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Strength and filtration stability of cement grouts at room and true tunnelling temperatures

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ABSTRACT

The overall objective of this work, carried out under the research project "True Improvement in Grouting High pressure Technology for tunnelling (TIGHT)" is to understand the behavior of cement grouts under true tunnelling conditions. This paper describes a systematic laboratory study to characterize uniaxial compressive strength (UCS) and filtration stability of grouts made up of three types of cement commonly used for tunnel grouting in the Nordic countries. Since in-situ tunnel conditions are different from those of the laboratory in terms of temperature, we made various cement grouts at different temperatures and tested in the laboratory. The water cement ratios of 0.6, 0.8, 1.0 and 1.2 were used for all three cements and grouts were made and cured at two temperatures; 8 °C and 20 °C. Strength of a total of 96 cylindrical specimens of 4 and 7 days age and permeability of four specimens of 7 days age were measured. Filtration tests were done for 36 cement grouts. Results of the laboratory tests show that strength of samples cured at 8 °C is lower than those cured at 20 °C. Strength of grout specimens decreases dramatically with increasing w/c ratio. Filtration of cement grouts at 8 °C is not that different from those at 20 °C and filtration stability increases with increasing water-cement ratio. Permeability of cylindrical specimens of different types of cement varies several orders of magnitude; from nano- to milli-Darcy.

1. Introduction

Grouting is a common method for sealing underground excavations and reduce or stop water inflow. There are different types of grouting material; cement based grouts and chemical grouts. Cement based grouts are the commonly used material for sealing tunnels and underground excavations. Due to strict requirements on maximum allowable water inflow, very fine-grained cements are often used since very small fracture apertures must be treated (Tolppanen and Syrjänen, 2003). Physical, mechanical and hydraulic properties of cement grouts can be affected by the grain size, water-cement ratio (w/c), cement condition and the mixing equipment (Eriksson et al., 2004). Further, curing temperature has considerable impact on the mechanical properties of cement grout specimens (Elkhadiri et al., 2009). Chemical grouts have so small particulates that can be considered as suspended solid grouts (such as sodium silicates) or free of suspended solids, called true solutions (such as acrylics and polyurethane). They have very low viscosity, high degree of penetrability, are often used for short term control of water inflow and have a lifespan of up to few years (Bobcock, 2016; ISRM, 1996). There are also other chemical grouts that may have longer lifespan of about 75–100 years (ISRM, 1996). Cement grouts are mainly used for treating soils and rocks with large pores or fissures while chemical grouts are used for cases where pore or fractures are very small, in the range of micrometers (Byle and Borden, 1995; Woodward, 2005; Bobcock, 2016). Chemical grouts are not the subject of this study and interested readers are referred to the widely available literature on this subject; e.g. ISRM (1996), Šňupárek and Souček (2000), NFF (2002) and Harrison (2013).

When deciding on the grouting procedure the basic questions to consider are: which grout material, grouting pressure, borehole spacing and grout volume is needed to reach the goal desired in the most economic manner? (ISRM, 1996). Selection of grout material plays a cen-

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tral role for the success of the grouting project. Some typical values of cement grouts, appropriate for rock grouting operations, are listed in Table 1. Further details on the properties of cement grouts, grouting parameters and various grouting methods can be found in NFF (2011), Tolppanen and Syrjänen (2003), Dalmalm (2004), ISRM (1996) and Byle and Borden (1995).

Plenty of data on strength and flow properties of cement grouts are available in the literature (Dalmalm, 2004; Eklund, 2005; Ortiz, 2015). These data, however, are usually for samples prepared and tested in room conditions. There are very few studies that report simulation of in-situ pressure or temperature in laboratory testing. True tunnelling conditions, particularly in the Nordic countries, have different temperatures than that of standard room condition. This paper focuses on the characterization of cement grouts prepared and tested at either 8 °C or 20 °C. The temperature of 8 °C is representative for in-situ tunnelling condition in the Nordic countries and 20 °C is close to room temperature, at which large datasets are available in the literature.

Several types of tests including determination of specific surface area, bleeding, setting time, rheology, filtration, uniaxial compressive strength (UCS) and permeability were carried out for the cement grouts. The results of UCS test and permeability on cured grout samples as well as filtration stability test on grout mixtures are presented in this paper.

2. Method

This paper presents the results of laboratory tests on grout samples made up of three types of cement with D_{95} ranging from 18 to 25 μm. The cements are anonymized and are given names A, B and C. Grain size distribution and physical characteristics of the three cements are presented in Fig. 1 and Table 2.

Different water-cement (w/c) ratios were used to explore its impact on the mechanical and flow properties of mixtures. The tests were carried out on both cured grout samples (UCS test and permeability) and grout suspension (Filtration test). The test data are summarized in Table 3 and experimental details are provided in the following sections.

2.1. Uniaxial compressive strength (UCS) test

2.1.1. Preparation of grout samples for UCS test

For mixing cement and water, a blender with 2000 rounds per minute (Fig. 2a) was used and the following procedure was followed. First, a definite amount of water with a certain temperature (see Tables 4 and 5) was poured into the blender while it was on standby mode. Second, the blender was set at 2000 rpm and turned on. The weighed amount of cement was poured into the blender within 30 s while mixing. The mixing continued for two more minutes after having all cement in the blender.

