Tunnelling and Underground Space Technology 71 (2018) 193–200

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

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

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ARTICLE INFO

Keywords:
Grouting
Tunnelling
Filtration stability
Permeability
Strength

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 central 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).

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http://dx.doi.org/10.1016/j.tust.2017.08.017
Received 19 March 2017; Received in revised form 30 June 2017; Accepted 16 August 2017

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

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.

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

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 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

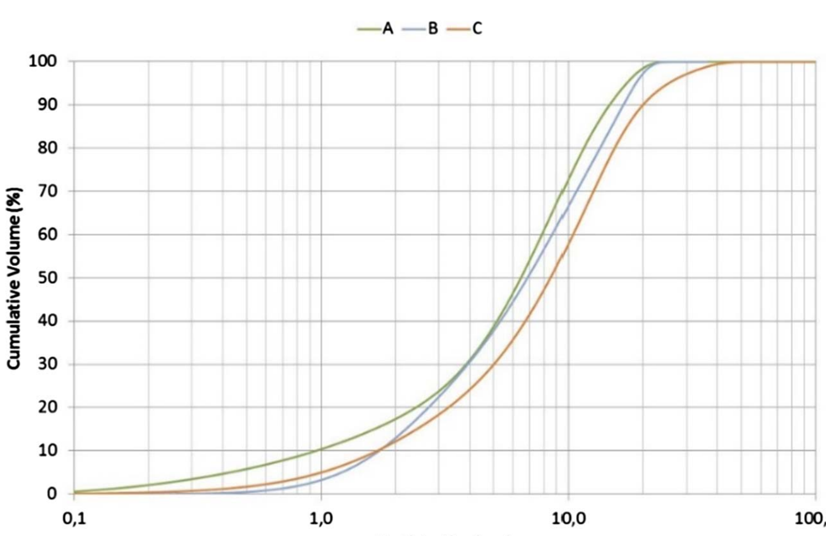

Fig. 1. Grain size distribution of cements A, B and C used in this study (after Skjølsvold and Justnes, 2016).