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Development of a sealing component/technique for corrosion protection of rock bolts

Final progress report

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Project information and status

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1 728 000	488 000	1 240 000

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1. Summary

As explained in the project description, this study consists of six work packages (WP1-WP6) with various predefined tasks. The aim of WP1, WP2 and WP3 was to develop an expansive dry mortar filled in a paper packet with the properties defined in the description of the project. As a starting point, after review of the commercially available products in the industry, Cembolt produced by WEBER, was selected as a reference. Accordingly, an extensive investigation including several chemical and mechanical tests was conducted to evaluate the properties of its infilling cementitious dry mortar as well as the wrapping paper. The results showed the benefits and the draw backs of the used materials as reference. Thereafter, the development of the dry mortar was done with intention to improve the weaknesses, especially concerning the shrinkage properties.

After investigation on the properties of the paper used in Cembolt, several paper samples have been evaluated. Two of the samples have showed better penetrability and strength properties than the others. Accordingly, several paper packets were made (with simple geometry) and filled with the reference and the newly developed dry mortars and tested to evaluate and compare their properties. The evaluations were part of WP3 where the paper packages were tested in the laboratory rig simulating conditions in the field. After the laboratory test 100 packages were prepared for the field test and packed into boxes in the beginning of summer 2020 for the field test.

In the meantime, the data collection and evaluation related to the environmental and cost analysis of the newly developed products compared to the traditional methods that are currently used in the industry (WP5) were started on October 2019 and finished by the end of 2020.

It took quite long time until a proper field test site was found to start WP4. The field trials were conducted on December 16th, 2020. During the trial approximately 80 paper packages were installed.

In general, the progress of the project well matched with the progress defined in the time schedule of the project. WP3 has been even started one month earlier than the plan in December 2019. Due to the time-consuming process of organization of the in-situ field tests, especially finding the proper site and the permission process it took over 5 months for the WP4 to be finished.

2. Main objectives

In this project, the main objective is to develop an expansive cementitious dry mortar filled in paper packets to install under the dome plates during construction of rock support systems in underground infrastructures. The final product is supposed to fill all the cavities and air voids under the dome plates to prevent the ingress of water and the associated corrosion. Accordingly, the main task in the current project, is to develop a proper dry mortar with sufficient expansion and strength properties and desired setting and hardening time. Finding the right paper with desired strength property in both dry and wet conditions, sufficient stretch ability, low permeability in lateral directions.

In WP3 and WP4, using the materials obtained from the results of WP1 and WP2, some prototypes will be produced and tested in both the lab- and the field-conditions to evaluate and demonstrate the efficiency of the method. The objectives of these WPs will also be fulfilled in the course of the project.

3. Benchmark testing

A. Objective

The objective of the experiments in the benchmarking tests is to evaluate the commercially available materials (Cembolt product from Weber) and compare their performance with SH cement.

B. Experiments

The experiments conducted:

Phase analysis

Phase analysis was performed using thermogravimetric analysis (TGA). Cembolt and SH cement samples were heated in a crucible in dry flowing nitrogen, at 20 K to 2000 K with the rate of 10 K/min.

Mixing protocol

The water was added with 0.38 water to solid ratio and mixing was performed at medium speed for 4 min in the Hobart mixer.

Hardening time

Initial and final setting of paste was measured with a Vicat needle apparatus. Measurements were performed according to the SS-EN 196-3,2016 standard[1].

Compressive strength

Compressive strength measurement, using 3 specimens of 40 x 40 x 160 mm (after 1 day, 7 day and 28 day) according to testing standard[2] SS-EN 196-1: 2016.

Heat of hydration

A TAMAir isothermal calorimeter was used to monitor the heat evolved during the cement hydration reaction at 20 °C for 24 h. The sample was mixed at room temperature at 0.38 water to cement ratio.

C. Results

Phase analysis of dry mortars using TGA

Thermogravimetric analysis showed that gypsum phase between 80 to 140 °C in the un-hydrated samples. Similarly, small quantities of portlandite was observed between 360 – 420 °C and carbonated phases (amorphous and finely divided calcite, CaCO3) was observed in 600 – 800 °C. The results suggested that Cembolt has similar composition to SH cement (see more details in Progress report 2).

[1] Swedish Standard SS-EN 196-3, 2016 " Cement Testing - Part 3: Determination of bonding time and volume resistance," Swedish Institute of Standards, SIS, Sweden, 2016.
[2] Swedish Standard SS-EN 196-1, 2016 " Cement Testing - Part 1: Determination of strength," Swedish Institute of Standards, SIS, Sweden, 2016.

Hardening time and strength properties of the paste

The set time results are presented in Table.1, along with compressive strength data. Both Cembolt and SH cement exhibited similar early set time. However, for final setting time of Cembolt was retarded by 70 min compare to neat SH cement. As shown in Table 1, Cembolt and SH cement samples produce similar early age strengths this is likely due to similar binder composition of both samples. However, at age of 7 day, Cembolt strength reduced by 9% of the strength exhibited by SH cement which can be attributed to long final set time of Cembolt samples. At age of 28 days, Cembolt strengths are increased by 7 % compare to SH cement.

Heat of hydration

During the heat evolution resulting from the hydration reactions of cement pastes containing Cembolt and SH cement performed at isothermal conditions was observed that Cembolt has high retardation compare to SH cement which was also observed in the set time measurement (see more details in Progress report 2).

Table1 Set time and compressive strength for Cembolt and SH cement.

	Cembolt	**SH cement**
Water Demand	38.0%	38.0%
Initial Set (min)	170	160
Final Set (min)	270	200
1 day	42.7	41.55
7 day	50.64	55.28
28 day	66.92	62.51

D. Conclusions:

- Both Cembolt and SH cement possessed similar phases and showed similar properties – initial set time and compressive strengths, possibly Cembolt has contained SH cement as a primary binder.
- In addition to SH cement, Cembolt may contain synthetic dispersing agent to enhance water dispersion during initial contact with water. This dispersing agent has adverse effect on the final set time and heat of hydration of Cembolt, eventually it resulted in reduction of strength at age of 7 days.

4. Development of Mortar (WP1)

A. Objective:

The objective of the experiments in WP1 is to find the right type and proportion of the cementitious binder as well as the other additives based on the predefined requirements.

B. Binder selection

To select the proper cementitious binders in this WP, the following requirements were considered:

- Moderate setting time (3-4 hour)
- High early strength development (≥ 40 MPA)
- Low plastic and drying shrinkage

Accordingly, SH-cement that fulfills well the defined requirements was selected as the first choice. The SH-cement is a rapid-setting cement that due to the complicated manufacturing process is more expensive compared to the normal setting cement. Therefore, for economical reason, Bygg cement, which is a regular setting cement was selected as the second choice.

C. Additives selection

Shrinkage mitigation

Due to the application requirements, the final product of WP1 does not contain sand or any larger aggregates. Thus, without any aggregate, the hydrated cement paste is prone to shrink and eventually crack. To overcome the risk of shrinkage cracking, innovative shrinkage mitigation strategies that utilize expansive additives have been developed. In this study, Calumax QXP8 was selected as an expansive additive for mitigation of drying shrinkage. Calumex® QX-P is an additive to Portland cement, specially developed as a shrinkage reducing agent based on calcium sulfoaluminate (C.S.A.). Similarly, for mitigation of plastic shrinkage, Expandit 10 RR additive was selected.

Water reducing admixture or dispersing agent

To increase dispersion, commercial high range water reducer was selected.

The water reducing admixtures are use in cement to increase dispersion of cement particles in aqueous phases with water and do not form cement – water agglomerates.[3] Melment® F 10 from BASF is high range water reducer and it is used for enhancing dispersion of cement particles in Portland cement-based systems.

Water retention agent

Water retention agent was added to increase absorption and water retention capacity of product. The commercial bio-based additive was selected - BERMOCOLL ME 1000 X.

D. Experiments

- Mixing protocol
  - Water to cement ratio = 0.38
  - Procedure have explained in the first section

[3] Dodson, V. H. (2013). *Concrete admixtures*. Springer Science & Business Media.

- Hardening time of paste
    - Procedure have explained in the first section.
- Compressive strength
    - Procedure have explained in the first section.
- Rheology of paste – flow measurement
- Slump flow measurement, using flow table and according to testing standard[4] SS-EN-1015-3-2006. Wet density of paste – Mut balance
- Wet density, using mud balance according to testing standard[5] SS-EN 445: 2007. Heat of hydration measurement
    - Procedure have explained in the first section

E. Formula development

Part 1. Comparison between Bygg cement and SH cement formula

The formula of each sample was included in the grey shaded part of the Table 2 and 3. The expansive agent was added at three dosage percentage (with respect to cement) levels 6, 8 and 10 % for SH cement and 6, 8 and 14 % for Bygg cement mortar.

Results

- The SH cement mortar displayed faster initial and final setting time compare Bygg cement mortar. Which resulted in the high early compressive strengths for SH cement mortar.
- During heat evolution at isothermal conditions for 24h at the temperature of 20°C (see more details in Progress report 2) it was observed that Bygg cement mortar has high retardation compare to SH cement mortar which was also reflected in the set time measurement. Due to presence of high aluminate phases and fine particle size, SH cement has high heat of hydration compare to Bygg cement.

Part 2. Final formula selection and testing

The SH-8%QXP mortar formula was selected for final modification. The formula was modified, and Expandit 10 RR additive was incorporated to induce expansion in the plastic state of mortar.

Results

- The Final formula (refer table 2, green shaded column) showed similar compressive strengths and other properties to SH-QXP8 formula. However, it showed higher set time compare to CH-QXP6 formula possibly due to inclusion of Expandit 10RR additive.

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4 Swedish Standard SS-EN 1015-3, 2006 " Methods of test for mortar for masonry – Part 3: Determination of consistence of fresh mortar (by flow table), " Swedish Institute of Standards, SIS, Sweden, 2006.

5 Swedish Standard SS-EN 445, 2007 " Grout for prestressing tendons – test methods," Swedish Institute of Standards, SIS, Sweden, 2007.

Conclusions

- SH cement binder showed superior compressive strength, short set time and good workability, which surpasses the selection criteria of binder discussed in the binder selection section. Thus, SH cement mortar was selected for further testing.
- In addition, SH-8% QXP and SH-8% QXP mortars displayed higher compressive strengths compare to SH-6%QXP mortar, thus SH-8%QXP mortar was selected for further testing.
- The final formula included all the additives and binders in appropriate prepositions, and it satisfies the benchmark requirements.

Table 2 Physical testing of SH cement-based mortar.

	Product formula			Final
	SH - 6% QXP	**SH - 8% QXP**	**SH -10% QXP**	**SH-8% QXP+Expandit**
SH cement	93.60%	91.60%	89.60%	91.40%
QXP	6.00%	8.00%	10.00%	8.00%
Melament F10	0.30%	0.30%	0.30%	0.30%
ME1000 X	0.10%	0.10%	0.10%	0.10%
Expandit				0.20%
Total	100.00%	100.00%	100.00%	100.00%
Testing				
Water Demand	38.00%	38.00%	38.00%	38.00%
Density (g/cc)			1.94	1.85
Flow 20 drops (cm)	16.7	17.1	16.4	17.98
Initial Set time	2:40	2:40	2:40	4:00
Final Set time	3:40	3:10	3:30	5:20
Compressive strength				
1 day	41.12	45.55	42.81	45.06
7 day	49.48	54	56.42	51.64

Table 3 Physical testing of Bygg cement-based mortar.

Product Formula

	Bygg +6% QXP	Bygg +8% QXP	Bygg +14% QXP
SH cement	93.60%	91.60%	85.60%
QXP	6.00%	8.00%	14.00%
Melament F10	0.30%	0.30%	0.30%
ME1000 X	0.10%	0.10%	0.10%
Total	100.00%	100.00%	100.00%
	Testing		
Water Demand	38.00%	38.00%	38.00%
Density (g/cc)	1.9	1.84	1.83
Flow 20 drops	19.1	18.6	18.45
Initial Set time	4	4	3:10
Final Set time	4:50	5:10	3:50
Compressive strength			
1 day	38.25	37.32	37.38
7 day	42.26	45.6	46.06

F. Measurement of plastic shrinkage in SH cement mortar.

As discussed in the previous section, SH cement mortar was selected for further experiments.

Effect of expansive agent Calumax QXP and Expandit 10RR on plastic shrinkage of SH cement mortar

Experiments

- The formulae were included in the Table 4.
- Mixing protocol
  - Water to cement ratio = 0.38
  - Procedure have explained in the first section
- Plastic shrinkage experiments were performed on commercial instrument designed by Walter-Bai.
- The well mixed paste was poured Walter-Bai tray and length change was measured using two LVDT sensors for 48 hours at 65% RH and 20 °C (see more details at Progress report 2).

Results

- The neat SH cement sample show negligible expansion after setting time and then it exhibits high shrinkage. After addition of expansive agent - Calumax QXP8, mortar showed expansion after setting time and this assisted in reducing overall shrinkage. The expansion was attributed to formation of ettringite in the mortar. It was observed that addition of dispersing agent Melament F10 does not have significant effect on the expansion and it showed similar trend to SH-QXP8 mortar. Whereas, mortar with water retention agent displayed high expansion after setting time and this was resulted in 97% reduction of shrinkage compare to neat SH cement mortar.