Two series of cement mixes with w/c ratios of 0.6, 0.8, 1.0 and 1.2 were prepared. One batch was prepared at the temperature of about 8 °C and stored in a temperature-controlled room at 8 °C to cure. Another one was prepared and stored at room temperature of about 20 °C to cure. Both series of grout specimens were stored at the respective ambient temperature (8 °C or 20 °C) until the specified age (4 or 7 days) at the same relative humidity and without any treatment.

Detailed data for preparation of the two series of cement mixes are presented in Tables 4 and 5. Table 4 shows the details for a cement mix prepared at about 8 °C. For this, we used cement with a temperature of about 8 °C and water with a temperature of about 1 °C. During the mixing process, the grout quickly becomes warm and reaches 8 °C or more. The mixes with 8 °C were then placed in a temperature controlled room at 8 °C to cure. Table 5 shows preparation process for samples at 20 °C, where cement powder with a temperature of about 21 °C and tap water with a temperature of about 12 °C were used. This led to the production of grout mixes with a temperature in the range of

Table 1
Typical values of cement grouts for rock grouting (ISRM, 1996).

Type of cement	Density, hardened (g/cm^3)	Grain size index, D_{95} (μm)	Strength after days	Uniaxial compressive strength (MPa)	Elastic modulus (GPa)
Portland cement	3	20–60	28	40–60	20–40
Superfine cement	3	8–15	28	> 45	20–40

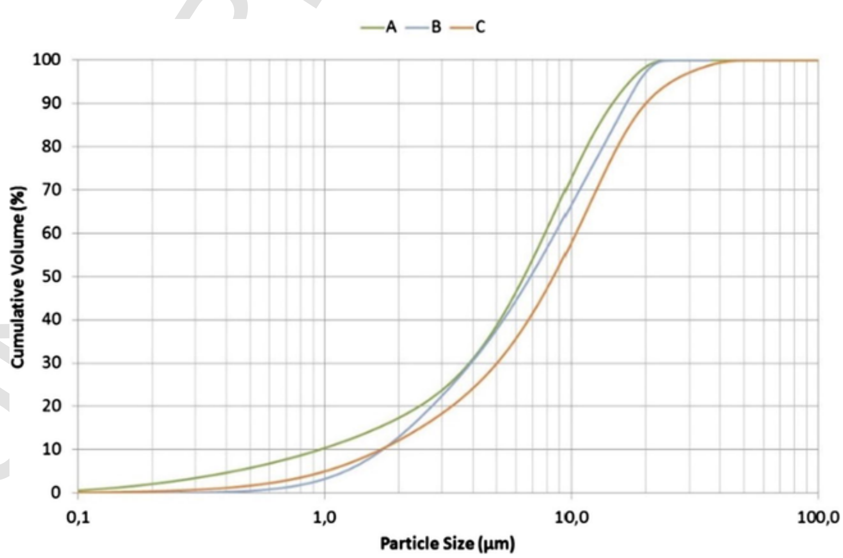

Fig. 1. Grain size distribution of cements A, B and C used in this study (after Skjølsvold and Justnes, 2016).

Table 2
Physical properties of cements A, B and C.

Cement type	Density (g/cm^3)	Blaine fineness (m^2/kg)	Specific surface, BET (m2/kg)	D_{95} (μm)
Cement A	3.17	729	1880	17
Cement B	3.16	541	1580	18
Cement C	3.10	706	1930	25

20 °C–22.5 °C. The mixes were put in room temperature of about 20 °C to cure. After curing to the specified age (4 or 7 days), both series of samples (8 °C and 20 °C) were tested in standard room temperature. Two specimens were tested from every mix to get a more representative value of the UCS. Impact of room temperature during testing of cured samples is considered to be insignificant since test duration for UCS is in the order of minutes.

The mixed grout was poured into cylindrical plexiglas forms (Fig. 2b–d). Diameter of the cylindrical specimens was 50 mm and their height was about 100 mm. Plexiglas cylinders with a diameter of 25 mm were also prepared to make samples for permeability measurement. Half of the grout samples were put in standard room condition (ca. 20 °C) and the other half in a temperature-controlled room (8 °C) for curing. The cured grout samples were tested for UCS at ages

Table 3
The type and number of tests carried out in this study. For details see Tables 4 and 5.

Cement types	Water-cement (w/c) ratio	Temperature of mix and curing	Test type/number			Comments
A, B, C	0.6, 0.8, 1.0, 1.2	8 °C or 20 °C	UCS[a]/96	Perm[b]/4	Filtration/36	Permeability was done for samples cured at 20 °C only

[a] UCS = Uniaxial compressive strength.
[b] Perm = permeability measurement.

