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Frost Resistance and Permeability of Cement Stabilized Gravel used as Filling Material for Pearl-Chain Bridges

Mia Lund, Kurt Kielsgaard Hansen and Kristian Hertz

*Department of Civil Engineering,
Technical University of Denmark,
Brovej, Building 118, DK-2800 Kgs. Lyngby, Denmark*

Abstract

The Pearl-Chain Bridge Technology introduces a new innovative arch bridge solution which combines the statical advantages of an arch bridge with a minimum of traffic disturbance. The arch-shaped substructure is stabilized by a filling material, e.g. cement stabilized gravel, which should meet several requirements on its moisture properties. In this paper the frost resistance, the liquid water permeability and the water vapour permeability of cement stabilized gravel are examined for two different cement contents. It is found that a small increase in cement content from 4% to 5% increases the 28-days compressive strength from 6.2 MPa to 12.3 MPa. The frost resistance of cement stabilized gravel with 5% cement content is better than for cement stabilized gravel with 4% cement content. The liquid water permeability coefficient and the water vapour permeability coefficient are significantly higher for a cement content of 4% compared to 5%.

1 Introduction

The Pearl-Chain Bridge Technology introduces a new innovative arch bridge solution challenging the traditional way of constructing highway bridges. Traditionally, arch bridges are known to be statically optimal; however, the need for extensive scaffolding is a major economical drawback that explains why slab bridges are typically preferred. The Pearl-Chain Bridge Technology introduces a concept which makes it possible to reintroduce the arch shape in highway bridging. The substructure of a Pearl-Chain Bridge is created of prefabricated Super-Light Deck elements (SL-Deck elements) which consist of a combination of light-aggregate concrete and strong concrete. Ducts are cast into the longitudinal direction of the SL-Deck elements and the Pearl-Chain arch structure is formed by collecting and post-tensioning several SL-Deck elements like pearls on a string, see Fig. 1.

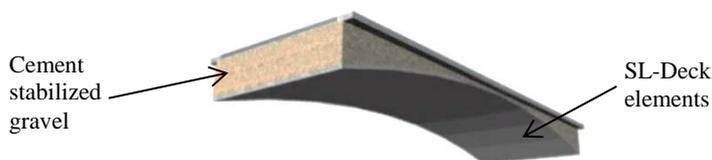


Fig. 1 Principle sketch of a Pearl-Chain Bridge.

The post-tensioning of the SL-Deck elements is carried out next to the highway, hereby establishing the substructure of the Pearl-Chain Bridge, and afterwards the bridge is lifted into place by use of a crane. Overall, this minimizes traffic disturbances; hence it is very much an economic favourable solution. After placement the arch structure is stabilized by a filling material which also supports the wearing course. The objective of the PhD project is to test and document the materials involved to various conditions since hard infrastructure such as bridges is expected to be in use for a period of 120 years. The objective includes development and implementation of suitable materials for the bridge, in particular the filling material above the arch structure. Apart from meeting the requirements to strength and stiffness the filling material is expected to be permeable, frost resistant, and to provide a low-cost stabilization of the arch.

Cement stabilized gravel is a potential filling material for Pearl-Chain Bridges. In Denmark, cement stabilized gravel has become a more and more widely used material in road constructions since it at a rather low addition of cement provides a significant increase in strength and stiffness compared to gravel. However, the field is characterized by a “trial and error” design process and there is a great lack in documentation of research work on cement stabilized gravel.

2 Methods

2.1 Specimen Preparation

This paper is connected with one type of gravel material having a size distribution between 0-16 mm, from Nymølle pit, Denmark. A sieve analysis performed in accordance with [1] classified the gravel as belonging to Envelope B with an oversize of 7% on the 16 mm sieve, cf. [2]. Fig. 2 shows the grain curve for the gravel material.

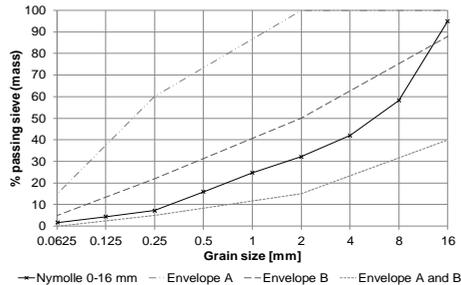


Fig. 2 Grain size distribution of gravel (Nymølle 0-16 mm) with envelopes according to [2].