- Similarly the addtion of Expandit 10RR in final formula increases the early and overall expansion compare to Binder8-1 (no Expandit 10 RR additive). Both formulas did not show shrinkage in 24 hours. Whereas, neat SH cement and Cembolt (commercial Weber product) showed shrinkage throughout the testing span.

Conclusion

- The addition of expansive agent (Calumax QXP) and water retention agent (Bermocall ME1000X) is efficient in reducing overall shrinkage for SH cement mortar.
- The final formula is dimensionally stable, and it show balance expansion and negligible shrinkage.

Table 4 Experiment design for Walter Bai plastic shrinkage measurement.

	Pure SH cement	SH cement + 8% QXP	SH cement + 8% QXP + Melament F10	SH cement + 8% QXP +Melament + ME1000X	Final formula
Experiment Name	SHcement1-pure	SHQXP8-Purecement1	SHQXP8-melamentF10	Binder8-1	Final formula
SH cement	100%	92.00%	91.70%	91.60%	91.64%
QXP		8.00%	8.00%	8.00%	8.00%
Melament F10			0.3%	0.30%	0.30%
ME1000 X				0.10%	0.10%
Expandit 10RR					0.20%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

5. Selection and testing of papers (WP2)

The development and testing of a prototype of a paper packaging was the purpose of this work package. The properties of the intended prototype were proper dimensions, sufficient strength and permeability to contain the developed cement mortar. The goal was to find a suitable paper quality and develop a packaging that can be filled with cement mortar. Commercial paper grades were collected, and a simple packaging prototype was designed for the first tests. The design was refined after the first tests and after dialog with the mortar development team. The proposed prototype was handmade for further testing and 40 samples were delivered.

Some risks are identified with the choice of a paper packaging and should be investigated further:

- The paper remains between the rock and the bolt an no direct contact is established
- The paper will degrade after the hardening of the mortar and leave cavities that can be filled with water and increase the risk for corrosion

Packaging requirements

The scope for this WP was to develop a paper packaging prototype

- With high strength and air permeability
- Specific geometry

The packaging requirements were somewhat contradictory. The preferred properties for the paper grade were:

- The packaging material should allow water penetration in order to wet the cement-based material, high permeability and water absorption
- The packaging material should withstand to be submerged into water for between 10 minutes and 2 hours. Not lose its shape/sturdiness or dissolve during preparation in water and have high tear strength
- The packaging should burst when the plate is mounted and tightened to the bolt and to the rock
- The packaging material should dissolve after the rock bolt is installed and the cement-based material sets/hardens to make direct contact between mortar and rock

Selection of paper grades

Discussions with a paper producer was a first step to collect commercially available paper grades. Billerud Korsnäs delivered three paper grade samples for the initial tests.

Prototyping

The packaging prototype design was an iterative process, were input from the tests, carried out by the mortar development team, were taken into consideration.

Four papers were selected and tested in the first round of testing. Commercially available paper grades from Billerud Korsnäs and one paper grade produced on FEX, the pilot paper machine at RISE Innventia.

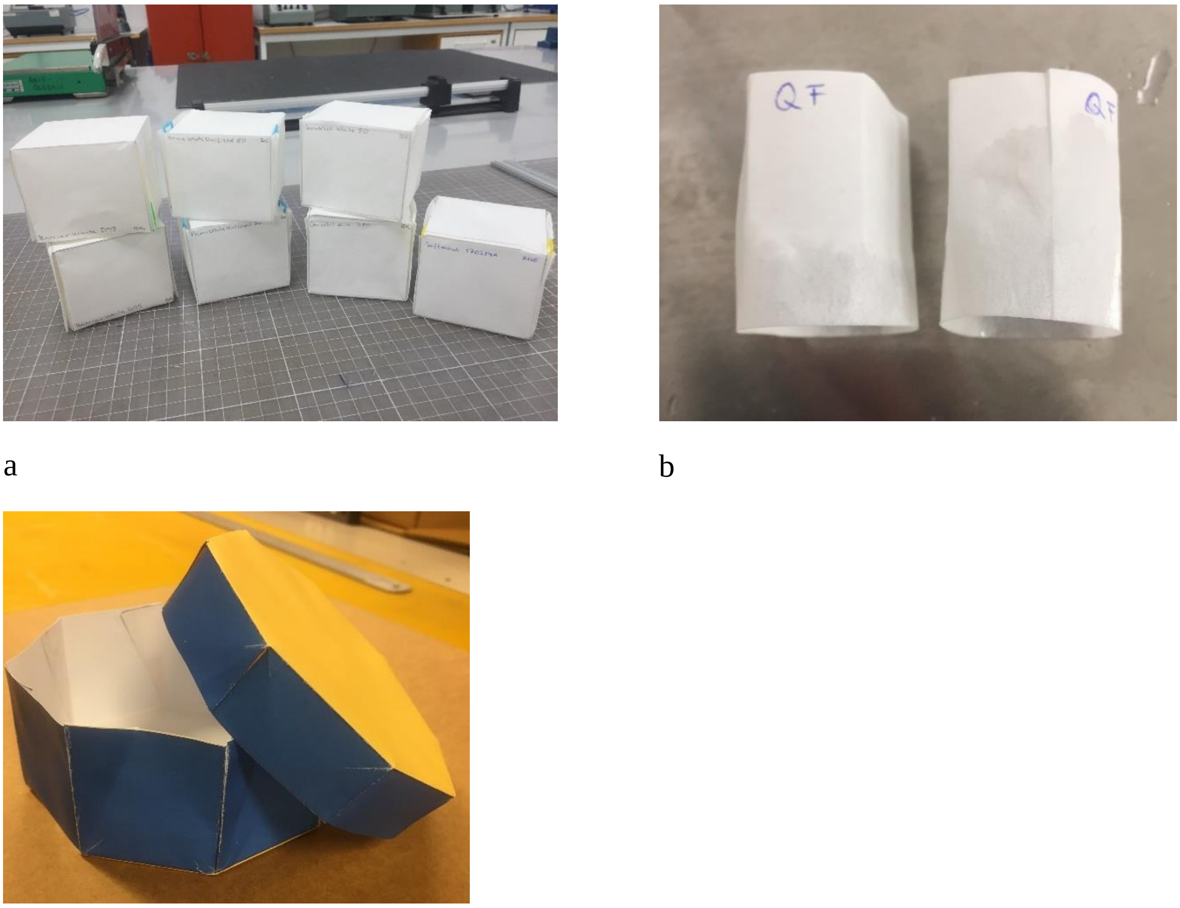
- Paper A was developed from soft wood in the RISE laboratory
- Paper B is a commercially available paper and it is used in cement bag packaging
- Paper C and D are commercially available papers with high water permeability

The paper grades are listed in Table 5.

Table 5 Paper grades for the water absorption test

Box	Paper grade	Supplier
A	Softwood, FEX-paper	RISE
B	Barrier White, D 95 g/m²	Billerud Korsnäs
C	Quick fill white, D 80 g/m²	Billerud Korsnäs
D	D Prime white unisized 80 g/m²	Billerud Korsnäs

Different techniques to produce suitable packaging were discussed, e.g. moulded pulp, folded paper. To consider: commercially available machines for the form, fill and seal operations and capacity requirements. The moulded pulp alternative is still under development and not yet commercially available. The top load carton/paper erector is a more suitable option. Design and development of a simple mock-up to test the water absorption of the 4 paper grades were carried out, see Figure 7a. The first test indicated that the water absorption capacity and sturdiness were best for paper C (Quick fill white) and Paper D (Prime white unisized 80) and they were selected for further testing. The new mock-ups were produced of these two preferred paper grades, now with a water-based glue (wood glue for indoor use). The glue was tested to see how durable it was when submerged in water, see Figure 7b. 30 new handmade mock-ups were made for the next test round. The results showed that paper C (Quick fill white) was the most suitable for further testing. The design of the shape of the final prototype was chosen to make it possible to produce in commercially available packaging machines and is easy to form, fill and seal, see Figure 1c.



a b

c

Figure 1 a) The first mock-ups in four paper grades, b) Simple test of the glue in water c) The final prototype

40 samples were handmade and delivered for further testing to the mortar development team. The tests were promising, and the team modified the prototype – the hight of the lid is now the same as of the bottom of the packaging.

Following objectives described the product testing in the paper packets.

A. Objective 1:

- The objective of the experiments is to test commercial Cembolt in water absorption testing.

Water absorption testing of commercial product – Cembolt

- In this product, mortar is filled in the paper cartridge which is consisted of water permeable paper. Thus, Cembolt was used for benchmark testing.

Experiment

- The Cembolt paper cartridges were fully submerged in the 20 °C water for variable time intervals.
- The sample weight was measured at before immersed in the water and after 10 min and 20 min respectively. The water to solid ratios were calculated.

Results

- At 10 min, enough water was absorbed through permeable paper without losing the sturdiness of paper cartridges (refer to Figure 10).
- The Cembolt samples were saturated with water at 10 min and there was not more absorption after 10 min.

Conclusion

- Cembolt paper has good water permeability and high strength require for Tunnel bolt application.

Table 6 Water absorption testing for Cembolt.

Submerged condition	**Submerged duration**	**Surface area**	**Water to product ratio**	**Wet Density**	**Comments**
Fully	10 min	485 cm^2 (cylinder)	0.422	1.86 g/cc	Sturdy appearance, paper was intact
Fully	20 min	485 cm^2 (cylinder)	0.419	1.84 g/cc	Sturdy appearance, paper was intact

B. Objective 2:

- The objective of the experiments is to find sturdy and water permeable paper for the tunnel bolt application.

Water absorption testing using 4 papers

Experiments

- Four papers were selected,
  - Paper A was developed from soft wood in the RISE laboratory.
  - Paper B is commercially available paper and it use in cement bag packaging.
  - Paper C and D are commercially available papers with high water permeability.
- The mortar from Cembolt paper cartridge was filled in the 7 cm^3 paper boxes and submerged in the water for 10 min of time interval (refer to Figure 2).

Results

- It was found that due to lose packaging, water entered in from the corners of the box thus accurate weighing measurements were not possible. Thus, the properties of paper were inspected by qualitative analysis.
- Due to impermeable nature, Paper B (Barrier white D95) didn't absorbed water and it crumbled after 10 min of testing.
- In contrast, Paper A (Soft wood Rise paper) was absorbed water however it was also crumbled after 10 min (refer to Figure 3).
- Paper C (Quick fill white) and Paper D (Prime white unisized 80) absorbed significant amount of water and they did not crumble after 10 min of testing**.**

Conclusion

- Due to water absorption capacity and sturdiness, paper C (Quick fill white) and Paper D (Prime white unisized 80) were selected for further testing.

Table 7 Experiment design for testing of 4 papers using water absorption test.

Name of Box	Type of paper	Cembolt mortar weight in box	Submerged condition	Submerged Duration
A	Soft wood Rise paper	300g	Fully	10 min
B	Barrier white D95	300g	Fully	10 min
C	Quick fill white D80	300g	Fully	10 min
D	D Prime white unisized 80	300g	Fully	10 min

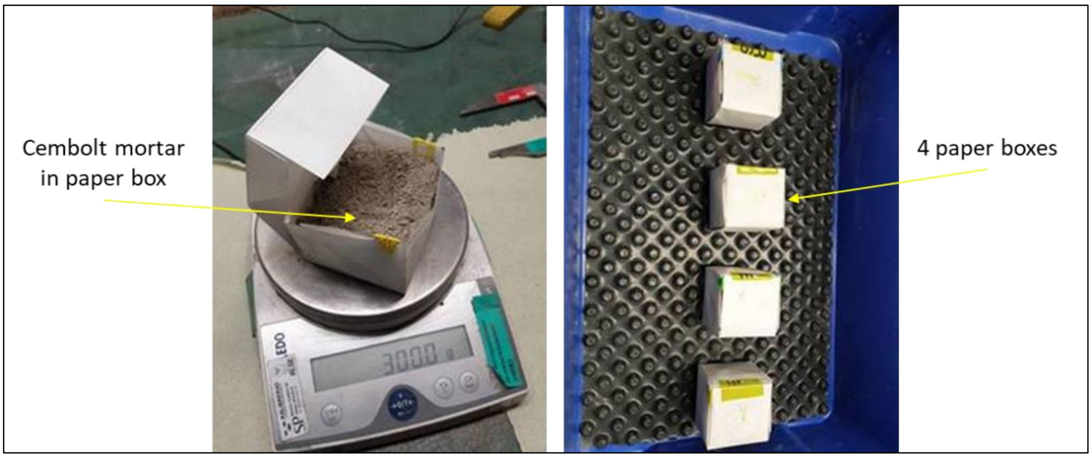


Figure 2 Experiment preparation for paper testing using water absorption test.

Figure 3 Condition of paper boxes after 10 min submerged in water.

C. Objective 3:

- The objective of the experiments is to compare water absorption capacity for Paper C (Quick fill white) and Paper D (Prime white unisized 80) using Cembolt mortar.

Water absorption testing for Cembolt mortar in Paper C and D.

Experiments

- Paper C (Quick fill white) and Paper D (Prime white unisized 80) were selected.
- The paper box was filled partially (50%) with Cembolt mortar and then submerged in the water for specific amount of time.
- Details of experiments are given in the Table 7.

Results

- Both papers are absorbed significant amount of water and they did not crumble after 10 min of testing. (refer to Figure 4)
- In paper C, water absorption was only in the perpendicular to the material whereas paper D absorbed the water in both perpendicular and lateral direction to material (refer to Figure 5)

Conclusions

- Both papers C and D are appropriate for Tunnel bolt mortar application however, paper C is preferable choice due to unidirectional absorption characteristics.