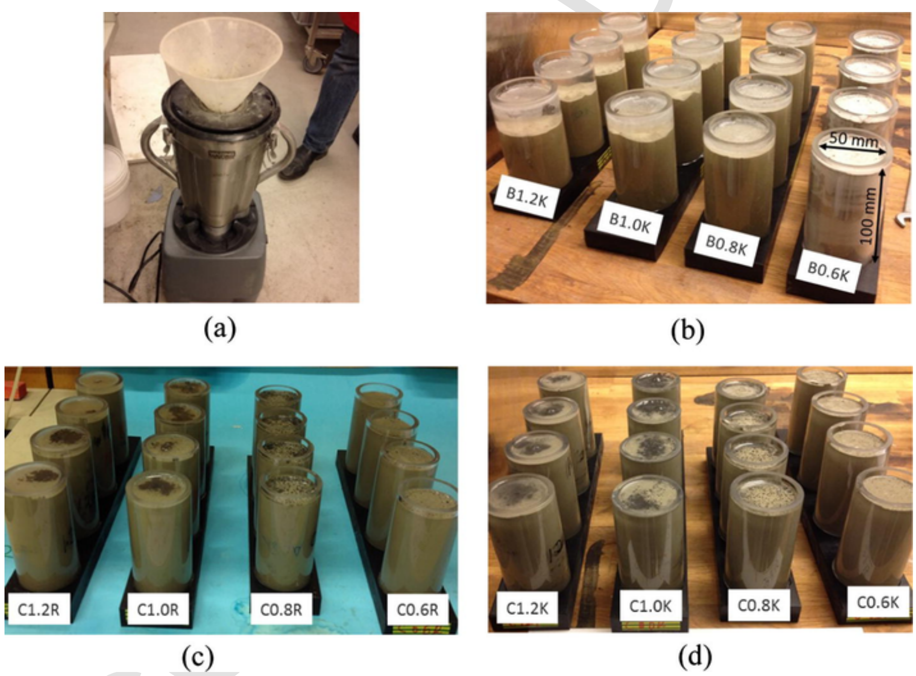

Fig. 2. The blender used for mixing cement and water (a), mixes of cement B with different w/c ratios at 8 °C (b), mixes of cement C with various w/c ratios prepared at 20 °C (c) and at 8 °C (d).

Table 4
Specifications for preparing cement blends at about 8 °C for Uniaxial Compressive Strength (UCS) and filtration tests. This example is for cement C.

Mix ID		1	2	3	4	Comments
w/c ratio		0.6	0.8	1.0	1.2	
Cement	Weight (kg)	1.0	0.8	0.8	0.7	Measure the actual temperature before mixing
	T (°C)	10.5	9.8	9.1	8.7	
Water	Weight (kg)	0.6	0.64	0.8	0.84	Measure the actual temperature before mixing
	T (°C)	0.8	1.1	1.2	1.1	
Temp. of mix (°C)		10.4[a]	9.4	8.7	8.9	Measure the actual temperature of mix immediately after mixing
Number of samples		4	4	4	4	Test 2 samples from each mix after 4 days and 2 samples after 7 days of curing

[a] Temperature of the blended grouts varied from 8 °C to about 12 °C, but the temperature-controlled room, where samples cured in, was set at 8 °C.

Table 5
Specifications for preparing cement blends at 20 °C for Uniaxial Compressive Strength (UCS) and filtration tests. This example is for cement C.

Mix		1	2	3	4	Comments
w/c ratio		0.6	0.8	1.0	1.2	
Cement	Weight (kg)	1.0	0.8	0.8	0.7	Measure the actual temperature before mixing
	T (°C)	21.3	21.3	21.3	21.3	
Water	Weight (kg)	0.6	0.64	0.8	0.84	Measure the actual temperature before mixing
	T (°C)	11.2	12.4	12.5	12.3	
Temp. of Mix (°C)		21.1	21.4	20.0	19.0	Measure the actual temperature of mix right after mixing
Number of samples		4	4	4	4	Test 2 samples of each mix after 4 days and 2 samples after 7 days of curing

of 4 and 7 days. Permeability was measured for samples of 7 days age only because of the budgetary constraints. The reason for choosing 4 and 7 days is that 4-day curing time may be close to operational time in tunnelling. The age of 7 days is rather standard for cement and concrete testing and thus provides possibility of comparing the results with the data in the literature.

Every grout mix is assigned an ID that includes three characters, e.g. A0.6K. First character (A) presents the type of cement. Second character is a number (0.6) that present w/c ratio and third, a letter indicating temperature of mix (where K = 8 °C and R = 20 °C). Thus, A0.6 K represents a grout made up of cement A with w/c ratio of 0.6 cured at 8 °C, and B1.2R represents a grout made up of cement B with w/c ratio of 1.2 cured at temperature of 20 °C.

The total number of specimens for UCS test was determined through a row matrix of one by five:

$$Total\ UCS\ tests = [F1 * F2 * F3 * F4 * F5] \quad (1)$$

where F1 = type of cement, F2 = w/c ratio, F3 = temperature of mix, F4 = age of cured grout sample, and F5 = number of plugs from each series.

Grouts of three types of cements with four different w/c ratios (0.6, 0.8, 1.0 and 1.2) were prepared for every cement type at two different temperatures of 8 °C and 20 °C. Two specimens from each series were tested at two different ages of curing. Thus, the total number of tested plugs for UCS are:

$$Total\ UCS\ tests = [3 * 4 * 2 * 2 * 2] = 96 \quad (2)$$

2.1.2. Testing procedure for uniaxial compressive strength test

The UCS test is an unconfined compressive strength test that is performed through axial loading of cylindrical samples. The uniaxial compressive strength test was performed according to the ISRM standard (ISRM, 2007) and loading rate was set such that failure occurred between 2 and 15 min. All UCS tests were performed in room temperature of about 20 °C.

