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# A Practical Construction Technique to Enhance the Performance of Rock Bolts in Tunnels

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***Abstract*—**In Swedish tunnel construction, a critical issue that has been repeatedly acknowledged is corrosion and, consequently, failure of the rock bolts in rock support systems. The defective installation of rock bolts results in the formation of cavities in the cement mortar that is regularly used to fill the area under the dome plates. These voids allow for water-ingress to the rock bolt assembly, which results in corrosion of rock bolt components and eventually failure. In addition, the current installation technique consists of several manual steps with intense labor works that are usually done in uncomfortable and exhausting conditions, e.g., under the roof of the tunnels. Such intense tasks also lead to a considerable waste of materials and execution errors. Moreover, adequate quality control of the execution is hardly possible with the current technique. To overcome these issues, a non-shrinking/expansive cement-based mortar filled in the paper packaging has been developed in this study which properly fills the area under the dome plates without or with the least remaining cavities, ultimately that diminishes the potential of corrosion. This article summarizes the development process and the experimental evaluation of this technique for the installation of rock bolts. In the development process, the cementitious mortar was first developed using specific cement and shrinkage reducing/expansive additives. The mechanical and flow properties of the mortar were then evaluated using compressive strength, density, and slump flow measurement methods. In addition, isothermal calorimetry and shrinkage/expansion measurements were used to elucidate the hydration and durability attributes of the mortar. After obtaining the desired properties in both fresh and hardened conditions, the developed dry mortar was filled in specific permeable paper packaging and then submerged in water bath for specific intervals before the installation. The tests were enhanced progressively by optimizing different parameters such as shape and size of the packaging, characteristics of the paper used, immersion time in water and even some minor characteristics of the mortar. Finally, the developed prototype was tested in a lab-scale rock bolt assembly with various angles to analyze the efficiency of the method in real life scenario. The results showed that the new technique improves the performance of the rock bolts by reducing the material wastage, improving environmental performance, facilitating and accelerating the labor works, and finally enhancing the durability of the whole system. Accordingly, this approach provides an efficient alternative for the traditional way of tunnel bolt installation with considerable advantages for the Swedish tunneling industry.

***Keywords*—**Corrosion, durability, mortar, rock bolt.

## I. INTRODUCTION

THE large number of rock bolts are being installed worldwide every year and its utilization continue to increase due to rapid growth of infrastructure. Fully grouted rock bolt is a reinforcement technique frequently used in civil and mining engineering worldwide to improve safety along roadways and large openings [1]. This support system has many advantages including efficiency, flexibility, ease of installation and low cost [2]. The rock bolts are used both in the underground excavations including tunnels, caverns, and subsurface repositories to increase stability of the slope [3]. To strengthen the thin rock fragments on the roof and the walls of the excavations, the bar in rock bolt system is inserted to the rock surface (borehole) and anchored to it by mean of a dome-shaped bearing plate fitted with a half sphere and a hex nut (see Fig.1).

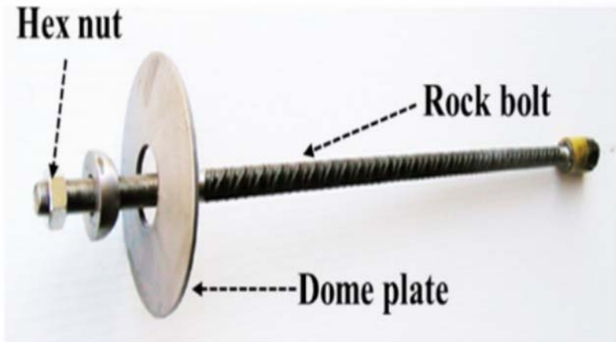


Fig. 1 Components of a mechanically anchored rock bolt

It has been suggested that the dome plate is one of the fundamental and integral parts of the rock support system. For efficient operation of rock bolt system, the dome plate requires to have a "soft" footprint with no sharp edges or corners (i.e., round shape), with an appropriate mechanical strength to match with the other components of the support system [4]. The failure of dome plate is greatly attributed to the installation practices and corrosion especially in the circumferential area where groundwater flows or drips over the exposed end of the reinforcement [5]. Case studies showed that rock bolt systems fail mostly due to pitting corrosion, but sometime, the failure may cause by combination of bending and stress corrosion cracking [1], [6]. Due to harsh underground conditions, the robust and specific corrosion mitigation techniques are required to protect the entire rock bolt system [7].