Table 8 Experiment design for testing Cembolt in paper C and D boxes.

Name of Box	Type of paper	Cembolt weight in box	Submerged condition	Submerged Duration	Water to product ratio
C	Quick fill white D80	152g	Partially – no top lid exposed	10 min	0.58
D	D Prime white unisized 80	152g	Partially – no top lid exposed	10 min	0.62

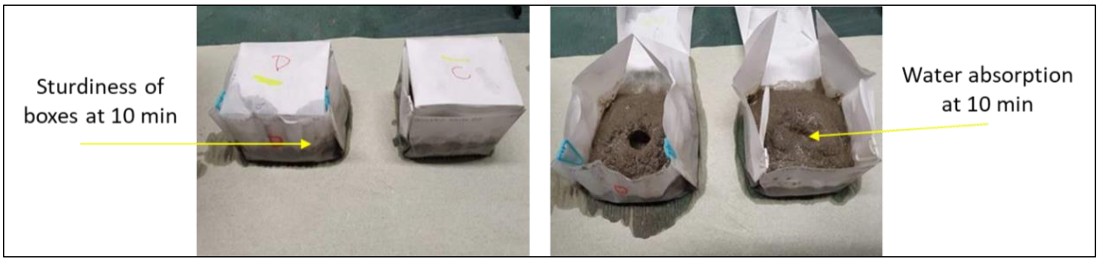


Figure 4 Water absorption and condition of boxes after 10 min.

Figure 5 Direction of water absorption in the paper C and D boxes.

D. Objective 4:

- The objective of the experiments is to test water absorption in Paper C (Quick fill white) and Paper D (Prime white unisized 80) using SH Cement mortar.

Water absorption testing for SH cement mortar in Paper C and D.

Experiments

- As discussed previously, SH cement mortar was selected for water absorption experiments (see more details in Progress report 2).
- The paper box was filled partially (50%) with SH cement mortar and then submerged in the water for specific amount of time.
- Details of experiments are given in the Table 9.

Results

- Both papers have absorbed similar amount of water after 10 minutes. The absorption saturation level was achieved after 10 minutes and there was not significant change in water absorption after 10 minutes.
- In paper C, water absorption was only in the perpendicular to the material whereas paper D absorbed the water in both perpendicular and lateral direction to material (refer to Figure 6)
- Paper C box displayed sturdiness till 30 minutes whereas paper D was D box broken at 30 minutes (refer to Figure 7).

Conclusion

- Both papers C and D are appropriate for Tunnel bolt mortar application however, paper C is preferable choice due to unidirectional absorption characteristics and long-lasting sturdiness.

Table 9 SH cement mortar formula for water absorption experiments

	SH cement + 8% QXP +Additives
Experiment Name	Binder8-1
SH cement	91.60%
QXP	8.00%
Melament F10	0.30%
ME1000 X	0.10%
Total	100.00%

Table 10 Water absorption for SH cement mortar in C and D paper boxes.

Name of Box	Type of paper	Water to solid ratio at 10 min	Water to solid ratio at 20 min	Water to solid ratio at 30 min
C	Quick fill white D80	0.72	0.75	0.76
D	D Prime white unisized 80	0.73	0.75	0.76

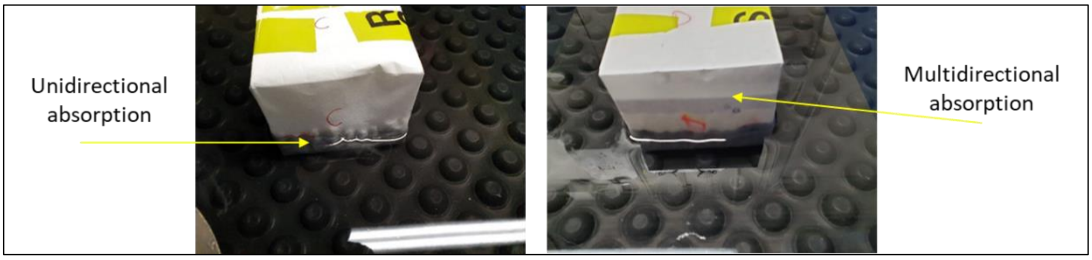


Figure 6 Water absorption mechanism for paper C and D.

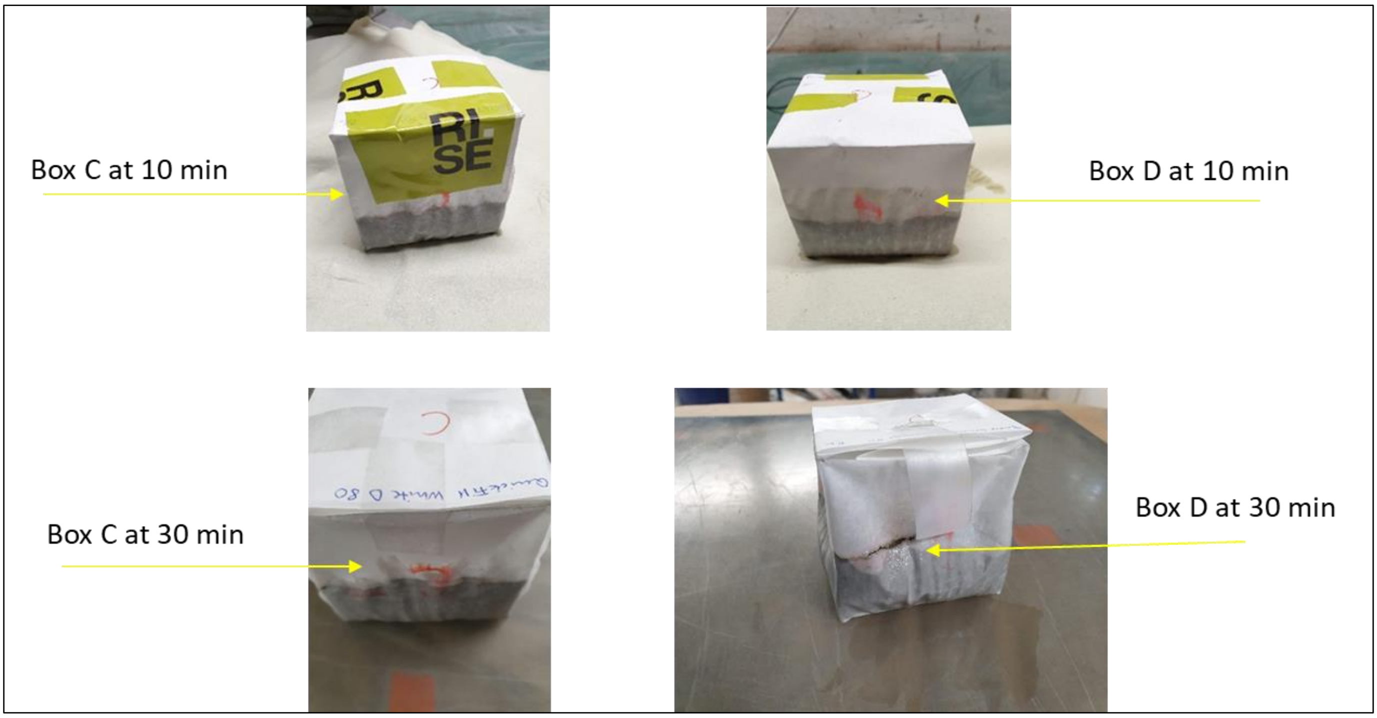


Figure 7 Condition of paper C and D in the water absorption test.

6. Laboratory test of prototype paper package (WP 3)

The first step in this WP was choosing the proper dimensions of the paper package prototype for laboratory test.

Paper package dimensioning

- Paper package volume and dimensions was calculated based on volume under dome plate, possible case of unfilled borehole depth h and the dimension of rock-bolt in the borehole (Figure 8). The package volume was calculated as V1+V2-V3 and multiplied by overfill factor of 1.2 as a safety factor.
- In the next step the extra volume of uneven surface with height h’ under the dome plate was added (Figure 9).
- Then from calculated final volume the package dimensions were calculated.

The dimensions

- The unfiled borehole depth h was assumed to be 40mm.
- The uneven surface height h’ was assumed to be 20mm.
- The calculated volume of paper package Vp ~0.330l.
- The package height hp=42mm.
- The diameter of the package dp=100mm.

Paper package prototype

- The final protype size was made as an octagonal box, with 100mm distance between parallel walls and with height of 42 mm (see Figure 11) and 10mm height lid.
- 40 pieces of such packages were produced for the laboratory test.

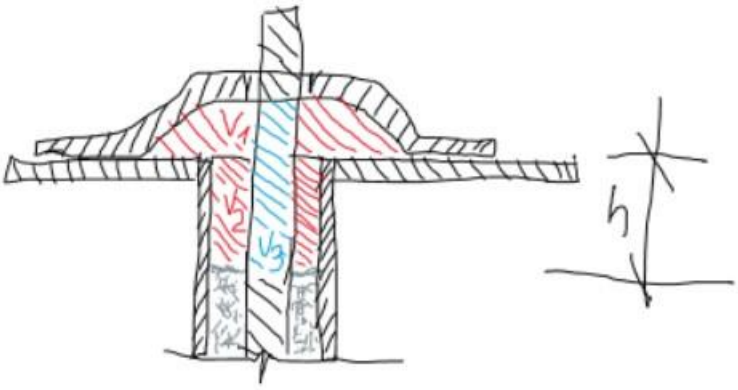


Figure 8 Volume under dome plate V1, unfilled borehole volume V2 and rock bolt volume V3.

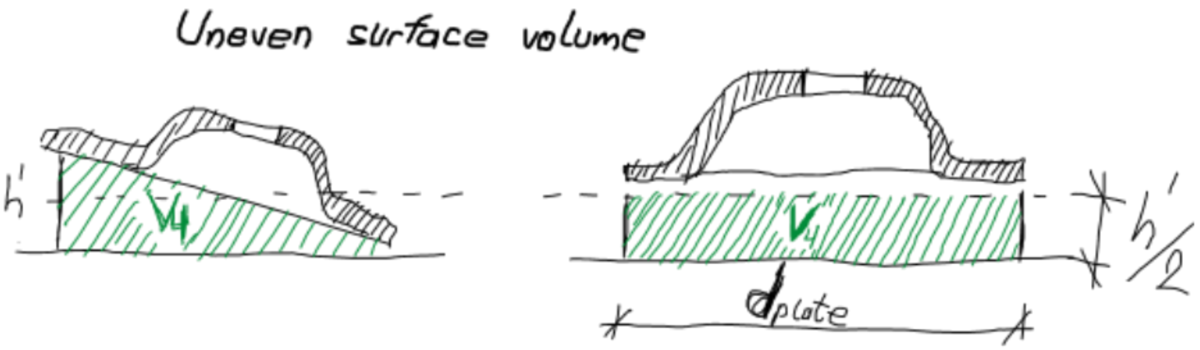


Figure 9 Uneven surface evaluation.