Axial deformation of the sample was measured along with the axial load. The strength of specimen, σ, was calculated using Eq. (3):

$$\sigma = \frac{P}{\pi r^2} \quad (3)$$

where *P* is the applied load and *r* is the radius of test specimen.

2.2. Permeability test

Sample preparation procedure for permeability plugs was the same as for the specimens used for UCS test. The only difference was the dimension of samples. Specimens for permeability test had an equal diameter and height of 25 mm. Four samples were chosen for permeability test, all cured at room temperature of 20 °C for 7 days.

Permeability was measured under constant-head water pressure. A pore pressure of 10 MPa, a confining pressure of 12 MPa and thus an isotropic effective consolidation stress of 2 MPa was applied on test specimens (Table 6). A pore pressure gradient of 0.2 MPa was applied between the top and bottom of the specimen, which allowed for the determination of permeability coefficient once the sample reached a steady state flow.

2.3. Filtration test

2.3.1. Test description

Filtration is defined as the separation of suspended solid components of a slurry on a filter medium while the liquid passes through (Oilfield Glossary, 2015). Filtration gives a fair assessment of the grout's penetrability (Eklund, 2003). Filtration of grout can be measured using a filter pump (Hansson, 1994) a pressure chamber (Widmann, 1996), NES-method (Sandberg, 1997), sand column (Schwarz, 1997), a penetrability meter (Eriksson and Stille, 2003), or a filter press (NFF, 2011). The API filter press test is a standardized method, and has been developed for drilling fluids in oil wells. It may also be used as a test method for grouts (NFF, 2011). In this study, we utilize a filter press type API LPLT 300 (Fig. 3a) to examine filtration stability of cement grouts.

A measuring scale has been defined to quantify the filtration stability of grout mixtures. Several intervals have been determined based on the passed amount of grout, named b_{Stop}, $b_{Filtration}$ and b_{All} (Fig. 4). The term b_{stop} indicates that a very small and filtrated amount of suspension (almost pure water) passes through the filter. $b_{Filtration}$ means that an obvious filtration of grains occurs while b_{All} indicates that the mixture has good filtration stability and no significant filtration occurs (Eklund, 2003).

Table 6
Permeability measurement of four cement grout specimens.

Cement type	Sample no.	w/c ratio	Curing/testing condition	Confining pressure (MPa)	Pore pressure (MPa)	Permeability k (cm/s)	Permeability K (mD)
A	A1.2R	1.2	20 °C, room	12	10	$1.83 * 10^{-7}$	$1.83 * 10^{-1}$
B	B1.0R	1.0	20 °C, room	12	10	$1.51 * 10^{-10}$	$1.51 * 10^{-4}$
	B1.2R	1.2	20 °C, room	12	10	$3.89 * 10^{-11}$	$3.89 * 10^{-5}$
C	C1.0R	1.0	20 °C, room	12	10	$5.35 * 10^{-10}$	$5.35 * 10^{-4}$

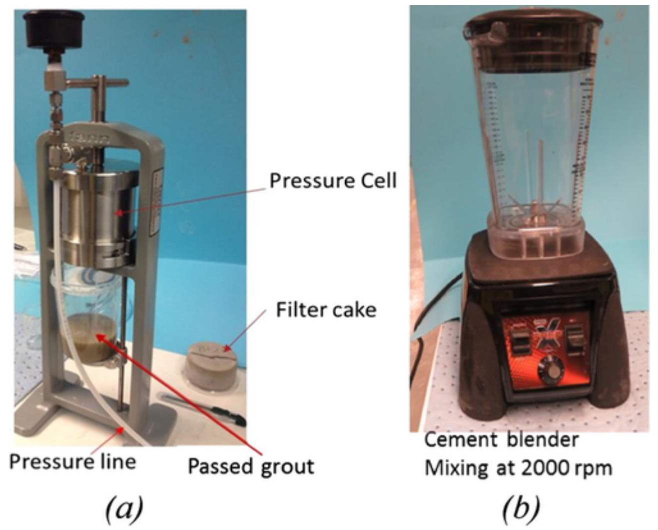

Fig. 3. An API Low Pressure Low Temperature (LPLT) 300 filter press apparatus available at NGI laboratory (a) and a cement blender (b) used in this study.

2.3.2. Sample preparation for filtration test

Grout samples for filtration tests were prepared using the same mixing procedure as for the UCS samples (see Tables 4 and 5). The prepared grout mixes were used immediately after blending as described in the testing procedure below.

2.3.3. Testing procedure for filtration test

Filtration of grout was measured in an API Standard filter press (Fig. 3a). It consists of mud reservoir mounted in a frame, a pressure source, a filtering medium, and a graduated cylinder for receiving and measuring filtrate. Cement grout is pressed through a filter of known permeability. Due to filtration, the grout may develop a filter cake which plugs the filter. The standard API filter press, used here, has an area of 45 cm^2 and is operated at a pressure of 100 psig (6.8 atm.). A filter of known mesh size is mounted at the bottom of the pressure cell and the cell is filled with a certain amount of grout mix, to about 6 mm from the top of the cell. The cell is then subjected to a pressure of 100 psig and the filtrate volume collected is reported as the standard filtrate volume. The amount of filtered grout is expressed as a percentage of total grout volume. For drilling muds, the filtered volume is normally collected in a 30-min time period. However, the 30-min filtration time may be inappropriate for cement grouts since they pass through the filter much faster. For the cement grouts tested in this study, all filtered volume passed through the filter and air reached the outlet of the pressure cell within few minutes.