To fulfil the high durability demands, the cementitious grouts are filled in the boreholes as well as are used for anchoring the bolt to the body of the rock mass. The cementitious grout is provided corrosion protection to the rock bolt system due to

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high alkalinity of the cementitious material [8]. Furthermore, it has been suggested that the outer parts of the rock bolts (i.e., the end parts outside of the borehole) is required to be covered with cementitious mortar to improve corrosion protection to the rock bolt system [1]. This is achieved by sufficiently filling the space between the supported rock and the dome plate with cement mortar during the installation and then by covering the outside parts with shotcrete after completing the installation. To assure all parts are sufficiently protected, it is required to fill all the cavities inside the boreholes and dome plate without any voids. The voids could increase local corrosion and eventually decrease the life of the rock bolt system. Similarly, the space under dome plate is necessary to fill precisely for avoiding any voids under the dome plate [2].

Across the world, the defective installation of rock bolt system is frequently found during quality control inspection of tunnels and underground excavations. The weak points are mainly detected in the fillings of the boreholes with cementitious grouts in the areas close to the rock surface, as well as in the cement mortar under the dome plate [9]. The faulty installations are caused by several factors such as: 1) the cement mortar does not have the right workability and sufficient volume that can cover entire dome plate, 2) the cement mortar does not fill the entire dome plate due to improper installation of the hex nut. In addition, the installation of rock bolt system is consisted of the several frequently repeated steps with heavy labor work. The severe and uncomfortable work conditions in underground workplace are led easily to execution error and bad workmanship. These problems have been acknowledged for defective installation of the rock support systems [9]. To address the issue, methods such as hollow rock bolts and the bottom-up grouting technique (e.g., in Sinorock hollow self-drilling rock bolts) are commonly used. However, these methods are expensive and require low viscosity and high pumpability grout. This highly pumpable grout penetrates through the crossing rock fractures and creates voids around the rock bolts [9].

Thus, this study is aimed to develop a robust and efficient technique which can increase durability and efficiency of the rock bolt installation process. In this study, the paper packaging is developed and filled with a non-shrinking cementitious mortar. The paper packaging is required to activate by submersion in the water. During installation, the packaging distributes the mortar under the dome plate which properly fills the area under the dome plate without any cavities, ultimately that diminishes the potential of water ingress and possibility of corrosion. This work summarizes the product development process, lab prototype evaluation and field testing of this innovative technique for the installation of rock bolts.

## II. Materials and Experimental Methods

### A. Cement and Additives

CEM I 52.5 R Portland cement (SH rapid hardening cement, Cementa, Sweden) and CEM II/A-LL 42.5 R Portland cement (Bygg cement, Cementa, Sweden) complying with EN 197-1 were used [10]. The additives were chosen in the powder form due to application requirement. A commercially available superplasticizer (SP) based on sulfonated melamine-formaldehyde condensate chemistry from BASF (Trostberg, Germany) was selected to improve dispersion of the water in the mortar. Similarly, cellulose ether-based water retention (WR) agent from Nouryon (Amsterdam, Netherland) was selected to increase water retaining capacity of the mortar. In addition, Calcium sulfoaluminate (CSA) based additive (Caltra, Netherland) was chosen to reduce shrinkage in the mortar. Furthermore, to improve expansion during plastic stage, aluminum powder-based additive (Ex) was selected from GRIMM Metallpulver GmbH (Roth, Germany). All chemical additives are commercial products available in the European market.

### B. Paper for Packaging

The goal was to find a suitable paper quality and develop a packaging that can be filled with the cement mortar. Three commercially available paper grades were selected from Billerud Korsnäs (Stockholm, Sweden) and one paper grade was produced on FEX, the pilot paper machine at RISE (Stockholm, Sweden). The details of the properties are included in Table I.

TABLE I
PROPERTIES OF PAPER REQUIRE FOR PACKAGING THE MORTAR

| Type | Paper grade | Supplier (Sweden) | Tensile strength (KN/m) | Tear strength (mN) |
|---|---|---|---|---|
| A | Softwood, FEX-paper | RISE | na | na |
| B | Barrier White, D 95 g/m² | Billerud Korsnäs | na | na |
| C | Quick fill white, D 80 g/m² | Billerud Korsnäs | 5.6 | 1200 |
| D | D Prime white unisized 80 g/m² | Billerud Korsnäs | 8.4 | 960 |

### C. Mix Design and Sample Preparation

To study effect of additives on the properties of mortar, the samples were prepared by blending Portland cement, additives in the plastic bag (see Table II). The plastic bags were shaken and vibrated for 2 minutes to assure uniform blend of all powder ingredients. Two types of mortar samples were prepared using either SH or Bygg cement (refer Table II) and these samples were used for the entire testing. Due to the application requirements, the mortar design does not contain sand or any larger aggregates. The dry mortar was mixed with deionized water in accordance with SS-EN 196-3: 2005 [11]. In the mortar composition, binder was considered as combination of Portland cement and CSA additive. For all the tests, mortar was mixed at fixed water to binder ratio (w/b) = 0.38. The composition of mortar is given in Table II.