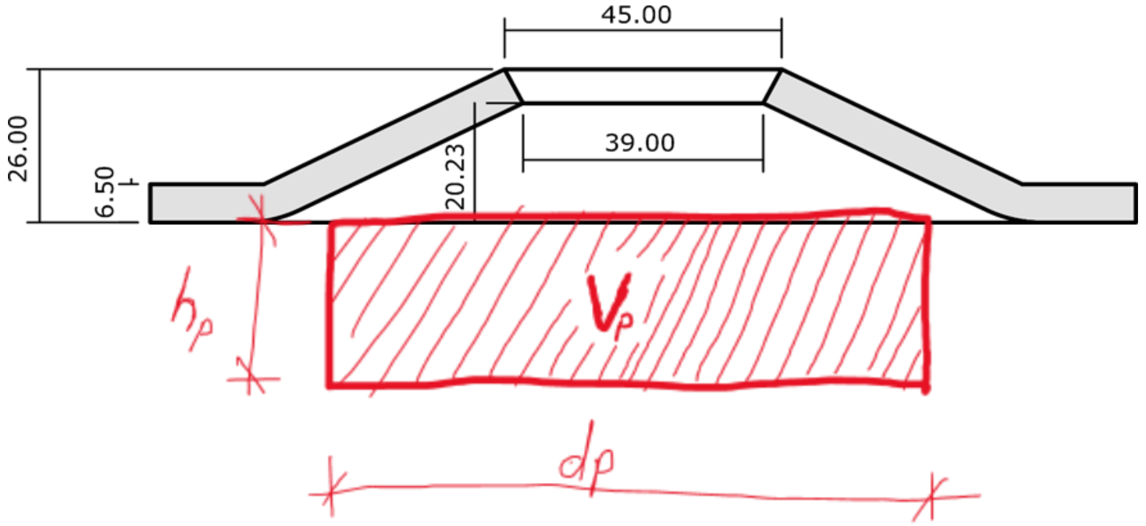


Figure 10 Paper package dimensioning regarding the dome plate

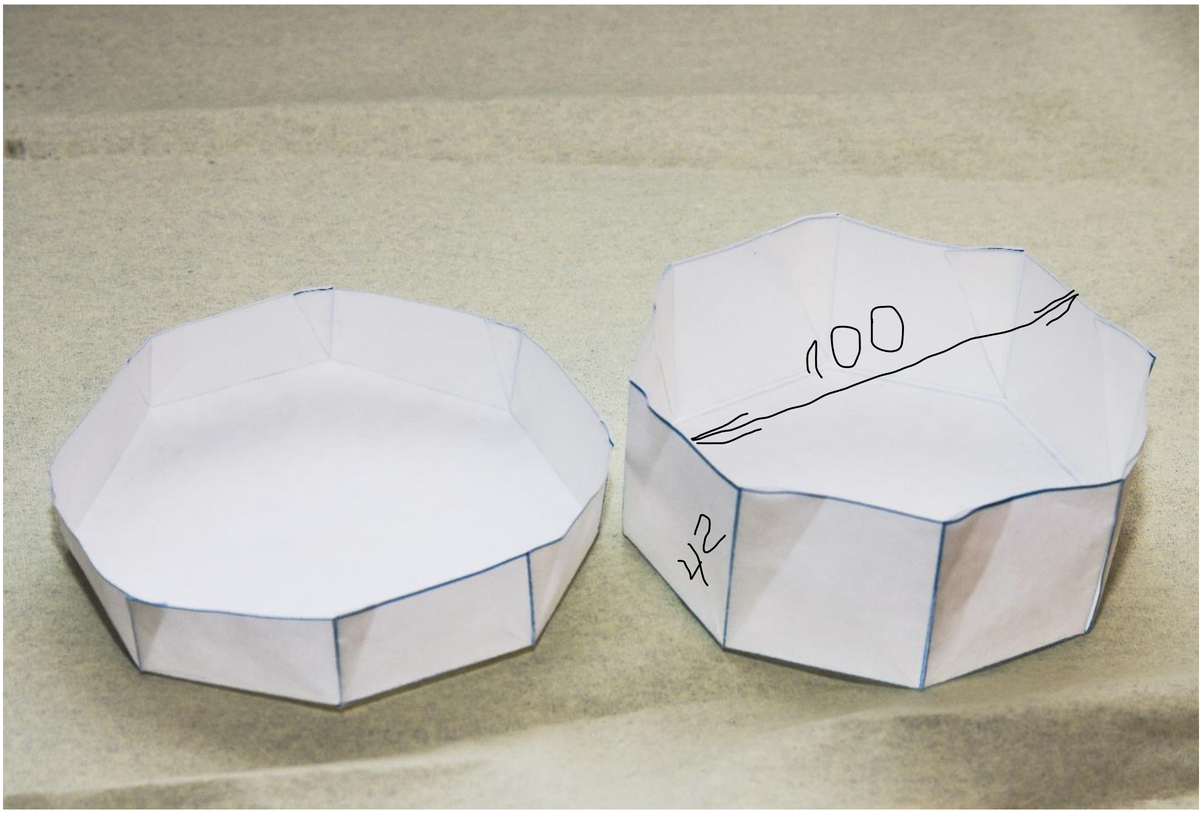


Figure 11 The paper package prototype.

The laboratory test rig

The objective was to design and produce a laboratory test rig to simulate dome plate installation procedure in real conditions.

- The laboratory test rig consisted of plywood plates screwed to the wooden stand for rock surface simulation and with four holes for borehole simulation (Figure 12 a).
- The borehole was simulated using Plexiglas tubes with inner dimeter of 45mm (Figure 12 b). Doe to the clear glass was possible to observe grout behavior.
- The test rig was equipped with the pivot rods for changing inclination angle of rock-bolts. The test was done for 0°, 45° and 90° inclination (Figure 12 c).
- To prevent rock-bolts from slipping the opposite ends to dome-plates were threated and bolted with the nuts (Figure 12 d).
- A day before testing the paper package the borehole was filled with the grout (Figure 13(a)) to simulate not fully filled borehole (Figure 13(b)). The color pigment was added to the grout in order to distinguish grout from paper package and borehole grout.

Figure 12 a) The laboratory test rig simulating four boreholes, b) with Plexiglas tube for borehole imitation, c) pivot point for changing inclination angle of the boreholes and d) the rock-bolt secured with the nut.

a b

Figure 13 a) Injecting the grout b) to simulate not fully filled borehole

First paper package prototype test

The aim was testing the paper packages by changing immersion in water duration, investigate grout spread under the dome-plate, investigate the rock-bolt inclination angle and the uneven surface effect on grout distribution under the dome-plate.

During first paper package test the hexagon box was filled with dry mix and then the lid was glued (Figure 14). After putting the package in to the water the escaping air from the dry grout started to gather under the lid (Figure 15 (a)) and the glue started to loosen. Due to these two factors after few minutes in the water the lid completely separated from the box (Figure 15 (b)). For the second approach the package was put to water with the lid downwards and the metal weigh was added to stop gathered air from rising the paper package. This helped to keep package integral in the water for 5 and then for 10 minutes. In both cases this was not enough to fully saturate the grout and some dry powder was present in the central part of the package (Figure 16 (a)) While tightening the dome-plate with the nut paper package burst and the wet grout spread to all directions (Figure 16 (b)). However, the 10 minutes soaking time was not enough for grout to penetrate in-to not fully filled borehole (Figure 16 (c)). But the soaking time was not an issue for the grout spread under the dome-plate: The next day when the dome-plates were removed the grout was evenly distributed (Figure 17).

Paper package improvement

Paper package lid in the first test was the weakest part of the package. To solve this problem instead of the lid the second package box was used (Figure 18 a) Paper package improvement by using second box instead of the lid, b) puncturing the package for better bursting towards borehole, c) putting the package to the water in vertical direction so that the air be able to escape through the jointsFigure 18 (a)). The connection was tight and there was no need to use the glue. To improve the grout penetration to not-fully filled borehole front part of paper package was perforated to create weak points for bursting (Figure 18 (b)). To help air escape from the package it was immersed to the water vertically. This way the air could escape through the package joint (Figure 18 (c)).

Rock-bolt inclination effect on paper package performance

In general, the inclination of rock-bolt did not affect grout penetration into borehole and distribution under the plates. But in case of 90° rock-bolt orientation the amount of waste was somewhat larger compared to other cases (Figure 19 (a)).

Soaking time effect on grout distribution

In spite, that when soaking for 12 minutes some dry material remained in the centre of packing, this duration was optimal for hardened properties of the grout (Figure 20 (b))(it felt stronger and more difficult to remove when cleaning the rig). Longer soaking times induced cracking of grout under the plate (Figure 20 (c and d)).

Uneven surface effect on grout distribution under the dome-plate

To simulate the uneven surface the wood strips were used to lift one corner of the dome-plate for 12 and 20 mm (Figure 21). The grout distribution in all cases was good, however, some cracks were observed in the grout (Figure 21 (c)). It was assumed that cracks might be induced by drying shrinkage and for the next test the edges of freshly mounted plate were sealed with thick grease to prevent water evaporation. But this did not stop the cracking (Figure 21 (b)), suggesting that uneven surface might cause the cracking of the grout.

Alternative paper package design- doughnut shape

Two packages were made with such size that the amount of grout would be same as in octagonal package (Figure 22 (a)). Packages performed well when soaking in water and the grout distributed evenly under the dome-plates, however more entrapped paper was observed in the hardened grout as well as paper concentration area (Figure 22 (b)). This was due to joining the ends of the package to form the doughnut. Probably this can be avoided if doughnut packing would be produced in jointless manner. The other disadvantage of such package is larger amount of entrapped paper due to higher surface are of the package compared to octagonal shape.

Grout penetration to not-fully filled borehole

After first trial described in section a, in almost all cases grout fully penetrated in to the cavity of not-fully filled borehole (Figure 23 (a-d). There was only one case of not fully penetrated grout in 20mm uneven surface test, where the grout surface inclination inside the borehole coincided with plate inclination (Figure 23 (e).

Paper from the package distribution under the plate

The paper distributes between grout and the simulated rock surface (Figure 24 (a)) and between the grout and the dome-plate (Figure 24 (b, c)). Some paper is pushed to borehole walls (Figure 24 (d)). Since the paper used for making the packages is more permeable to water in perpendicular direction to the paper surface than in the parallel direction the remaining layer of paper between grout and rock or plate should not act as moisture bridge.

Conclusions

- The most optimal soaking time for the paper package is 12 minutes.
- Soaking package in vertical position facilitates air removal from the package and more even water penetration from all directions.

- Grout distributes under the dome-plate evenly disregarding the package soaking duration and the inclination angle of rock-bolt. However longer soaking duration (greater than 15 minutes) increase risk of cracking.
- The uneven rock surface does not affect grout distribution under the dome-plate but might induce the cracking of the grout.
- Doughnut shape package gives more entrapped paper in the grout compared to cylindrical shape packaging.

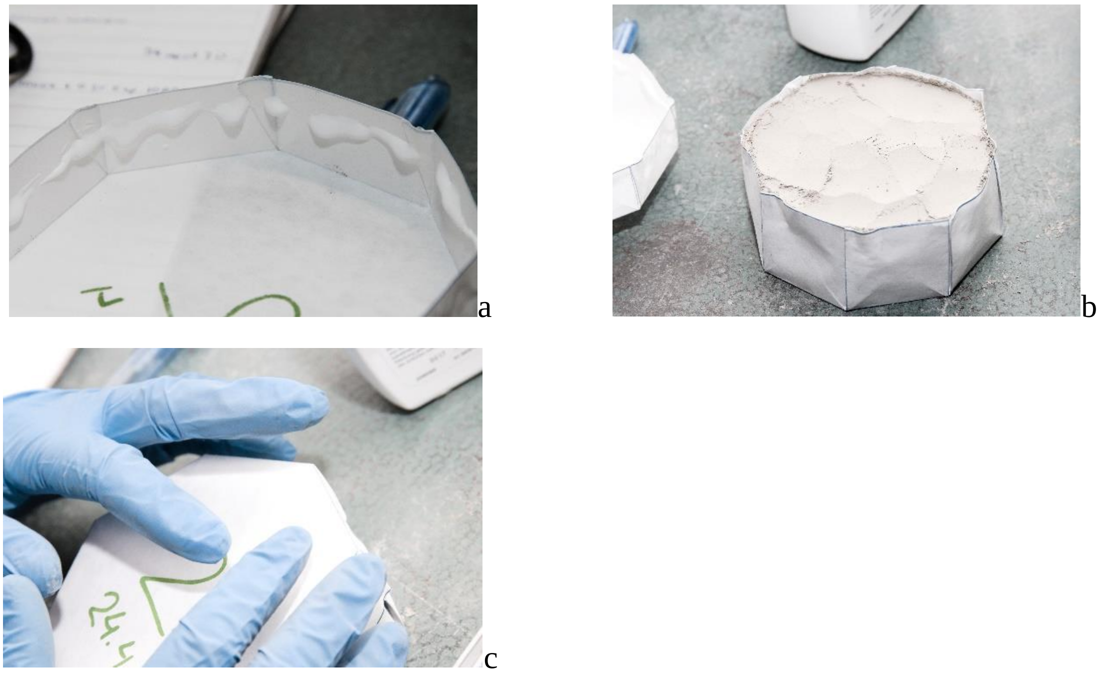
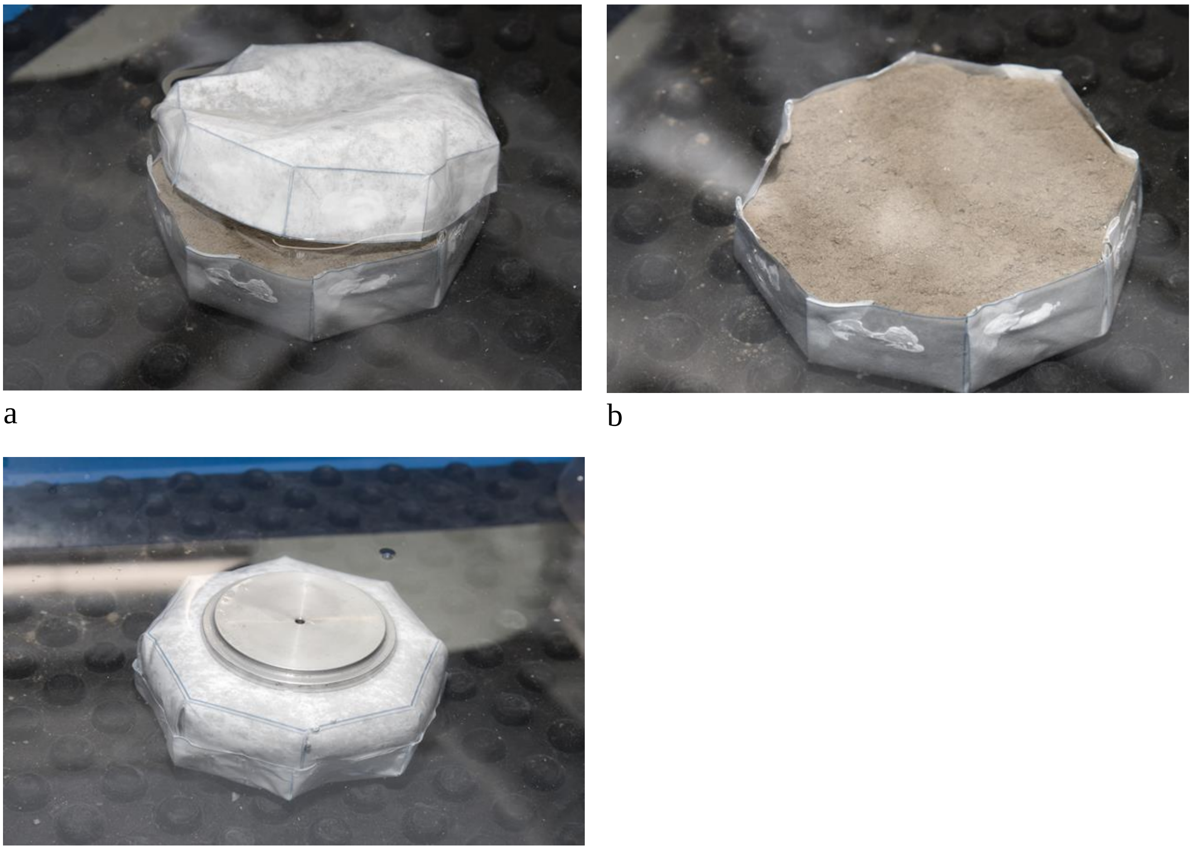