The size of filter for the filter press test depends on the grain size distribution of the mixture of interest. The grain size distribution of the three cements is provided in Fig. 1. The filter size was selected based on the grain size of the cements and the approximation that the smallest fracture aperture that grains can penetrate is about three times the grain size distribution index (D_{95}) (Bergman et al., 1970). The D_{95} of the three cements varies from 18 to about 25 μm. Therefore, we used filter sizes of 63 and 75 μm.

3. Experimental results

All grout samples tested in this study are made up of cement and water only and no additive was added during preparation. Possible effect of additives on compressive strength, permeability and filtration stability is thus, neglected.

3.1. Results of uniaxial compressive strength

As an example, the results of uniaxial compressive strength (UCS) test on 16 specimens of cement A, cured for 4 days are presented in Fig. 5. Each panel presents stress-strain curves from UCS test on four specimens; two of them cured at 8 °C (given suffixes K1 and K2) and two at 20 °C (suffixes R1 and R2). A clear observation is that the strength of cement grouts cured at 8 °C is lower than those cured at 20 °C. Further, the strength of grout specimens decreases significantly with increasing w/c ratio from 0.6 to 1.2 (Fig. 5). Stress-strain curves of the specimens with w/c ratio of 0.6 shows a stiffer (higher slope) and almost brittle behavior. Slope of the curves decreases gradually and the specimens show rather ductile behavior when w/c ratio increases from 0.6 to 1.2.

Uniaxial compressive strength of the cement grouts cured at 20 °C has a maximum of about 30 MPa for w/c ratio of 0.6 and a minimum of about 3 MPa at w/c ratio of 1.2. Similarly, strength of the samples cured at 8 °C has a maximum of about 20 MPa at w/c ratio of 0.6 and a minimum of about 1 MPa at w/c ratio of 1.2.

The results of UCS for all cements (A, B and C) cured for 4 and 7 days are presented in Fig. 6. Each histogram bar presents an average UCS value from two specimens. The average values for all cement mixes, plotted in Fig. 6, shows the following trends:

1. UCS of cement grouts cured at 8 °C is usually lower (about 30%–50%) than those cured at 20 °C (compare Fig. 6a with Fig. 6c or Fig. 6b with Fig. 6d).
2. Strength of cement decreases with increasing w/c ratio. This is true for all cements. The decreasing trend is more dramatic for cement A where UCS drops from about 18 MPa to 1 MPa when w/c ratio increases from 0.6 to 1.2.
3. UCS of cement grouts increases with increasing their age from 4 to 7 days (compare Fig. 6a with Fig. 6b or Fig. 6c with Fig. 6d). An exception is for specimens at 20 °C with w/c ratio of 0.6 that show almost the same or lower strengths for samples cured for 7 days than those cured for 4 days (Fig. 6c and d). This is usually not the case for cement and concrete specimens. A reason for this deviation might be the nature of UCS test that produces scattered results.

According to IRSM (1996), typical values of UCS for superfine cements used for grouting are greater than 45 MPa (Table 1). As mentioned above, UCS of grout samples with w/c ratio of 1.0 and 1.2 is very low, ranging from 1 to 6 MPa. This implies that grouts with such w/c ratios may not improve the strength of the rock mass significantly,

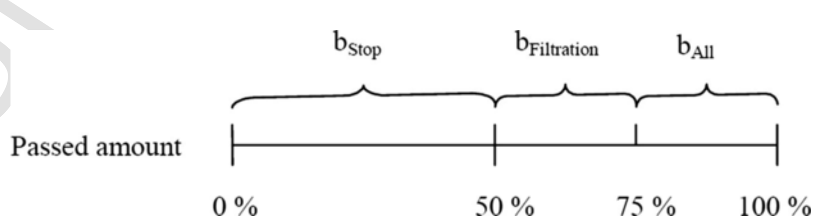

Fig. 4. Measuring scale for filtration stability (after Eklund, 2003).

