase was $CaCO_3$ due to the release of Ca^{2+} from dissolution of $Ca(OH)_2$ and further reaction with the CO_2. The solubility of CO_2 in water can be described below:

$$CO_2 + H_2O \overset{k1}{\Leftrightarrow} H^+ + HCO_3^-$$

$$HCO_3^- \overset{k2}{\Leftrightarrow} H^+ + CO_3^{2-}$$

By considering the above reaction for solubility of CO_2 in water we have calculated the saturation index of Cacite ($CaCO_3$) in the water samples of Lundby and Telia tunnels. We have considered two pH values i.e., pH 10 and 13. pH 10 is the pH which is measured for the water sample of Lundby tunnel. pH 13 is the expected pH in the pore solution of the grouted cement. Thus by calculating the SI indexes at pH 10 and 13 we shall mimic the effect of running water and pore water on the dissolution behavior of minerals.

In the Figure 9 below the SI indexes of $CaCO_3$ (calcite) at pH 10 and 13 are shown.

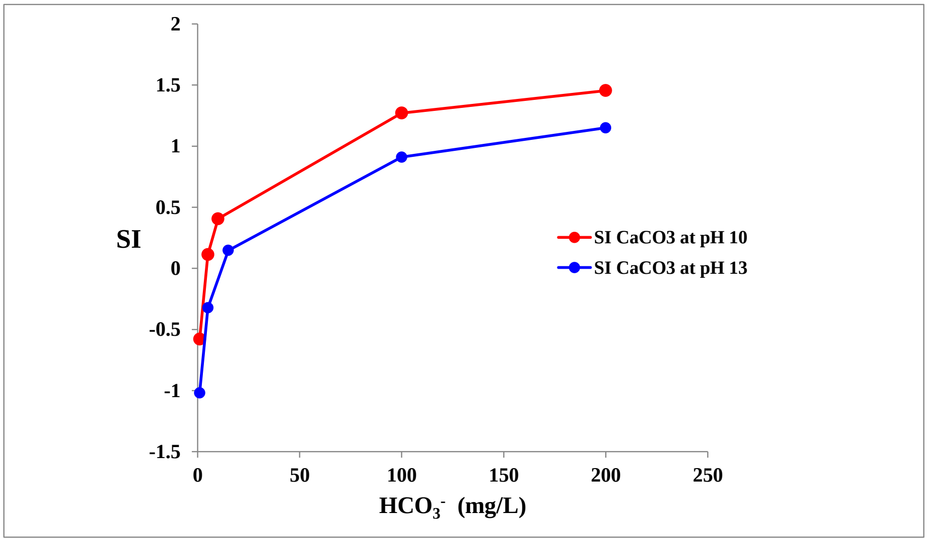


Figure 9. Saturation indexes calculated by using the water composition of water sample taken from Lundby tunnel. The SI of $CaCO_3$ is shown at increasing concentration of HCO_3^-.

The figure shows that at 5 and 15 mg/L concentration of HCO_3^- in this solution the SI of $CaCO_3$ becomes positive. This means that at very small amount of dissolved CO_2 at pH 10 as well as at pH 13 the $CaCO_3$ phase will be starting to form. This practically mean that as soon as the alkaline solution generated by the dissolution of portlandite will come into contact with CO_2 the $CaCO_3$ phase will be formed. Note that we have tested the same calculations by using CO_3^{2-} concentration and found similar results.

In the Figure 10 below the SI of $Ca(OH)_2$ in the solution of Lundy tunnel is shown.