### D. Experimental Methods

#### 1. Mechanical Testing of Cement Paste

The experiments were performed on the mortar samples specified in Table II. The slump flow in accordance with testing standard SS-EN 1015-3 was immediately measured after mixing to evaluate the workability of the cement paste [12]. Similarly, mud balance technique was used to measure the density of the cement paste in accordance with testing standard SS-EN 445 [13]. The setting time was evaluated using Vicat needle technique in accordance with testing standard SS-EN 196-3 [11]. For compressive strength measurement, fresh mixes were casted in 40 × 40 × 160 $mm^3$ molds and cured under water at 23°C with accordance with testing standard SS-EN 196-1 and the measurement was conducted at 1 day and 7 days [14].

TABLE II
MIX PROPORTIONS OF CEMENT MORTAR

| | SH (%) | Bygg (%) | CSA (%) | SP | WR | Ex | w/b |
|---|---|---|---|---|---|---|---|
| | | | **Mechanical and calorimetry testing** | | | | |
| SH1 | 94 | | 6 | y* | y | | 0.38 |
| SH2 | 92 | | 8 | y | y | | 0.38 |
| B1 | | 94 | 6 | y | y | | 0.38 |
| B2 | | 92 | 8 | y | y | | 0.38 |
| | | | **Shrinkage testing** | | | | |
| SH-SR-1 | 100 | | | | | | 0.38 |
| SH-SR-2 | 92 | | 8 | | | | 0.38 |
| SH-SR-3 | 92 | | 8 | y | y | y | 0.38 |

*Yes, the additive was included.

### 2. Isothermal Calorimetry Testing

The heat flow evolved due to the cement hydration was determined under isothermal conditions at 20 ± 1°C by an eight-channel conduction calorimeter (Tam Air TA Instruments, New Castle, USA) in accordance with SS-EN 196-11 [15]. Prior to mixing, all materials were maintained at 20 ± 1°C for 24 h. The mortar samples were tested based on the composition mentioned in the Table II. The mixing was performed manually in a glass beaker, with the aid of a glass rod at fixed w/b = 0.38. Each ampoule was filled with 7 g of paste and instantaneously placed into the isothermal calorimeter channel to measure the heat of hydration at 20 ± 1°C. The entire process, which includes mixing, placement of the paste into the ampoule and positioning of the ampoule in the calorimeter, took less than 5 min. All data were recorded for a total of 24 h.

### 3. Shrinkage Measurement

Dimensional variations in the first 24 hr. of hydration were measured using the Walter + Bai shrinkage measuring test device (Löhningen, Switzerland) type SWG-H-400 on a 70 × 70 × 70 $mm^3$ (length 400 mm) triangular prism mortar samples. The experiments were performed in a climate-controlled room at 25°C and 65% relative humidity. For shrinkage measurement, only SH cement mortar samples were selected (see Table II).

### 4. Water Absorption Measurements of Cement Mortar

In this study, the final product was consisted of paper packaging packed with cement mortar. This packaging was submerged in the water to activate hydration of the mortar. Thus, the mortar is not conventionally mixed but instead it is hydrated by water absorb through the paper packaging. Thus, it is crucial to understand effect of additives and characteristics of paper on the absorptivity of water in the cement mortar.

For absorption experiments, the cement mortar (composition SH-SR-3, see Table II) was filled in the 7 $cm^3$ paper boxes (Fig. 2) and submerged in the water for the specific time interval. The paper boxes were manually constructed using four types of papers (see Table I). The weight of sample box was measured before submersion in the water (dry condition) and then after 10 min and 30 min respectively (wet condition). The water to solid (w/s) ratio was calculated by following equation:

$$\frac{\text{Water}}{\text{Soild}} = \frac{\text{Wt.at time interval}_{\text{Wet}} - \text{Initial wt.}_{\text{Dry}}}{\text{Initial wt.}_{\text{Dry}}} \quad (1)$$

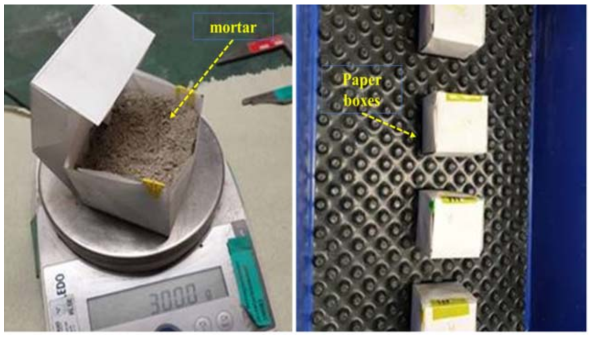


Fig. 2 Experiment preparation for water absorption test

### 5. Lab Prototype Testing

The final protype of paper packaging was built as an octagonal box, with dismissions: 100 mm distance between parallel walls and height of 42 mm and with 10 mm height lid (Fig. 3). The multiple packages were produced and filled with dry mortar (composition same as SH-SR-3, see Table II).