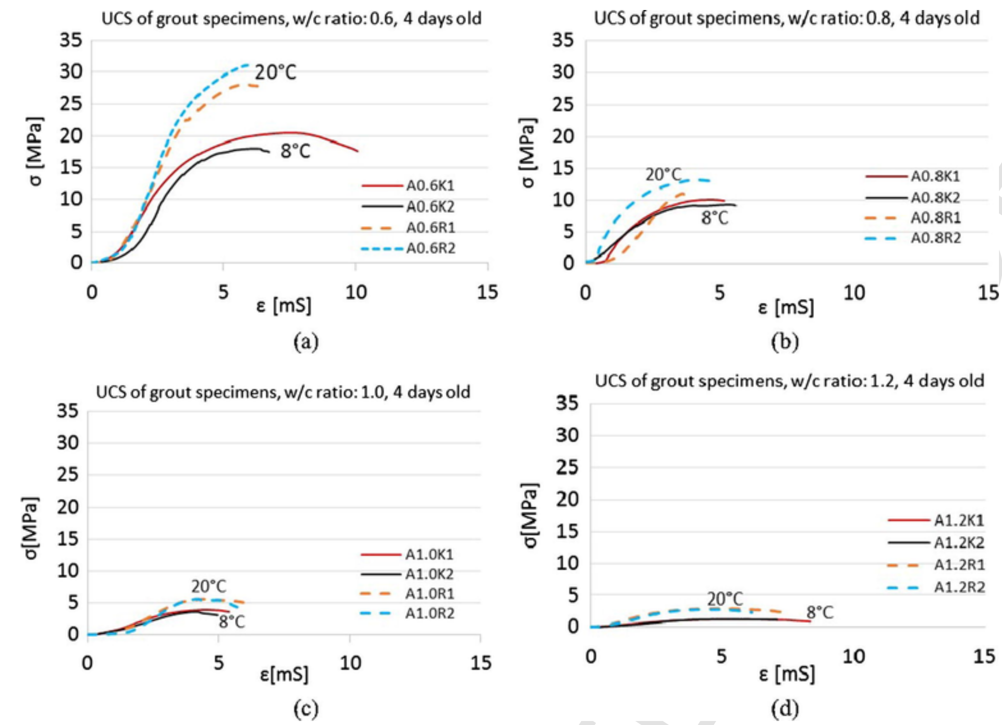

Fig. 5. Uniaxial compressive strength test of cylindrical specimens of cement A cured for 4 days at either 8 °C (with suffix K) or 20 °C (suffix R). Different panels presents samples with various water to cement ratios.

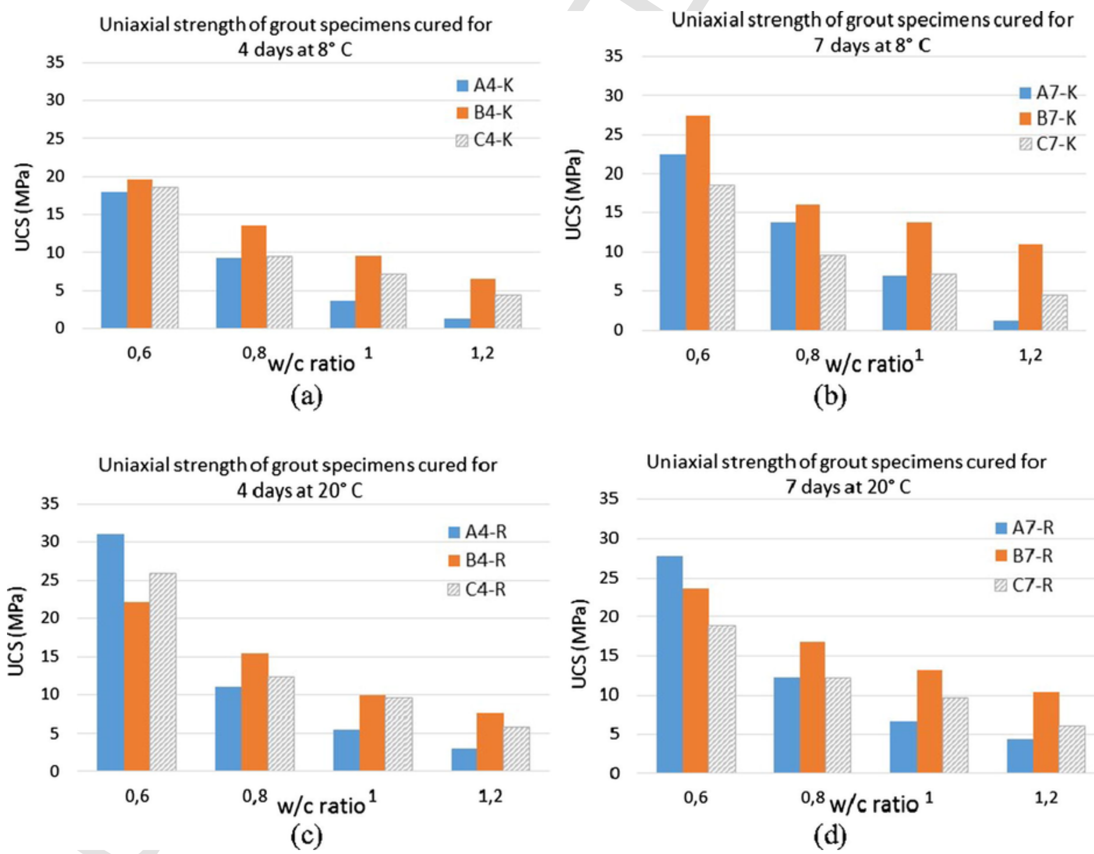

Fig. 6. Uniaxial compressive strength of cement specimens cured for 4 and 7 days at either 8 °C or 20 °C. Index to sample names in the figure: First letter represents the type of cement, second number represents the age of cement, and third letter stands for curing temperature; K for 8 °C and R for 20 °C. For example A4-K refer to Cement A cured for 4 days at 8 °C.

nor its rock mass quality. This is particularly true for cement A that has a compressive strength of about 1–3 MPa for w/c ratios of 1.2 and 1, respectively.