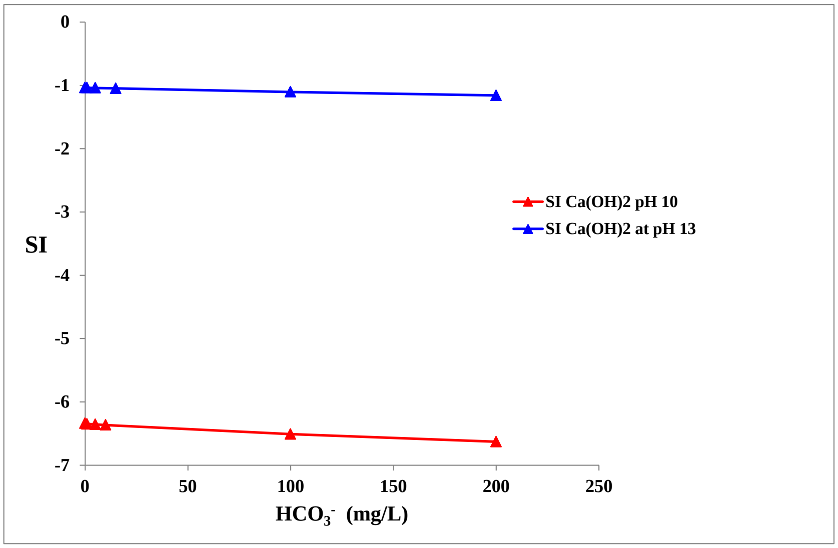


Figure 10: Saturation indexes of $Ca(OH)_2$ in the water solution of Lundby tunnel.

The above figure illustrate that the portladite will be soluble (SI negative) at pH10 and 13. The figure also illustrate the fact that solubility of $Ca(OH)_2$ increases at lower pH values than higher pH values.

The next question explored was that how the solubility of portlandite ($Ca(OH)_2$) is affected by the formation of $CaCO_3$?. This may illustrate the process of dissolution $Ca(OH)_2$ in the presence of $CaCO_3$.

Saturation index of $Ca(OH)_2$ in the presence of $CaCO_3$ 1 -100000 mg/kg were calculated. The results are shown in the figure below.