Figure 14 a) Filling the paper package with dry grout mix, b) covering the lid with glue, c) and gluing it to the package



a b c

Figure 15 a) Dissolving glue and the air pocket under the lid, b) fully separated lid after few minutes in the water, c) the weigh on the lid to stop it from floating

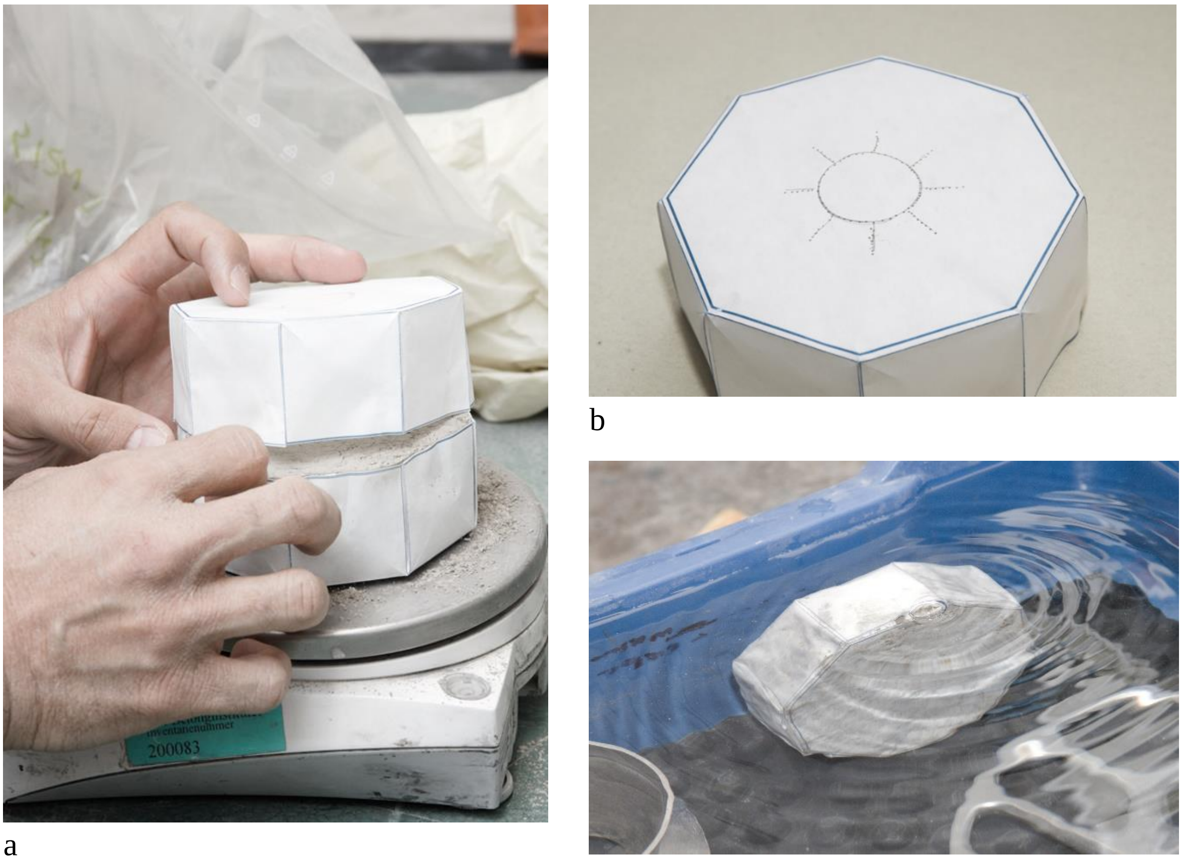

a


b


c

Figure 16 a) Visible dry grout in the central part of the package after 10 minutes in the water, b) the grout spreading under the plate after burst of the package, c) grout did not penetrate not-fully filled borehole under the dome-plate

Figure 17 The grout spread under the plate



a b c

Figure 18 a) Paper package improvement by using second box instead of the lid, b) puncturing the package for better bursting towards borehole, c) putting the package to the water in vertical direction so that the air be able to escape through the joints

a b c

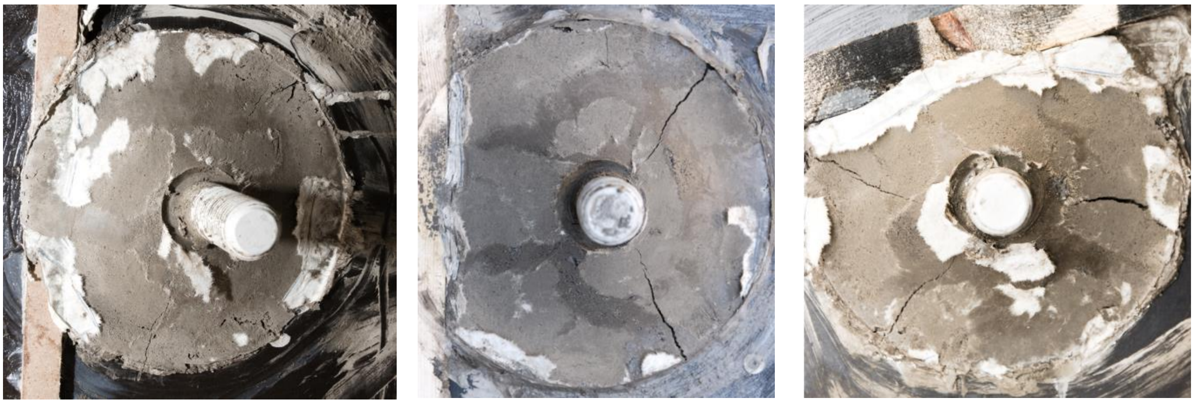
Figure 19 a) Rock-bolt inclination effect on paper package performance, the amount of waste material for 90°, b) 45° and c) 0°

a

b

c d

Figure 20 Paper package soaking time effect on grout penetration under the dome-plate at: a) 10 minutes, b) 12 minutes, c) 15 minutes and d) 20 minutes



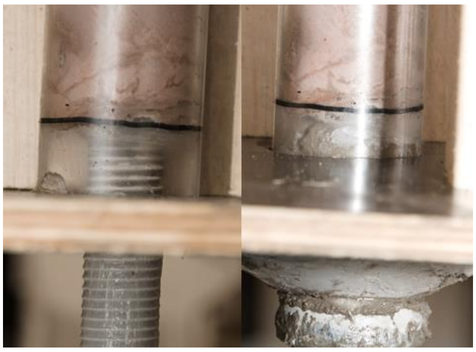
a b c

Figure 21 Uneven surface effect on grout distribution under the dome-plate: a) 12 minutes paper package soaking time and 12mm obstacle; b) 12 minutes paper package soaking time, 20 mm obstacle and sealed edged with the grease to prevent evaporation of water during grout hardening; c) 12 minutes paper package soaking time, 20 mm obstacle without sealed edges

a

b

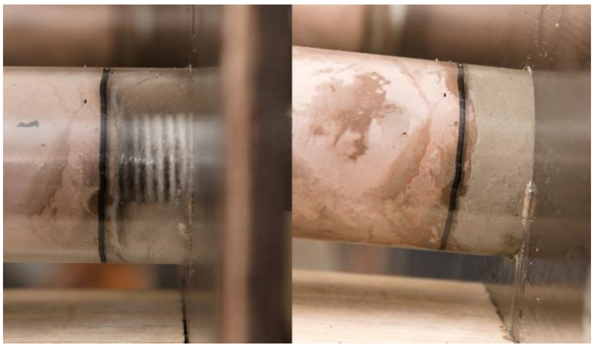
Figure 22 a) Doughnut shape package and b) even grout distribution under the plate with paper concentration area



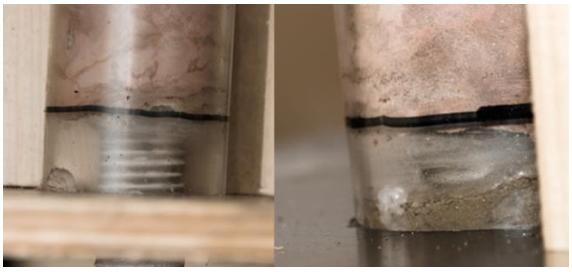
a

b

c



d



e

Figure 23 Grout penetration into the borehole. Pictures showing borehole empty space before and after installation of dome-plate.

a

b

c

d

Figure 24 Paper from paper package distribution a) between grout and simulated rock surface, b and c) between grout and dome-plate and d) paper pushed to borehole walls

7. Development of a sealing component /technique for corrosion protection of rock bolts - WP4 In-situ testing

A. Introduction

Abbreviations

In this report the following expressions is used:

The newly developed product is named “puck”.

A “package” is a box or cartoon with a fixed number of pucks, like a delivery package.

“Self-draining immersing box” or just “box” is equipped with holes in walls and bottom letting water in and out when immersing.

“Immersing box” is the water filled box where the self-draining box is immersed.

Basic preparations

Having done the development steps in WP1 Grout, WP2 Paper packet and WP3 Lab testing, it was now time for testing the new method in real tunneling.

Preparations for the field tests started early April, by planning the test procedure and writing documents as followed:

- Safety Data Sheet were prepared by the firm Kemrisk AB. See Appendix A
- A presentation was made to introduce the operators in the problem and the new method.
- A questionnaire, for the operators to answer after testing. See Appendix B
- A manual for using the products were developed. See Appendix C
- GDPR-allowance document was prepared. See Appendix D

All documents were written in both Swedish and English, as we didn´t know where or by whom the tests were supposed to be executed.

RISE prepared manually a series of 120 products to be tested.

To find a test site

Now it was only to find a site for the testing, but this was however not an easy task. As Trafikverket is the main client for tunnels and involved in the reference group, we found that one of Trafikverkets sites could be adaptable. Therefore, we started late May to contact Trafikverket Stora Projekt.

The question was one by one transferred to five project leaders in different projects. Due to different reasons it was not possible in the first four sites, but the fifth answer was positive. The whole operation took six months.

The actual project was FSE305 Södra Lovön. A new contractor, Norwegian AF Group, was established on site late October. In an early stage ten persons in the organization got sick in Covid 19, and another delay due to quarantine was a fact. December 4th we finally got a clear sign from Trafikverket. We could plan for execution before Christmas, namely December 15th and 16th.

B. Test method used

Test group

The tests were executed by four experienced operators, two Norwegians and two Swedes. To prepare bolts and manage practical things during tests, a construction leader rock from Trafikverket and one of the contractor managers was helpful.

For supervising, monitoring and documentation during testing, the development vice project leader was present, assisted by an experienced and independent tunnel worker. Additionally, two researchers involved in the development project were following the testing visually and documenting by photographing.

Information before testing

The operators involved in the tests were informed by the development project vice project leader. The information was transferred orally with help of a Power Point presentation and some written documents. The content was synoptic the following:

- Use of rock bolting in tunneling
- Trafikverkets demands on durability for transport tunnels, AMA and TRVK Tunnel 11
- How high demands on durability can be achieved
- How this corrosion protection is supposed to be done today
- Disadvantages with current method
- Short description of the new technique
- A short presentation of the development projects stages, WP1 – WP6
- What involved operators is supposed to do
  - Four operators involved (two teams)
  - Twenty installations each
  - Answer a questionnaire, comparing the new method to current method
  - Why we cannot execute the current method in the tests
- Permissions needed for this field test
  - Trafikverket have organized the preparations on site
  - Contractor assists with operators, bolts and needed equipment
  - Operators agree/disagree to be identified by filling the GDPR-document

Test area

Tests were to be executed in main tunnel 302-S2, where only around 20 meters tunneling remains before break through. Bolts for testing were installed at two different areas in the tunnel. Test area A was situated at the front south west, and test area B was located at the opposite front north east of test area A.

Forty rebar bolts were installed in each test area. The bolts were mounted without washer, half sphere and hex nut. The protruding bolt end was from 150-300 mm, which is 50-200 mm more than necessary. Threads was roughly cleaned (see Figure 25), but not protected except for a few that was partly covered with tape.

Figure 25. Bolt covered by hardened injection grout

Bolts installed in test area A

All bolts in test area A were installed on the walls, of which lower row was partly reachable from tunnel bottom. Most of these bolts were installed on naked rock, which gave uneven surface with sharp-edged structures (see Figure 26), not alike the situation occurring when mounted on sprayed concrete as described in Trafikverkets regulations. Some bolts were installed in the border line between sprayed area and naked rock where shotcrete is very thin, also resulting in uneven surface with sharp edges.

Figure 26. Bolt in the uneven rock surface with sharp corners

Bolts installed in test area B

Forty rebar bolts were installed without washer, half sphere and hex nut. The protruding bolt end was from 200-300 mm, which is 100-200 mm more than necessary. Threads was roughly cleaned, and some of them were protected with thread-tape (see Figure 27).