3.2. Results of permeability test

Permeability was measured for four cement grout specimens (Table 6). The specimens cured for 7 days at 20 °C then were tested in room temperature. The results showed that permeability of samples varies from $5.35 * 10^{-5}$ to $1.83 * 10^{-1}$ mD. Cement A has the highest permeability while cements B and C have much lower permeability values. Permeability value of $1.8 * 10^{-1}$ mD is typical for low porosity consolidated sandstones and about one order of magnitude higher than permeability of non-fractured igneous rocks. Thus, cement A with w/c ratio of 1.2 may not be appropriate for cases where strict water tightening of rock mass is required. However, the permeability values presented here are from four measurements only. For a systematic comparison of permeability of different cements and mixes, a large number of permeability measurements are required. Permeability has usually a positive correlation to porosity. Therefore, the highly permeable grout specimen A (with a w/c ratio of 1.2) may develop higher porosity during curing than grouts of cements B and C. Porosity also affects the strength of specimen negatively. Results of the compressive strength test showed that grout specimens A had the lowest strength, B had higher and C had the highest values. This is consistent with the permeability values measured, the higher the permeability, the lower is the strength and vice versa. This difference in hydro-mechanical behavior of the cement grouts may be due to the difference in their composition.

3.3. Results of filtration test

The results of filtration test on gouts from cements A, B and C are presented in Table 7 and Figs. 7 and 8. Filtration stability of the three cements varies significantly. It increases with increased w/c ratio (Fig. 7).

For Cement A, the passed amount of grout at 8 °C is about the same or slightly higher than that at 20 °C. For Cement B, the values are very close or slightly lower than those at 20 °C. For Cement C, more grout penetrates at 8 °C than that at 20 °C (Fig. 8), i.e. grout is more stable at 8 °C and separation of water and cement grains does not occur during grout flow, which makes it suitable for sealing underground works.

Cement A has the greatest filtration stability (passed percentage) amongst the three cement grouts tested. About 85% of cement A passed through a filter of 75 μm at w/c ratio of 0.6 and the passed amount increased to 98% with increasing w/c ratio to 1.2. For cement C, about 70% of grout passed through a filter of 75 μm at w/c ratio of 0.6 and increased to about 92% with increasing w/c ratio to 1.2. Cement B on the other hand, behaved quite differently. It showed a passed percentage of 15% only at w/c ratio of 0.6 and reached a maximum of about 40% at w/c ratio of 1.2. Cement B shows large cake building and weak filtration stability while cements A and C show great filtration stability where large percentage of the grouts pass through the filter size of 63 and 75 μm.

Table 7
The results of filtration test on cements A, B and C at two temperatures of 8 °C and 20 °C and through two filter sizes of 63 and 75 micro-meters (μm).

Cement type	w/c ratio	Temperature (°C)	Filter size (μm)	Passed amount (%)
A	0.6	8	75	83.7
		20	63	87.8
			75	86.4
	0.8	8	75	93.5
		20	63	91.8
			75	91.1
	1.0	8	75	97.7
		20	63	95.3
			75	97.2
	1.2	8	75	98.4
		20	63	95.9
			75	97.8
B	0.6	8	75	15.7
		20	63	17.7
			75	17.9
	0.8	8	75	27.3
		20	63	27.7
			75	27.8
	1.0	8	75	34.5
		20	63	36.7
			75	35.2
	1.2	8	75	38.3
		20	63	40.8
			75	40.5
C	0.6	8	75	72.7
		20	63	63.9
			75	71.0
	0.8	8	75	91.0
		20	63	81.9
			75	83.3
	1.0	8	75	94.5
		20	63	91.9
			75	89.5
	1.2	8	75	94.1
		20	63	90.9
			75	91.6

Filtration stability is strongly controlled by the grain size of grout. Grain size distribution and D_{95} of the three cements were presented in Fig. 1 and Table 2, respectively. The grain size of cement B is smaller than that of cement C. Further, the D_{95} of cement B is much smaller than that of cement C (18 μm versus 25 μm) and is close to D_{95} of cement A (17 μm). However, cement grouts B shows a much weaker filtration stability than cements grouts A and C. This implies that grains of cement B bind together and flocculate when mixed with water and form particles equal to or larger than 75 μm and clog the filter. Thus, the grain size of cement itself is less important than the size of the particles in the ready mixed grout for penetration into cracks and pores.

More than 90% of grout mixes of cement A at all w/c ratios passed through filter sizes of 63 and 75 μm. According to the measuring scale

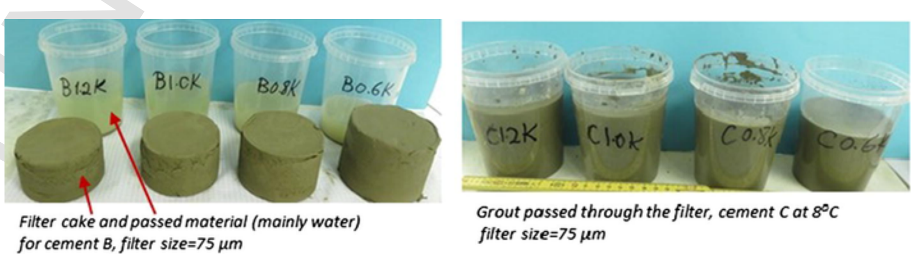

Fig. 7. The results of filtration test for cements B (left) and C (right), both for grouts at temperature of 8 °C.