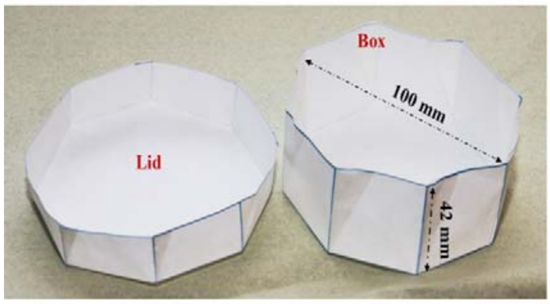


Fig. 3 Dimensions of the paper packaging

For prototype testing, the laboratory testing rig was constructed to simulate rock bolt installation procedure in real conditions. The rig was consisted of plywood plates screwed to the wooden stand for rock surface mock-up and with four holes for borehole prototype (Fig. 4a). The test rig was equipped with the pivot rods for changing inclination angle of rock-bolts. The tests were performed for 0°, 45° and 90° inclination of pivot rod simulating inclined rock surfaces (Fig. 4b). The borehole was simulated using Plexiglas tubes with inner dimeter of 45 mm (Fig. 4c). Furthermore, rock bolts were threaded and bolted with the nuts to avoid falling from opposite end of the dome plate (Fig. 4d). Before the paper packaging testing, the borehole was filled with the mortar to simulate partially filled borehole. The color pigment was added to the borehole mortar to recognize mortar from paper package. During the testing, prefilled mortar packaging was submerged under the water for specific time intervals (12 min, 20 min and 30 min). Then after, the packaging was pushed on the rock bolt and secured using dome plate and hex nut.

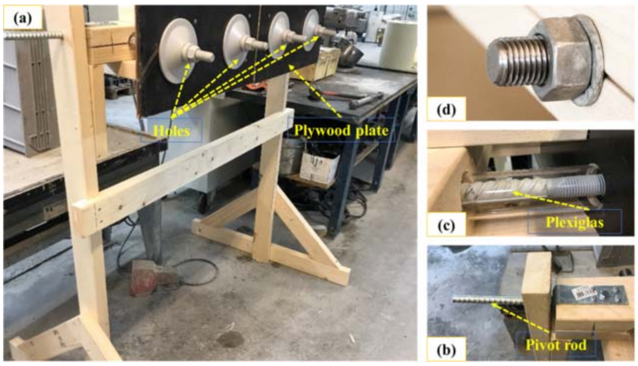


Fig. 4 Testing rig for lab prototype tests: a) The testing rig simulating four boreholes and rock surface b) pivot point for changing inclination angle of the boreholes c) Plexiglas tube for simulated borehole, and d) the rock-bolt secured with the nut

### 6. *Field Testing*

The field testing in the tunnel was performed to analyze performance of the product in the practical conditions. For field testing, single packaging was mentioned as puck. For testing, the multiple pucks were arranged vertically in the self-draining box. This self-draining box (refer Fig. 5c) was equipped with holes in walls and bottom allowing water movement after submersion in the water. Before tests, the required formalities were completed at tunneling test site provided by Trafikverket (Stockholm, Sweden). Tests were executed in main tunnel at the site where forty rebar bolts were installed in each test area. The bolts were mounted without washer, half sphere and hex nut and roughly cleaned (Fig. 5b), but not protected except for a few that was partly covered with tape. All bolts were installed on the vertical walls or on the roof, and they were mounted either on the bare rock or sprayed rock (Fig. 5a). Before installation, the box was submerged in the water trey for 10-12 minutes (Fig. 5c). Then after, the mounting of the puck was started within 11-15 minutes due to maneuvering the platform in the position for installing washers on the bolts.

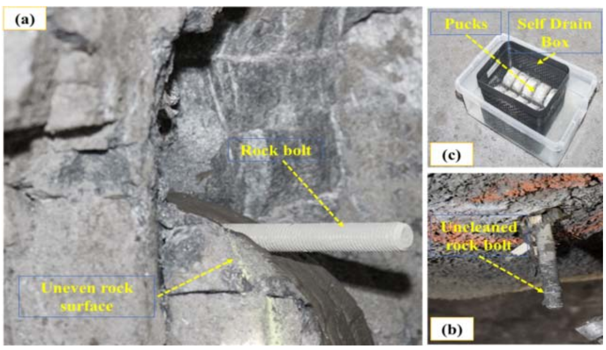


Fig. 5 Preparation of the field test, a) rock bolt on the uneven rock surface b) uncleaned rock bolt from tunnel ceiling c) submersion of pucks in the self-draining box

## III. Results and Discussion

### A. *Analysis of Mortar Properties*

The main objective of this study is to develop a paper packaging packed with non-shrinking cement-based mortar that can withstand load against deformation and punching of the dome plate by rock bolt at high pulling loads. In addition, the mortar is required suitable set time which is enough for finishing installation but not prolong to provide the possibility of erosion in the case of water ingress into the borehole during the installation process. Thus, selection of the cementitious binder is one of the crucial steps in the development process since the major properties of the product are dependent on the binder composition and performance characteristics.