Bolts were installed on the walls and roof, and all of them on sprayed rock. This gave more realistic and soft shaped structures, compared to test area A. Two bolts were incorrect installed with threaded end inside the bore hole and could not be used for testing.

Figure 27. Removal of protective tape from bolt.

Equipment

A steady working platform, type AMV, with large platform approximately 4 x 2,5 m² was established at the work area (Figure 28).

Figure 28. Working platform used for the tests.

Besides a battery powered hex nut spanner, and self-draining boxes for the pucks as well as plastic immersing box was used. At test area B also a smaller but deeper box was used for immersing the last three puck packages (Figure 29).

a

b

Figure 29. Package with pucks immersed in water (a) escaping air bubbles (b).

C. Observations during execution

Execution in test area A

The first box was immersed for ten minutes. Self-draining function was very efficient (Figure 30). Then start mounting was delayed for around 11 minutes due to maneuvering the platform in position for installing washers on the bolts took severe time. This was probably because of personal not used to this platform. When another operator took over, it was done in less than a minute.

Figure 30. Pucks in self-draining box after immersing.

Figure 31. Successfully installed washer with puck on quite even surface,

The first three bolts were located on very sharp-edged rock surface. To achieve good filing, bolt number 3 was installed with two pucks (Figure 32 (a) and (b)). This was a lucky concept and was used for bolt 8 as well. Therefore, eight bolts were installed by using the ten pucks in the first box.

a

b

Figure 32. Installation with twin pucks: before installation (a) and after tightening (b).

The second box was immersed for ten minutes, and the mounting started around one minute later. This caused an increased volume of dry cement from the middle of the pucks running out from hole made when penetrating pucks. To avoid this spillage, some bolts were installed with attached half sphere as well. It seems to be effective to decrease wasted material.

Summary of test area A is as follows.

- Five boxes with ten pucks each was used for installing 40 washers on respective bolts.
- Immersing was done on the tunnel bottom, and the time was ten minutes for all boxes.
- Three bolts were installed with two pucks.
- Two pucks were broken, mainly as a result of the delayed start with box number 1 that made paper soft.
- Five pucks were residual, and therefore rejected.
- Time for installing seems to be approximately one minute for each bolt. Moving truck and platform is surplus time.
- Unsprayed rock surface resulted in less good quality result for some bolts. Where rock surface was less uneven, quality seems good.

Execution in test area B

The installations in this test area were more convenient according to the concrete sprayed surfaces. Many bolts were located at the tunnel ceiling (Figure 33), and this was both good and bad. It seems to be more efficient in the ceiling in order to achieve complete filling. On the walls cement sometimes runs out while spanning hex nut as a result of gravity. Quality was enhanced by resting the pucks 3-4 minutes after immersing.

Figure 33. Installation in tunnel roof on pre sprayed rock.

Figure 34. Void in outer part of bore hole.

Figure 35. Sealing with twin pucks.

Hex nut spanner went out of battery power after approximately ten bolts. A spare battery was found, and the uncharged battery was recharged. On most bolts the operator had to start with cleaning the threads on the bolts from cement grout spilled when installing the bolts.

Summary of test area B is as follows.

- Five boxes with ten pucks each was used for installing 38 washers on respective bolts.
- The first two boxes were immersed on tunnel bottom. The next three boxes were immersed on the platform, and this seems to be an effective method. It´s easier to handle the material as well as controlling the immersing time correctly.
- Three boxes were immersed for ten minutes, while the remaining two boxes was immersed 11-13 minutes. It was found that immersing ten minutes and resting 3-4 minutes was a good strategy to achieve correct quality and avoid spilled material.

- Two bolts were installed with two pucks due to uneven surface (Figure 35). This worked well.
- Threads had to be cleaned by attaching a hex nut and driven forward and reverse on the threads, taking a lot of time as protruding end and threads was unnecessary long. This of course consumed a lot of battery power. Battery was changed twice while installing in test area B.
- Installation was interrupted by blasting in the tunnel. During this time everybody went up to surface waiting for gases and dust to be ventilated. This took around two hours ten minutes.
- Two pucks were broken when taken from the box. This was especially the first puck in each box. Slightly longer immersing time can have affected this.
- Six pucks were rejected due to blasting interruption. Four pucks were residual, and therefore rejected.
- Time for installing seems to be less than one minute for each bolt, but long protruding bolt end made cleaning and hex nut driving quite time-consuming. Moving truck and platform is surplus time.
- Result was overall good quality.

Summary

The observed results from execution in the tunnel can be summarized as follows.

- Dry pucks seem to be well protected in self-draining package with plastic cover
- Immersing can be done on tunnel bottom, but also on the working platform
- Immersing time of ten minutes seems most convenient
- Resting for 3-4 minutes after immersing saves material waste
- Wasted pucks caused by broken paper wrapping is around 5 %
- The first puck taken from package is a little difficult to handle
- Pucks must preferably be used at latest half an hour after immersing ends
- Protruding bolt end must not be too long
- Technique for protecting the threads from cement would save a lot of time
- When uneven surface, twin pucks can be used
- Time needed for installing washers with pucks is around one minute each

Statistics from installed bolts are shown in Table 11.

Table 11. Installed bolts for testing.

Bolts for testing	Test area A	Test area B	Total	Share
Installed	40	40	80	100%
Incorrect	0	2	2	2,5%
Used	40	38	78	97,5%
Naked rock	40	0	40	
Sprayed rock	0	38	38	

Used pucks are shown in Table 12.

Table 12. Used pucks for testing.

Use of pucks	Test area A	Test area B	Total	Share
Immersed	50	50	100	
Residual	5	10	15	
Used	45	40	85	100,0%
Broken	2	2	4	4,7%
Twin pucks	3	2	5	5,9%

D. Results and analysis of questionnaire

The answered questionnaires were now studied in detail. As the statistical material was quite limited, it´s hard to state evidence and ensure results. Besides you can see that some of the questions are not satisfactory answered due to compared technique used today. That is why some of the conclusions are unsurely evaluated. Hereunder you can see my comments to the answers.

1. The operators think that the product is not appealing, perhaps understandable.
2. Function is clear to almost everyone just by looking at it.
3. The manual is easy to understand.
4. They think that dimensions on package are ok.
5. The weight of the package in dry conditions are ok.
6. The weight after saturation is also ok.
7. The sealing of the package is not a relevant question as it is provisional for this series.
8. The package is good for transportation.
9. The weight of the product is satisfactory.
10. The product dimensions are ok.
11. All think that the products sustain well in dry condition.

12. The immersing time are spread answers. Some think it´s too short, some too long and it´s hard to evaluate this. Recommended ten minutes seems to be ok.
13. All think it´s hard to take products out of package after saturation. The paper is easy to break, but it´s mainly for the first one. The result can be affected of too long waiting.
14. Paper packet remains intact during handling gave low to high score. Very spread answers make it hard to evaluate. One that get a break gave low score and opposite.
15. The waste of material when burst by bolt is medium.
16. When comparing the waste of material to traditional method the new technique is somewhat better. This might have been compared with the wrong method.
17. The operators think that speed of installation is slower compared to traditional method. The same comment as Q16.
18. All operators think that preparations are more time consuming. The same comment as Q16.
19. All operators think that the new method is more exhausting. The same comment as Q16.
20. The quantity control is medium compared to traditional method. This question is perhaps not enough clear.
21. The quality is medium to high compared to traditional method.
22. The new technique seems to reach expectations medium to high.
23. Widely spread answers. Some products were discarded and gave low rate. The operators who didn´t feel that gave top score.
24. A hole in the middle should make the product better.
25. If the new method is better than traditional method gave widely spread answers.
26. The operators gave medium score to use the product again.

The operators answered 98 questions totally, and the possible maximum score is therefore 490. The total score given were 286 which results in 58 % satisfactory with the new technique.

The detailed answers are summarized in Appendix E.

E. Conclusions

Field test in combination with production is a difficult task, but very important to see the functionality in real use. It also permits finding out how the operators feel about the new product.

The newly developed product does have functionality for its purpose, and the main goals are achieved as follows.

F. Installation quality

Roughly half part of the pucks tested were installed on naked rock surface. On those uneven and sharp-edged rock surfaces, the operators had no chance to achieve good quality. However, when installed on pre sprayed rock as usually described according to AMA, TRVK and the Q-system, the result was better than by using the traditional method. The texture made most cement grout stays behind the washer. When spanning the hex nut, grout was pressed out from the washer edge as presumed, ensuring voids and air pockets being filled. The material waste was low compared to handling stiff grout by hand, or as often used, not hardened grout from anchoring.

G. Working environment

No mixing of cement grout is necessary, and therefore no lifting of heavy cement bags. No cleaning of equipment is to be done either. The new method does save operators from the dirty filling of grout with hands overhead. Most of the waste is also avoided which prevent operators from being dirty.

The packages used were easy to handle, both dry and after moistening. The packages are not too heavy, and the paper wrapping were enough stable to stand the installation without breaking too early. Bursting the puck with protruding bolt end made little amount of dry cement leaking out, but after a short resting time this problem was minimized. Spanning the hex nut was made by battery driven hex nut spanner, which was a convenient and rapid method.

H. Productivity

The installation of washer with the new product takes roughly one minute each. Moving position on working platform is not included. This is approximately the same time as with traditional method, but for this method you must add time for establish mixing equipment, mixing grout and for cleaning mixing equipment. That seems to be quite favorable for the new method, especially when installing small quantities.

I. Required improvements

By testing in real conditions, we were able to find out how the new method can be improved to reach set goals even better.

- **Improved self-draining box design**
  The box solution with self-draining function, aimed for immersing pucks, seems to be very efficient and easy handled. However, it must be tailored to fit pucks more exact. That will make it easier to fill box with pucks from delivery cartoon, as well as picking pucks from box and install on the bolt without breaking the paper wrapping. It will also ease picking the desired number of pucks for each situation, reducing pucks from being wasted.

- **Immersing box design**
  A steadier box is needed to prevent accidents causing water to run out of the box. Furthermore, it was successful to immerse the pucks on the working platform. To ease this the box must be deeper not allowing water to flash out when moving platform.

- **Automatic time setting**
  It is very important to immerse the pucks exactly ten minutes. This could be secured by a simple alarm clock or similar. Then you can also program resting time and maximum time for using after immersing.

- **Delivery packet**
  Using a tailored self-draining box, admits choosing the number of pucks in each packet. In the field test we used a box containing ten pucks. Most of the operators thought this was ok, but one of them wanted more pucks in each packet. Perhaps twelve are the most convenient number. That will not make it too heavy to handle dry or wet, and twelve pucks are still easy to install during the maximum installation time around thirty minutes from completed immersing.

  Delivery packet can be rather compact even with twelve pucks as they will not need to be spaced. The packet must of course be protected against moisture during transport and storage with plastic cover.

- **Installing bolt aid**
  To ease the use of pucks the protruding bolt end must not be too long, but of course not too short either. The threads must not be dirtied by cement grout during bolt installation, making trouble attaching washer with hex nut.

  Both these requirements might be solved by a designed installation/protection aid, in form of a casing, preferably in plastic material. The casing should guide the right protruding bolt length and serve as protective cover on the threads. Furthermore, the casing should be shaped to ease manual bolt installation and save operator from concentrated pressure causing wounds on hands. The casing can be re-used several times which also helps saving environmental impact.

8. WP5- Environmental impact and cost analysis

The main goal of this task is to assess environmental and economic performance of conventional and new solutions for making grout under dome plate, as well as compare the environmental and economic performance of both solutions. The methods used for environmental and economic assessment are Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) respectively.

A. Life cycle Assessment (LCA) Method

The importance of environmental protection and specifying the environmental impacts related to produced and also consumed products have drawn attention to the development of methods that can make these impacts more understandable. One of these methods is Life Cycle Assessment (LCA) (ISO, 2006b).

LCA can help in (ISO, 2006b):

• identifying the possible areas of improvements in a product's life cycle from environmental points of view;

• decision support to have more informed decisions;

• selection of appropriate environmental performance indicators, including measurement techniques;

• marketing, such as producing an environmental product declaration.

LCA is a technique to assess the potential environmental impacts and to quantify material and energy consumptions associated with a product's life cycle, e.g. from cradle to grave (from extraction of raw materials, materials preparation, manufacturing, distribution, use, end of life treatment, recycling and disposal) (ISO, 2006b).

LCA studies include four phases, goal and scope definition, life cycle inventory, impact assessment and interpretation of the results (ISO, 2006b). Figure 36 shows the interactions between four phases of the LCA. They are discussed in sections below.

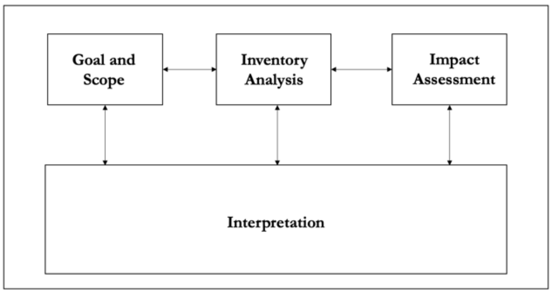


Figure 36 *Phases of LCA*

Goal and scope of the LCA

The goal of LCA mainly describes the reasons for performing LCA, the applications of the LCA results (for whom the results are intended to be used). Scope includes the functional unit, system boundary and assumptions.