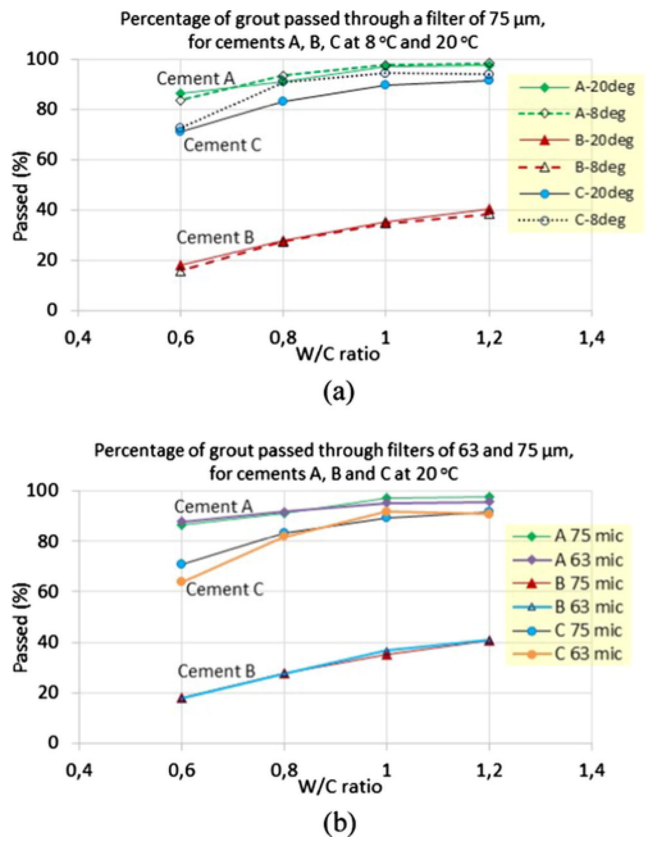

Fig. 8. The results of filtration tests on grouts of three different cements mixed and tested at 8 °C and 20 °C.

presented in Fig. 4, cement A fits in the class b_{All} which indicates it has very good filtration stability and no significant filtration occurs. Cement C with w/c ratio of 0.6 shows filtration and cake building and falls in the class $b_{Filtration}$. When, however, w/c ratio exceeds 0.8, stability of grout increases and more than 80% passes through the filter (b_{All}). Conversely, cement B shows significant filtration and less than 40% of grout passes through the filter (b_{stop}). Cement B has strong filter cake building and most cement stops on the filter size of 63 or 75 µm. If these results are applicable for penetration of grout in rock fissures, cement B will not be able to penetrate effectively into cracks with an aperture of about 75 µm.

4. Conclusions

Three commonly used cements for tunnel grouting were selected for laboratory testing. The D_{95} of the cements ranges from 17 to 25 µm. Various mixes of the three cements, with w/c ratios of 0.6, 0.8, 1.0 and 1.2 were prepared at about 8 °C and 20 °C. The mixes of each cement were divided into two batches; one mixed and cured at 8 °C (which is supposed to be the in-situ temperature in tunnels in the Nordic countries) and the other at 20 °C. The cured samples were subjected to mechanical testing with uniaxial compressive strength and permeability measurement. The fresh grout mixes were tested for filtration stability using an API filter press test with filter sizes of 63 and 75 µm. The highlights of this study can be summarized as:

- The strength of grout mixes prepared and cured at 8 °C is generally lower (about 30%–50%) than those at 20 °C. This implies that strength of cement injected into the rock mass and cured in-situ may be lower than the strength measured at room temperature.
- Compressive strength of cement grouts with lower w/c ratio is higher than those with higher w/c ratio and the strength increases with increasing age of cement grout specimens, as expected. The strength of cement grouts of 4 days old with w/c ratio of 0.6 is about 18–20 MPa at 8 °C while it is between 1 and 6 MPa at w/c ratio of 1.2, for all cement grouts. Similar trend was also observed for grouts of 7 days old. Compressive strength of 4 days old grouts cured at 8 °C decreases from 20 MPa to less than 5 MPa when w/c ratio increases from 0.6 to 1.2. This reduction is more dramatic for cement A where its strength decreases from 18 MPa to 1 MPa with increasing w/c ratio from 0.6 to 1.2.
- The strength of cement grouts with w/c ratio of 1.0 and 1.2 is very low, ranging from 1 to6 MPa for 4 days old grouts to about 5–10 MPa for 7 days old grouts. Grouting the rock mass with such mixes may not result in any significant improvement of strength of rock mass or its quality.
- The permeability of cylindrical specimens made up of cements B and C is low but for a sample made of cement A (with w/c ratio 1.2) it is relatively high; about 0.18 mD. If this is true for grout in-situ, such a mix of cement A may not be a good candidate for water tightening of underground excavations.
  Integrating results of the UCS test and permeability measurement implies that cement grouts A may contain highest but those of B contain lowest porosity. The evidence is that the cement grouts A have the highest permeability and lowest strength, whereas cement grouts B have the lowest permeability and highest strength. This may be due to the difference in composition of the cements.
- Filtration stability of cement grouts at 8 °C is almost the same as that for 20 °C. Cement A had the best filtration stability, where about 90% of the grout passed through a 63 µm filter, while cement B had the lowest filtration stability where less than 40% of the grout passed through the filter. Filtration stability of cement grouts is affected by w/c ratio and grain size distribution of cements but not much by the grout temperature.

The conclusions above suggest that for selecting the type of cement and characteristics for rock mass grouting may include additional criteria than those normally applied in the industry today.

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