TABLE III
Mechanical and Shrinkage Results of the Mortar

| | SH1 | SH2 | B1 | B2 | SH-SR-1 | SH-SR-2 | SH-SR-3 |
|---|---|---|---|---|---|---|---|
| **w/b** | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 |
| **Density (g/cc)** | na | 2 | 1.9 | 1.8 | | | |
| **Flow (cm)** | 16.7 | 17.1 | 19.1 | 18.6 | | | |
| **Initial Set time (min)** | 160 | 160 | 240 | 240 | | | |
| **Final Set time (min)** | 220 | 190 | 290 | 310 | | | |
| **Compressive strength 1 day (MPa)** | 41 | 45 | 38 | 37 | | | |
| **Compressive strength 7 day (MPa)** | 50 | 54 | 42 | 46 | | | |
| **Change in length (%)** | | | | | -0.36 | -0.05 | 0.1 |

Table III shows the results of the cement mortar with the two types of cements: SH cement and Bygg cement. It was observed that SH cement mortar reduces initial and final set time about 30-40% compared to Bygg cement mortar. This was attributed to fineness of SH cement, the hydration heat generated from fine SH cement (Blaine fineness = 550 $m^2/kg$) was larger and faster compared to Bygg cements ((Blaine fineness = 490 $m^2/kg$)) which results in reduction in the set time [16].

In isothermal calorimetry the rate of heat liberation (heat flow) is recorded as function of time which provides information on the rate of cement hydration in the presence of additives [17]. Fig. 6 represents the heat flow curves of cement mortar containing SH or Bygg cement binder. The heat flow for each sample was normalized by using weight of cement. It was indicated that SH cement binder accelerates the cement hydration, and it has higher heat flow compared to the Bygg cement mortar (Fig. 6). The high heat flow of SH cement mortar is either on account of the high fineness or clinker composition favorable for cement hydration reactions [18].

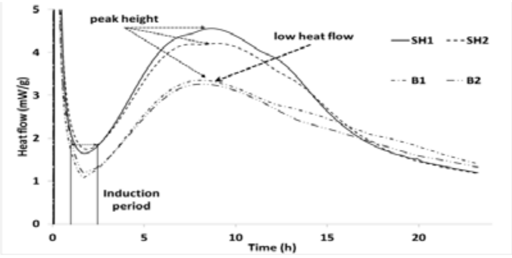


Fig. 6 Experimentally measured isothermal heat flow for mortar with SH and Bygg cement binder

Taken together, high heat of hydration and low set time were resulted in high early compressive strength of mortar containing SH cement. At 1- and 7-day, SH cement mortar was increased strength of mortar about 18 % compared to Bygg cement. It was observed that addition of CSA additive reduces set time and increases compressive strength of the SH cement mortar. The blending of Portland cements with CSA additive influences not only the hydrate assemblage but also the enhances kinetics of the hydration reaction that results in the fast setting and high early strength for CSA embedded Portland cement mortar [19]. Furthermore, it was observed that the binder composition has insignificant effect on the density of the mortar, and it remained in the range of 1.8-2.0 g/cc. The SH cement mortar was displayed lower slump flow compared to Bygg cement mortar. The reduction in the flow was attributed to high fineness and aluminate content of the SH cement clinker. The SH cement contains high percentage of tricalcium aluminate ($C_3A$), after hydration, it produces more ettringite phases. It is commonly stated that the superplasticizers (SP) are adsorbed on the ettringite surface [18]. Thus, less SP remains available for dispersion of un-hydrated cement particles. As a result, fresh slump flow is negatively affected [20].