Processes included in the system understudy in LCA focus on fulfillment of one of the functions of the system based on the goals of the study, which is called a functional unit. The functional unit determines what is being studied. It also defines the quantified performance of the product system to provide a reference to which the inputs and outputs of the system are

related. (ISO, 2006b). Functional unit is mainly useful to compare several systems that provide the same function. For instance, comparing the LCA results of a wooden bridge and that of a concrete bridge whose function is providing a service for pedestrians and the reference flow to be compared is a specific volume (e.g. m^3) of the bridges.
System boundary identifies which stages of the product's life cycle (e.g. production, use and disposal) and processes, based on the goals and scope of the study, are included in the analysis of the product (ISO, 2006b).

Life Cycle Inventory (LCI)

During Life Cycle Inventory (LCI) analysis, data collection is carried out to identify and quantify all input and output flows to and from the system boundary related to the required functional unit (ISO, 2006b).

Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) is a vital phase of any LCA. An LCIA helps interpret emissions and resource consumption data that are associated with a product's life cycle in terms of environmental burdens, human health, and resources. The chosen impact categories in this study are presented in Table 13.

Environmental Impacts	**Units**
Acidification potential, average European (AP)	Kg SO_2- Eq
Climate change, GWP 100a (GWP)	Kg CO_2- Eq
Fossil cumulative energy demand (Fossil CED)	MJ-Eq
Nuclear cumulative energy demand (Nuclear CED)	MJ-Eq
Stratospheric ozone depletion (ODP)	kg CFC-11-Eq
Resources, minerals and metals (ADP)	Kg Sb-Eq
Urban land occupation potential (ULOP)	m^2a

Table 13 Environmental impact categories are estimated in this study by applying LCA

Interpretation

The interpretation phase contains the following elements (ISO, 2006a):

- identification of the significant issues based on the results of the LCI and LCIA phases of LCA;
- an evaluation that considers completeness, sensitivity and consistency checks;
- conclusions, limitations, and recommendations.

The goal and scope and interpretation phases frame the study, while LCI and LCIA produce information on the system. The interpretation of the results gained from LCI or LCIA should be carried out based on the goal and scope of the study (ISO, 2006a).

B. Life Cycle Cost (LCC) Analysis

The LCC analysis is a way to predict the most cost-effective solution; it does not guarantee a particular result, but allows the planner, designer and/or architect to make a reasonable comparison between alternate solutions within the limits of the available data. The LCC will be carried out according to the international standard ISO 15686-5:2008 (Building and construction assets-Service life planning-Life cycle costing) and the European Standards EN 15643-4:2012 (Framework for the assessment of economic performance planning) and EN 16627:2015 Sustainability of construction works - Assessment of economic performance of buildings -calculation methods.

Data quality requirements and data management

The economic assessment shall be calculated excluding VAT. Cost data will be used from partners, literature data and Eurostat.
All costs will be taken into account, namely investment costs (CAPEX) and operative costs (OPEX). Typically, investment costs are business expenses that are not dependent on the level of goods or services produced by the business. Conversely, operative costs are volume-related (and are paid per quantity produced). Raw materials are typically operative costs, while the capital cost to build the production line is an investment cost.
Generally, the LCC analysis is divided in four steps, considering the same functional unit and system boundary defined for the LCA:

1) Identification of main process steps, the relevant equipment and their features such as the life span, the installed power, etc.;
2) Definition of the amount of raw materials and energy consumed, considering a yearly production
3) Definition of the costs associated to the process, investment (CAPEX) and operative (OPEX) that constituted by the equipment purchase costs and the expenditures for the raw materials, energy, maintenance and personnel, respectively
4) Calculation of the Total cost (C) per functional unit is calculated as the sum of OPEX and CAPEX.

Discount rate

The indicator in the LCC is the only indicator in this sustainability assessment that depending on when in time the effect occurs. It could be explained with that if you have a certain amount of money and save it on a place where the rate is higher than the inflation (real discount rate [r]) the value of the money will increase by time if you want to use it in the future. Real discount rate is the rate adjusted by inflation and could be calculated as:

$$r = n - i$$

where:
r= real discount rate
n=nominal rate (the rate from a bank for example)
i= inflation
According EN 16627:2015 the real discount rate is set to 3%.

Net Present Value, NPV

According EN 16627:2015 the value today for an economic transaction in the future could be calculated by using the discount factor CF (T), calculated according to the equation:

$$\boldsymbol{CF(T)} = \frac{\mathbf{1}}{(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{T}}} \qquad \text{Equation 1}$$

where
r is the annual real discount rate
T is the number of years in the future

Net Present Value is the sum of the discounted future cash flows:

$$\boldsymbol{NPV} = \sum \boldsymbol{CF(T)_i} \times \boldsymbol{C_i} \text{ Equation 2}$$

where
C_i is the real cost or benefit for a specific product or service.

C. Database for filling a dome plate with grout

In this study functional unit considered is materials required for filling under one dome plate. In other words, materials required for producing the grout under the dome plate. Data have been collected and referred to one dome plate. As life cycle of both solutions is assumed to be 120 years, use phase of the products and end of life of the products are excluded from the analysis. Therefore, the system boundary includes just processes related to production phase (production of materials required for filling under one dome plate). Therefore, LCA and LCC analysis is from cradle-to-gate. Moreover, the system boundary includes transportation of materials to the construction site, which is assumed to be in Stockholm. Figure 37 and Figure 38 show system boundaries considered in this study and included processes in the system boundary for both conventional solution and new solution respectively.

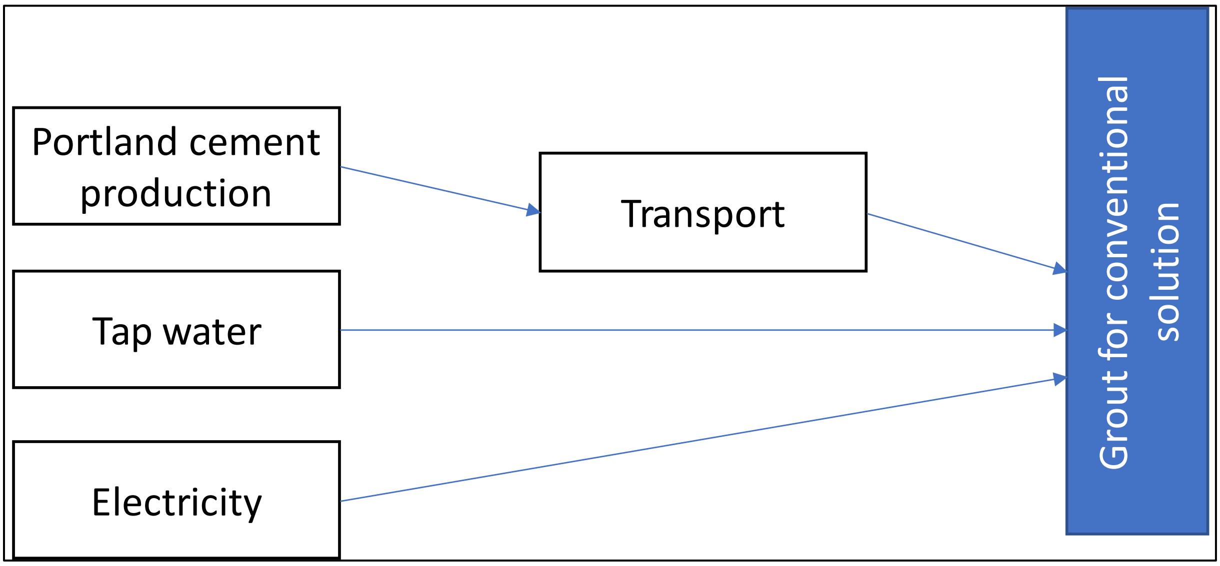


Figure 37 System boundary considered for LCA and LCC of conventional solution and processes included in the system boundary

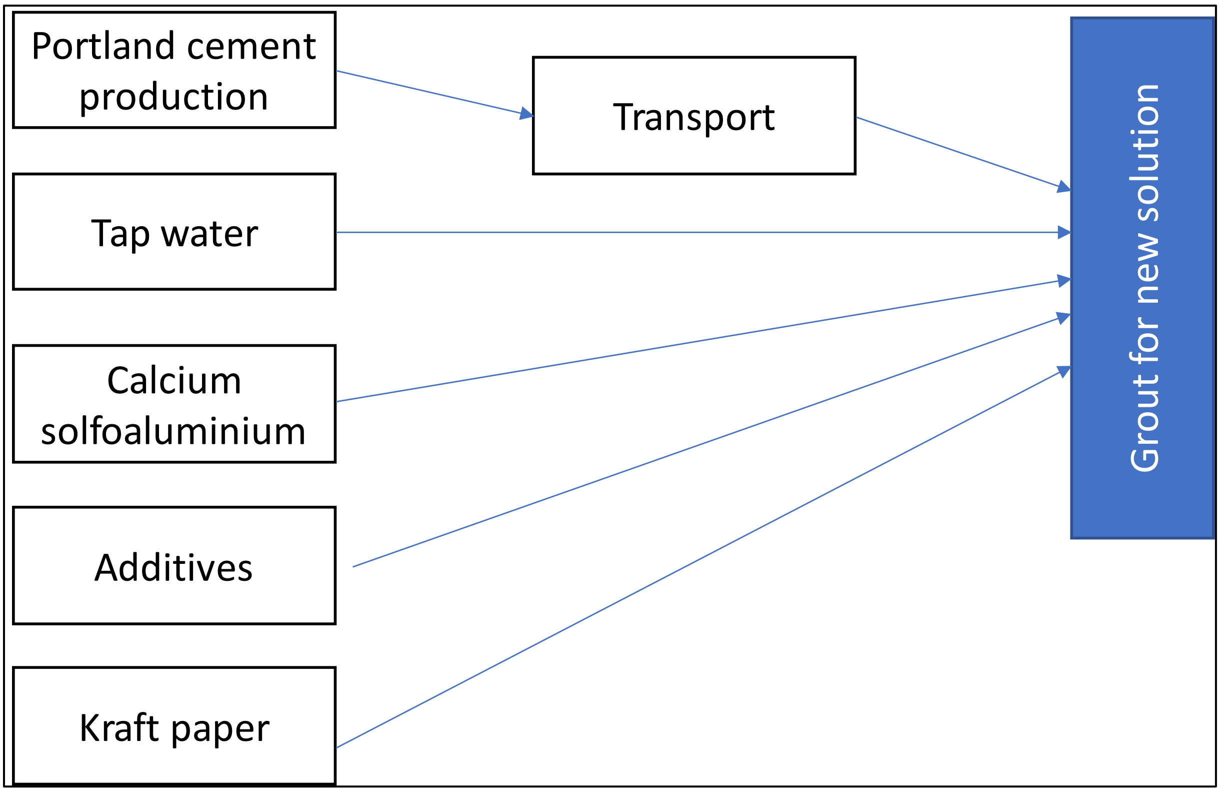


Figure 38 System boundary considered for LCA and LCC of new solution and processes included in the system boundary

Inventory of one dome plate for conventional solution

Table 14 presents materials required for filling under one dome plate for conventional solution. These data will be used for the LCA model.

Table 14 Inventory of filling under one dome plate for conventional solution (cradle-to-gate)

Conventional solution				
Processes information				
Place of manufacturing	Unknown			
Geographical representativeness	Sweden			
Reference flow (one unit of the product)	Materials required for filling under one dome plate			
Confidentiality of the dataset	No			
Data sources used for this dataset	Data were provided by BESAB (+ secondary data)			
Inputs and outputs of production phase				
Inputs	**Amount**	**Unit**	**Transport (km)**	**Comments**
Cement	4.9	kg	230	Anläggningscement CEM I 42.5 N, includes cement waste at the construction site
Tap water	1.23	kg	-	
Energy consumption at manufacturing site for mixing materials				
Electricity	1.2	kWh		Swedish electricity mix
Output				
Mix of filling materials for under one dome plate				

Inventory of one dome plate in new solution

Table 15 presents materials required for filling under one dome plate for new solution. These data will be used for the LCA model.

Table 15 Inventory of filling under one dome plate for new solution (cradle-to-gate)

New solution				
Processes information				
Place of manufacturing	Unknown			
Geographical representativeness	Sweden			
Reference flow (one unit of the product)	Materials required for filling under one dome plate			
Confidentiality of the dataset	No			
Data sources used for this dataset	Data were provided by RISE (+ secondary data)			
Inputs and outputs of production phase				
Inputs	**Amount**	**Unit**	**Transport (km)**	**Comments**
Cement	0.5	kg	230	Snabbhårdnande, SH CEM I 52.5 R
Tap water	0.39	kg	-	
Calcium solfoaluminate	0.044	kg	-	
Additives	4.4E-3	kg	-	
Kraft Paper	2.7E-3	kg	-	
Electricity	1.2	kWh		Swedish electricity mix
Output				
Mix of filling materials for under one dome plate				

LCC data for filling materials under one dome plate for conventional solution

Table 16, total production cost of conventional solution, including materials, transportation, energy, labor and equipment costs, is presented. This table shows the total cost of each input based on inventory table in Table 14.