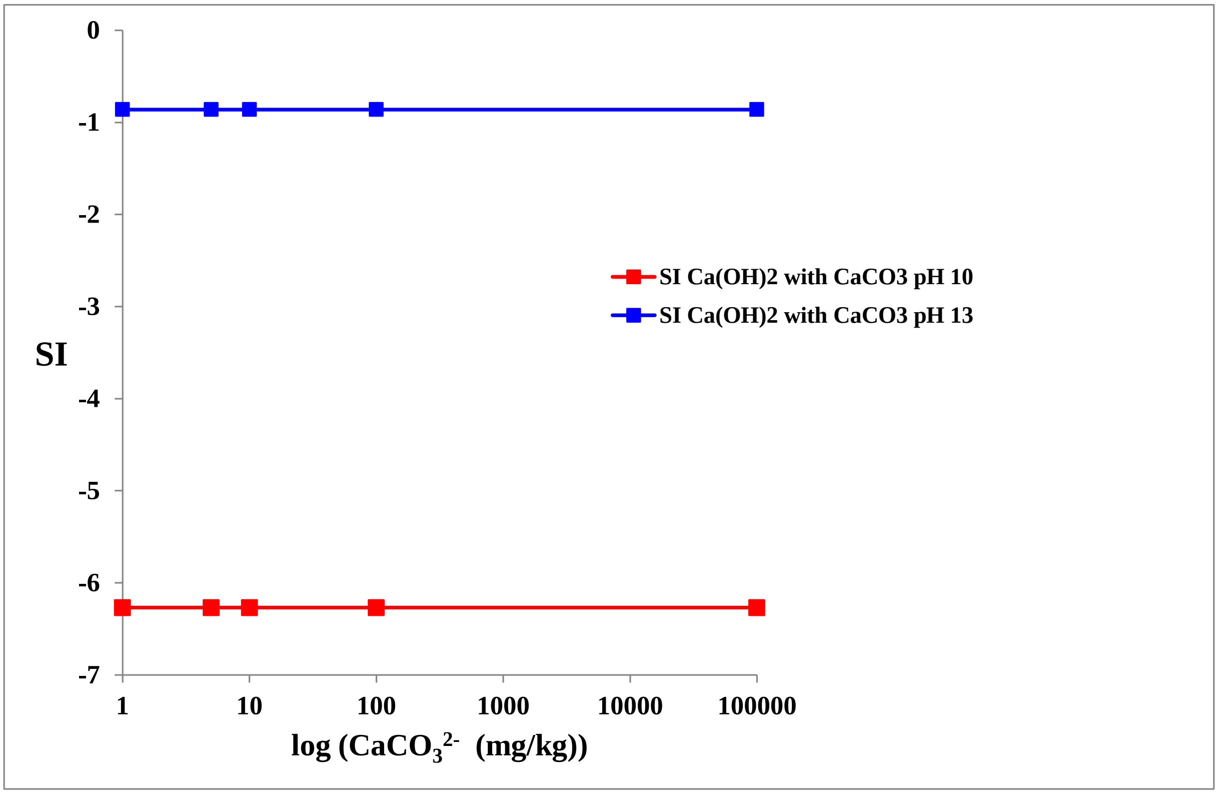


Figure 11: SI index of $Ca(OH)_2$ in the water sample of Lundby tunnel at varying concentration of $CaCO_3$.

The results indicate that the portlandite ($Ca(OH)_2$) will be soluble in the presence of $CaCO_3$. This means that thermodynamically the portlandite from the grouted material will be dissolved no matter how much carbonation of the sample has happened. On the other hand formation of $CaCO_3$ may affect the kinetics of dissolution process of $Ca(OH)_2$ due to pore structural changes of the grouted material.

We have also performed similar calculations for Telia tunnel water samples. The results showed the same trends therefore are not shown in this report. Full results will be present in separate report.

The saturation indexes of quartz and amorphous silica for Lundby and Telia tunnels water samples are shown in Table 5 below.

Sample	Lundby Tunnel	Telia Tunnel
Quartz	0.075	0.433
Amorphous silica	-1.1123	-0.8520

The results showed that in Lundby tunnel sample pH 10 and dissolved amount of SiO_2 (mg/L) the solution is saturated with respect to the Quartz and undersaturated with respect to the amorphous silica. The same trend is seen for Telia tunnel which had pH 8.3 and 17 mg/L dissolved SiO_2. There is slightly higher dissolution of silica at higher pH than at lower pH values.

D13.2. Conclusion based on Modeling:

The main conclusions of modeling are following;

- i) In the highly alkaline solution generated by the dissolution of portlandite the $CaCO_3$ phase will be formed at very low dissolved concentrations of CO_2.
- ii) The solubility of portlandite is not affected by the amount of $CaCO_3$ but is highly dependent on the pH of the solution. If the pH of water is low there will be more dissolution of portlandite compared with the solution of high pH values.
- iii) Amorphous silica is more soluble than quartz in these water environments. A slight tendency of increase in solubility with increasing pH is also possible.

D14. Discussion regarding performance of grouting

- The studied cement in Lundby are samples taken fron the grouted borehole plug. With knowledge of how the grouting was done it means that the plug most certainly consist of a grout that was initially grouted with low water to cement ratio. This means that no grout samples from the actual fractures were found. Never the less it was by "luck" that we were able to find a poor cement in the grouted borehole and is probably due to "erosion" of the grout during actual grouting of the borehole
- If the plugging of the borehole was successful the fractures would also have to some extent been sealed. This means that it would have been possible to find some grout n the fractures but were not. More boreholes would have been appropriate but was not done.
- The cored borehole leaked some 0,2-0,5 l/min after the drilling was finished and this was also the water sampled for ground water analysis. The leakage indicate not sealed fractures even though that this part of the tunnel allot of grout was pumped. The borehole were after core drilling grouted with INJ30 with a WCR of 0,8 (2% setcontrol II).
- In the Telia tunnel, cement in one sample was found and in a natural fracture some 10 meters along the core. The cement had elements of portlandite and may be due to that it has been dissolved and the cement is not stable anymore.

References

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