The plastic shrinkage was measured as described and percent change in the length was evaluated by reference to original length of the sample (400 mm). In Table III, negative values were indicated shrinkage (deformation) whereas positive value were indicated no shrinkage (expansion). It was observed that neat SH cement sample exhibits high shrinkage compared to mortar samples containing CSA based additive (Fig. 7). After addition of CSA additive (SH-SRA-2), mortar was displayed expansive behavior at early age and this phenomenon was assisted in reducing overall shrinkage by 15% compared to neat SH cement (SH-SRA-1). This early age expansion was induced due to hydration of aluminate phases in the CSA additive. The hydration is caused supersaturation of ettringite phases and gave rise to the crystallization stress, responsible for the expansion [21]. Finally, dimensionally stable mortar was obtained by combination of CSA and expansive additive (SH-SRA-3) in which, no shrinkage was noted after 24 hours. The added expansion in the mortar was achieved using an expansive agent such as aluminum powder. After reaction with water, it produces expansive gas results in the expansion of mortar in plastic stage [17]. Overall, the types of reactions that generate the expansive force and the magnitude of expansion are dependent on concentration of CSA and expansive additive in the mortar.

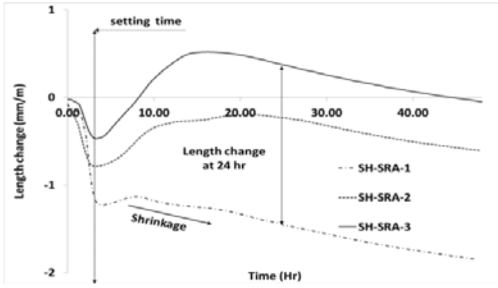


Fig. 7 Experimentally measured shrinkage in the mortar using Walter Bai shrinkage device

### *B. Effect of Paper Quality on the Water Absorption*

The sturdiness of paper boxes in water were analyzed using visual inspection method. Fig. 8 showed that paper C (Quick fill white) and paper D (Prime white unisized 80) absorb significant amount of water and they did not disintegrate after 10 min of testing. This was attributed to high tear strength and tensile strength of the paper C and paper D (see Table I). Due to impermeable properties, paper B (Barrier white D95) could not absorb water but disintegrated after 10 min of testing (Fig. 8). In contrast, highly permeable paper A (Soft wood Rise paper) was absorbed excessive water and disintegrated after 10 min (Fig. 8).

Based on the initial qualitative screening, paper C and paper D were selected for further testing. The absorption capacity of paper C and paper D were analyzed using absorption measurement technique (refer to (1)). It was observed that both paper boxes absorb similar amount of water in the mortar at w/s = 0.73. Although, significant absorption was completed within in the first 10 minutes, the absorption was continued till 30 minutes at saturation limit (w/s = 0.76). At 30 min, the paper C box was remained undamaged under water, whereas paper D box was disintegrated (Fig. 9). The sturdiness of paper C was anticipated to the higher tearing strength: 1200 mN compared to paper D: 960 mN (see Table I). Additionally, it was observed that the paper C absorbs water in the direction perpendicular to vertical plane of box, whereas paper D absorbs water in the multiple directions: perpendicular and parallel to the vertical plane of the box (Fig. 9). This distinct absorption behavior is due to structural properties of paper which are influenced by fiber characteristics including fiber length, type, lumen width, and wall thickness [22].

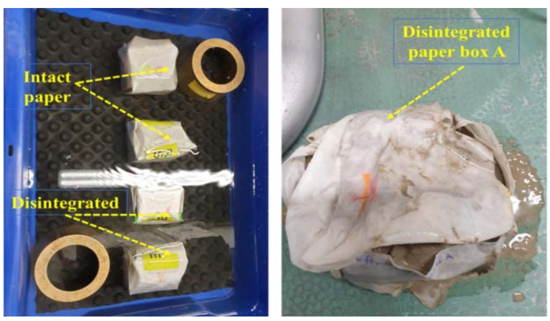


Fig. 8 The condition of the paper packaging after 10 min submersion in water

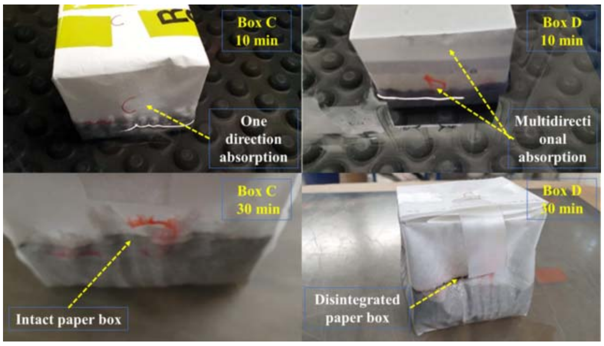


Fig. 9 Effect of submersion time on the paper packaging made with paper type C and paper type D

*C. Lab Prototype Testing*

The lab prototype testing was conducted on the testing rig using the paper packaging filled with the mortar. In this testing, various practical aspects were considered such as mortar spread under the dome plate, inclination of rock bolt, uneven rock surface and optimum submersion time for the packaging in the water.