Table 16 production cost of conventional solution (LCC data for conventional solution)

LCC data for conventional solution				
Production cost				
Material/ Transport/ Energy/ Labor	**Unit**	**Cost per unit (SEK)**	**Total cost (SEK)**	**Comments**
Materials/ Transport				
Cement	kg	1	4.9	It includes transportation costs
Energy				
Electricity	kWh	0.7	0.84	
Labor + equipment				
Labor + equipment	Shift	12600	135.5	93 dome plates done in one shift

LCC data for filling materials under one dome plate for conventional solution

Table 17, total production cost of new solution, including materials, transportation, labor and equipment costs, is presented. This table shows the total cost of each input based on inventory table in Table 15.

Table 17 production cost of new solution (LCC data for new solution)

LCC data for conventional solution				
Production cost				
Material/ Transport/ Labor	**Unit**	**Cost per unit (SEK)**	**Total cost (SEK)**	**Comments**
Materials/ Transport				
Cement	kg	1	0.5	It includes transportation costs
QXP (Calcium solfoaluminate)	kg	7.15	0.31	It includes transportation costs
Melament F10	kg	26.2	0.04	It includes transportation costs
ME1000X	kg	62.8	0.1	It includes transportation costs
Expandit 10RR	kg	26.2	0.03	It includes transportation costs

Kraft Paper	kg	14.2	0.04		It includes transportation costs
Labor + equipment					
Labor + equipment	Shift	12600	63		200 dome plates done in one shift

D. LCA results for two solutions

In this section, environmental impacts of two solutions using LCA are presented. In addition, this section presents the environmental comparison between two solutions.

LCA results of conventional solution

Table 18 shows the total environmental impacts caused by conventional solution. Figure 39 shows contribution of each process included in Figure 37 for production of materials required for filling under one dome plate to different environmental impacts.

Table 18 Total environmental impacts caused by conventional solution

Environmental Impacts	Total amount	Units
Acidification potential, average European	7.75E-03	Kg SO_2- Eq
Climate change, GWP 100a	4.46	Kg CO_2- Eq
Fossil cumulative energy demand	19.67	MJ-Eq
Nuclear cumulative energy demand	6.32	MJ-Eq
Stratospheric ozone depletion (ODP)	1.18E-07	kg CFC-11-Eq
Resources, minerals and metals (ADP)	5.32E-06	Kg Sb-Eq
Urban land occupation potential (ULOP)	6.51E-03	m^2a

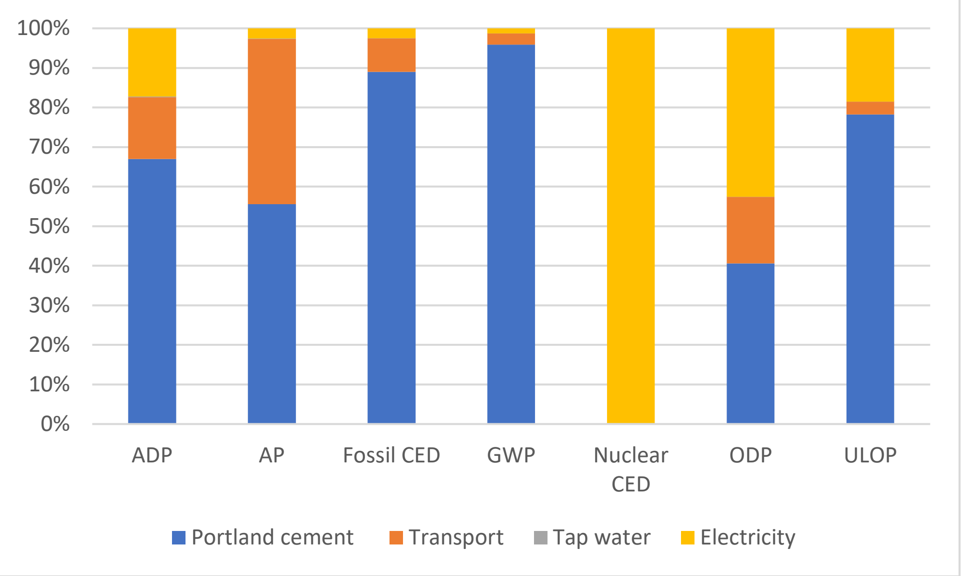


Figure 39 Contribution of different processes to the environmental impacts in conventional solution

As shown in Figure 39, the main contributor to different environmental impacts is Portland cement production process, except for nuclear cumulative demand where electricity is the main contributor. This is mainly because electric power is mainly supplied by nuclear power in Sweden.

LCA results of new solution

Table 19 shows the total environmental impacts caused by new solution. Figure 40 shows contribution of each process to different environmental impacts included in Figure 38 Figure 36for production of materials required for filling under one dome plate to different environmental impacts.

Table 19 Total environmental impacts caused by new solution

Environmental Impacts	**Total amount**	**Units**
Acidification potential, average European	7.51E-4	Kg SO_2- Eq
Climate change, GWP 100a	0.42	Kg CO_2- Eq
Fossil cumulative energy demand	2.12	MJ-Eq
Nuclear cumulative energy demand	1.21	MJ-Eq
Stratospheric ozone depletion (ODP)	1.2 E-8	kg CFC-11-Eq
Resources, minerals and metals (ADP)	6.92 E-7	Kg Sb-Eq
Urban land occupation potential (ULOP)	8.79E-4	m^2a

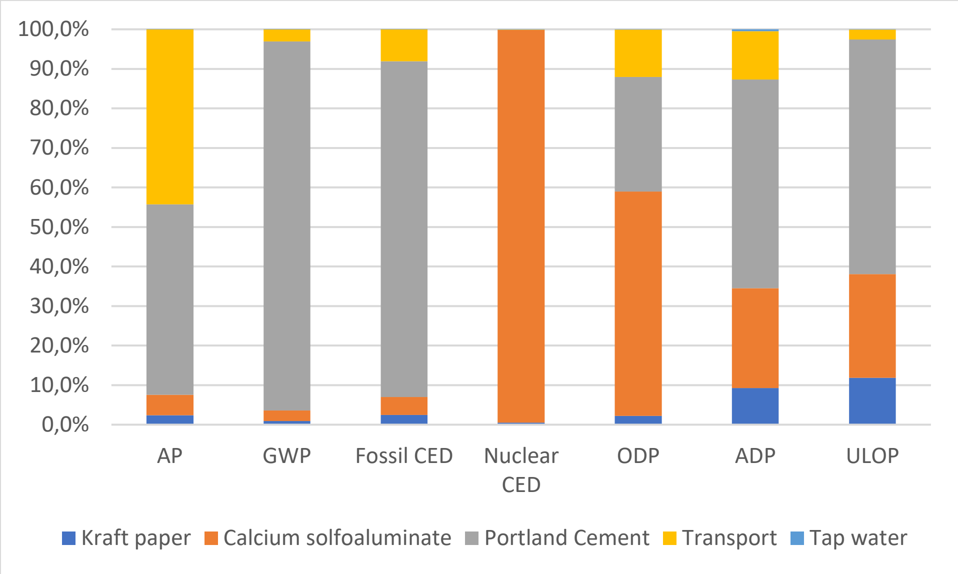


Figure 40 Contribution of different processes to the environmental impacts in new solution

As shown in Figure 40, the main contributor to different environmental impacts is Portland cement production process, except for nuclear cumulative demand where calcium solfoaluminate is the main contributor. This is mainly because in production of calcium solfoaluminate electric power is power is required, and as already mentioned the mainly supplier of electricity in Sweden is nuclear power.

Environmental comparison between conventional and new solution

Figure 41 shows the comparison between environmental impacts caused by conventional solution and new one. The new solution generated significantly less amount of environmental impacts compared to the conventional one as shown in Figure 41**Fel! Hittar inte referenskälla.**. As an example, global warming potential decreased by 91% in new solution compared to the conventional one. This is mainly due to the use of considerably less amount of cement in the grout for new solution compared to that of conventional one. This has been considered as the environmental benefits of the new solution where the cement consumption has been decreased significantly.

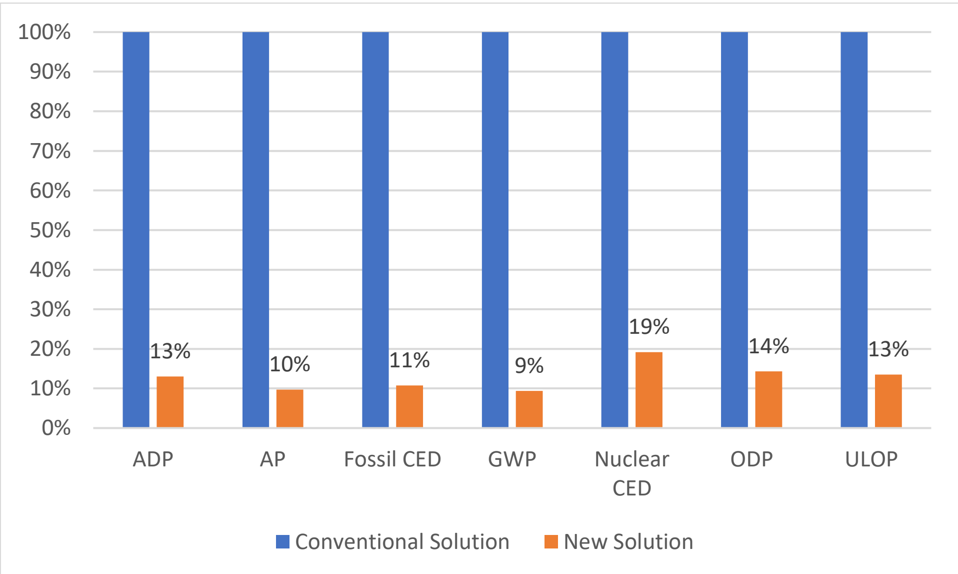


Figure 41 Environmental comparison between conventional solution and new one

E. LCC results

This section shows total cost to produce materials required for filling under one dome plate for both conventional and new solution. In addition, it compares the production cost of both solutions.

LCC results of conventional solution

Table 20 shows the production cost of the conventional solution which happens currently and subsequently total NPV from $\boldsymbol{NPV} = \sum \boldsymbol{CF(T)_i} \times \boldsymbol{C_i}$ Equation 2. As already mentioned, the production cost refers to the summation of costs of different inputs required to produce grout for filling under one dome plate in conventional solution.

Table

Lifecycle	0	Total
Production	141	
Total		141

LCC

Table 21 shows the production cost of the new solution which happens currently and subsequently total NPV from $\boldsymbol{NPV}=\square\boldsymbol{CF(T)_i} \times \boldsymbol{C_i}\square$. As already mentioned, the production cost refers to the summation of costs of different inputs required to produce grout for filling under one dome plate in new solution.

Table 21 LCC results of new solution

Lifecycle Phases / Year	0	Total NPV (SEK)
Production phase	64	
Total NPV (SEK)		64

Economic comparison between conventional and new solutions

Figure 42 shows the economical comparisons between conventional solution and new solution. As shown in Figure 42, new solution is more cost effective compared to the conventional one. The total net present value of the new solution is 55% less than that of the conventional one. Significant reduction in the cost is because the new method takes less time for filling under the dome plate. Therefore, labor cost decreases. In other words, more numbers of dome plates are done in one shift in the new solution with the same number of labors.

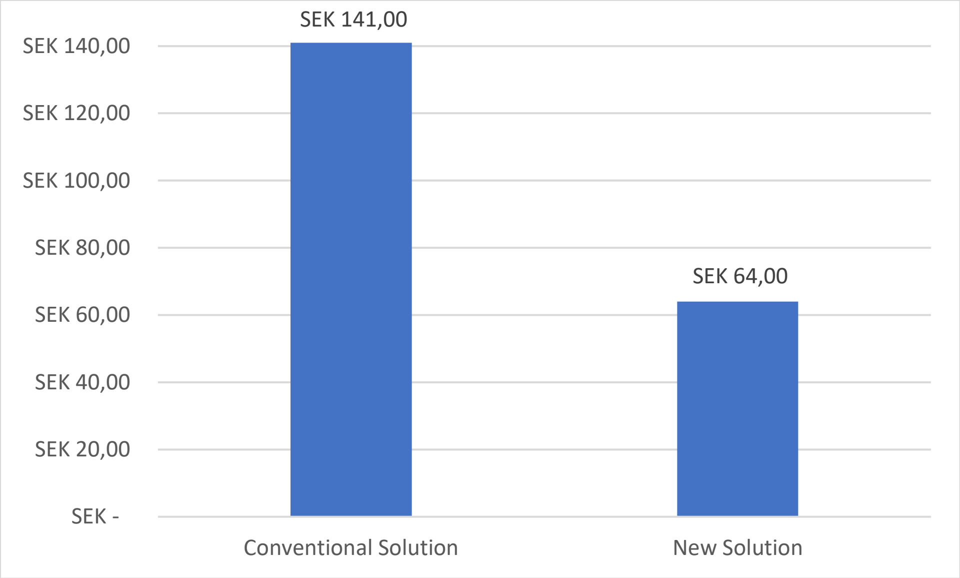


Figure 42 Economic comparison between conventional solution and new solution

F. reference

ISO, 2006a. ISO 14044- Environmental management - Life cycle assessment - Requirements and guidelines. The International Organization for Standardization (ISO).

ISO, 2006b. ISO 14040- Environmental management - Life cycle assessment - Principles and framework. The International Organization for Standardization (ISO).

9. Concluding remarks

This development project has resulted in a new method for sealing grouted bolts, as well as achieve corrosion protection for outer parts of the rock anchoring, intensively used as support in hard rock tunneling. The new solution is following the project goals meaning durability as desired, enhanced installation terms, increased productivity with significantly reduced environmental impact and life cycle costs compared to the traditional method.