It was observed that lid of the packaging was the weakest part of the package. To avoid detachment from packaging, lid was built separately and inserted firmly around the box (Fig. 10a), that eliminates need for adhesive for attaching lid to the box. Furthermore, the paper packaging was perforated at weak points to achieve opening in the controlled direction (Fig. 10b). It was observed that entrap air releases from mortar when packaging submerges in the water that air pressure pushes the lid and disintegrates the packaging. Thus, mortar packaging was submerged vertically in the water bath to provide escape route for air though packaging joint (Fig. 10c).

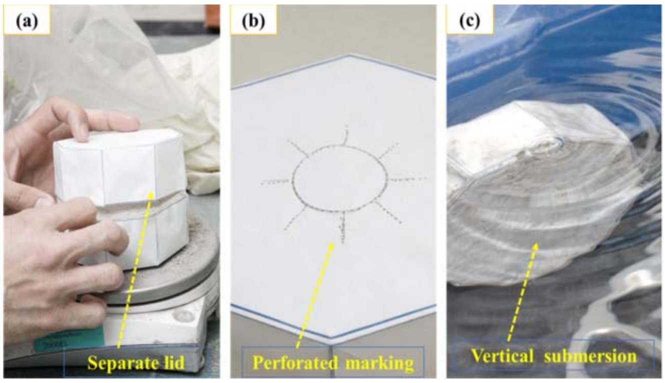


Fig. 10 Improvement of paper packaging: a) use of separate lid, b) generate directional bursting zone by piercing the packaging, c) reduce entrapped air pressure by vertical submersion of packaging in water

It was crucial to find optimum submersion time for packaging in the water. It was found that 12 min was optimum submerging time to produce hardened mortar without cracks (Fig. 11a). Whereas longer submerging times (20 min to 30 min) were induced shrinkage cracks in the mortar under the dome plate (Fig. 11b, Fig. 11c). During tightening of dome plate on the mortar packaging, excessive water was accumulated on the surface of the mortar which could lead to plastic shrinkage due to evaporation of the accumulated water [18].

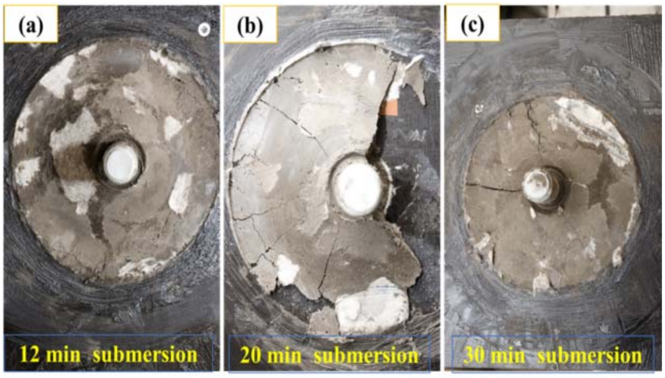


Fig. 11 Effect of submersion time of the paper packaging on the performance of the mortar under the dome plate at: a) 12 minutes, b) 20 minutes, and c) 30 minutes

During installation of rock bolts, the inclination of rock-bolt usually does not have effect on the penetration of mortar into borehole however the inclination could reduce workability and increase wastage during application of mortar under the dome plate [9]. The paper packaging was tested at 90° (vertical plane), 45° (inclined plane) and 0° (horizontal plane) (Fig. 12a, Fig. 12b, Fig. 12c). It was visually inspected that packaging installation at 90° (vertical plane) generates more wastage of mortar compared to other cases (Fig. 12a).

To simulate the uneven surface, the wood strip was used to elevate one corner of the dome-plate at 12 mm (Fig. 13). Despite uneven surface, the mortar was distributed evenly under the dome plate, however few cracks were observed in the mortar. These cracks may be induced by additional stress due to uneven surfaces, suggesting additional mortar require to mitigate stress cause by uneven surfaces. The lab prototype data demonstrated that the newly developed mortar with packaging is successfully applied under the dome plate at uneven and inclined surfaces and is stable during the whole testing period.

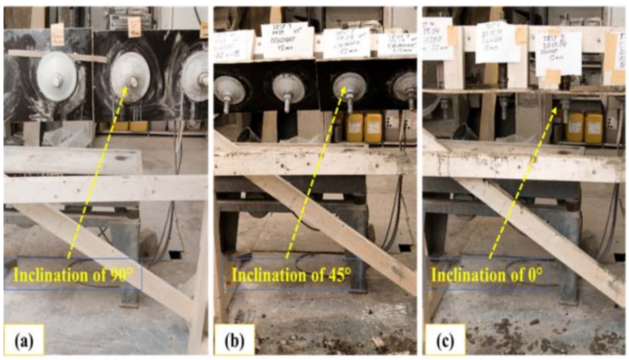


Fig. 12 Effect of inclination of rock-bolt on the efficiency of paper packaging technique, a) 90°, b) 45° and c) 0°


Fig. 13 Effect of uneven surface on the distribution of mortar under the dome-plate

### *D. Field Testing*

The functionality of the product was also tested in field testing at the working tunnel site. Total eighty bolts were anchored by cement grout and then dome plates were mounted using the packaging filled with new cement mortar (also known as puck). For each run, five boxes with ten pucks were used for installing 38-40 washers on the respective bolts and the installation was completed with rate of less than or equal to 1 min for each bolt. The additional time was required in the cleaning of the bolt and moving of the installation platform. For even rock surface, it was observed that the installation of puck was straightforward process (Fig. 14a). However, for unsprayed and uneven rock surface, the installation was required more time and resulted in the poor installation quality. Thus, dome plate was installed with two pucks to improve quality of the installation (Fig. 14b, Fig. 14c). Furthermore, many bolts were located at the tunnel ceiling (Fig. 15a, Fig. 15b), where the upright installation process was increased the distribution of mortar due to support of dome plate at bottom of the puck, whereas installation process was parallel to vertical wall; thus, wastage was increased due to absence of bottom dome plate.

Overall, in this innovative technique, installation quality was improved, and wastage was reduced since mortar was uniformly distributed evenly under the dome plate without any voids or air pockets. Additionally, work conditions and productivity were enhanced due to clean application technique and comfortable handling of pucks.

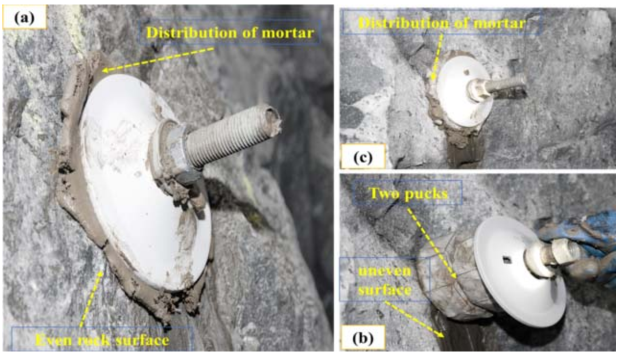


Fig. 14 Application of pucks on the tunnel wall, a) at even rock surface, b) two pucks at uneven rock surface, c) distribution of mortar at uneven rock surface

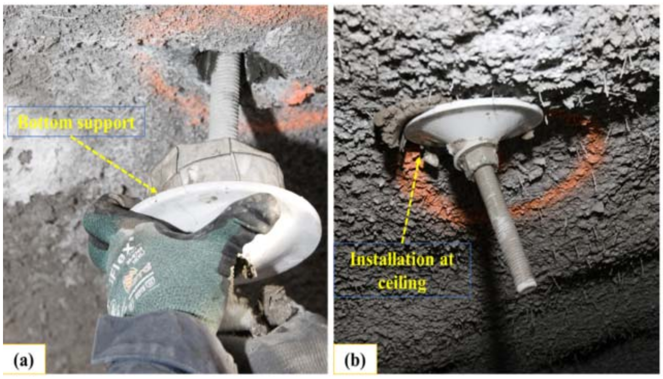


Fig. 15 Application of pucks on the tunnel ceiling a) during installation process, b) after installation of puck

## IV. Conclusion

The practical construction technique is developed for application of mortar under the dome plate. The mechanical performance and dimensional stability of mortar is thoroughly investigated through laboratory experiments. The newly developed mortar containing paper packaging are successfully tested in lab prototype and field experiments.

For mortar development, SH cement binder is showed superior compressive strength, short set time and dimensional stability, which surpasses the selection criteria of binder required for mortar application under the dome plate. The selected additives are provided functionality including water dispersion, retention, and dimensional stability to the mortar.

For development of packaging, both paper C (Quick fill white D80) and paper D (D Prime white unisized 80) are appropriate due to their water absorption capacity, high tearing, and tensile strength. However, paper C (Quick fill white D80) is chosen due to unidirectional absorption characteristics and long-lasting sturdiness.

The lab prototype testing is demonstrated that packaging requires 12-minutes of submersion time and submersion in the vertical position to obtain optimum performance of the packaging. The steep inclination and uneven surfaces do not affect distribution of mortar under the dome plate, but they might introduce stress cracking in the mortar. The field work at tunnel is showed that handling was eased, material waste is decreased, and performance is improved compared to traditional method.

The results presented are improved the performance of the rock bolts by accelerating durability and reducing waste of material and finally providing user friendly method to accelerate the labor works. It delivers an extensive methodology for R&D of advanced technique in the installation of rock bolts. Accordingly, this innovative approach provides an efficient alternative for the traditional way of tunnel bolt installation with considerable advantages for Swedish and international tunneling industry.

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