Two different cement contents of 4% and 5% of the dry material were chosen. These two cement contents were considered because they were expected to correspond to strength class $C_{5/16}$ and $C_{12/15}$, with 28-days compressive cylinder strengths of 5 MPa and 12 MPa, respectively, cf. [2]. For Pearl-Chain Bridges a cement content as low as possible is desired due to economic considerations. The optimal water content was determined from proctor tests in accordance with [3] by including the influence of cement. The mixture was prepared by mixing gravel, low alkali cement and water in the right proportions for three minutes. The specimens were cast in accordance with [4] using the vibrating table compaction method. Split moulds with a diameter of 150 mm and a height of 300 mm were used. The minimum degree of compaction, which is defined as the ratio between the actual density of the specimen and the optimal density determined from proctor tests, was 97.4%.

2.2 Experimental Procedure

2.2.1 Compression Test Setup

The compressive strength and the modulus of elasticity were determined from the same test setup on cylinders measuring D150mm/H300 mm. The standardized procedure described in [5] and [6] was followed except that only two extensometers were used. Fig. 3 (left) shows the installation of the strain measuring device.

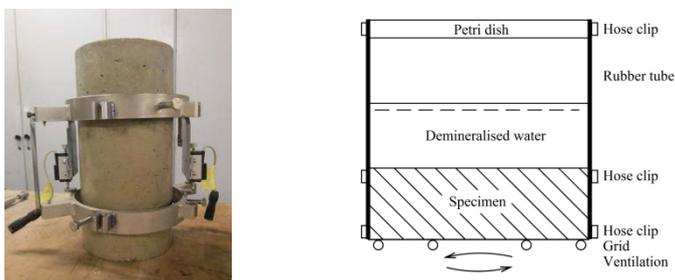


Fig. 3 Test setup for compression test with two rigid rings, each one tightly fastened with three screws to the specimen, and two extensometers placed between the rings on opposite sides (left). Principle sketch of cup setup used for permeability tests (right).

The compression tests were carried out on a TONI 3000 kN machine at a velocity of 3 or 5 kN/s for 4% cement and 5% cement contents, respectively.

2.2.2 Freeze-Thaw Test Setup

For the freeze-thaw tests a cylinder was cut in two cubes with dimensions of 10 x 10 x 10 cm. One cube was exposed to freezing-thawing while the other cube was stored in water at room temperature for later strength comparison. The freeze-thaw tests were carried out on water saturated and salt water saturated specimens. Fick's second law of diffusion was used to make a conservative estimate of the time needed for the chlorides to penetrate the specimen; hence the specimens were soaked in a 3% NaCl solution for 40 days. Each specimen was wrapped into two layers of plastic and placed in a freezing cabinet which was set to follow the temperature variation in Fig. 4 automatically. The temperature variation was determined from [7] and a total duration of 28 hours per cycle was hereby applied in order for the prescribed limitations to be kept. The core temperature was measured on two specimens during the testing, see Fig. 4.

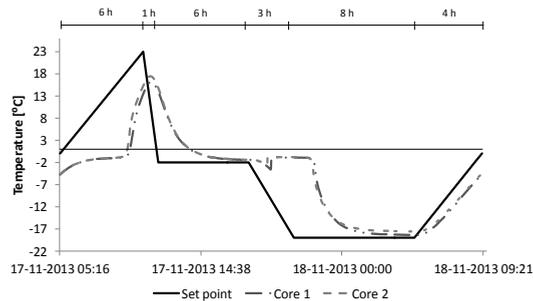


Fig. 4 Temperature variation during one freeze-thaw cycle. The core temperature has been measured on two different specimens.

After approximately every 6th cycle the ultrasound wave speed and the mass were measured for each specimen. After 20 cycles and after 56 cycles the compressive strength was determined for half of the specimens as well as for their reference which had been water stored during the course of freezing-thawing.

2.2.3 Permeability Test Setup

The specimens used for the permeability tests were cut from the D150mm/H300mm cylinders such that they had a height of 5 cm. The specimens were vacuum water saturated with boiled cold demineralised water for three hours and rested for further 24 hours. Hereafter the cups were assembled as shown in Fig. 3 (right). A rubber tube was mounted around a specimen and tightly fastened by use of two hose clips. Approximately 5 cm of boiled cold demineralised water was poured on top of the specimen and the cup was closed by placing a petri dish at top of the rubber tube and tightening it with a hose clip. The cups were placed on a grid in a climate room with a constant relative humidity of 65% and a constant temperature of 22°C. A fan was placed below the specimens to remove penetrated water and the tests were ended when the weight loss was constant in time.

3 Results

3.1 Compressive Strength of Specimens

The compression tests were carried out on specimens after 7 days and after 28 days. For all specimens the stress-strain curves were recorded from which the modulus of elasticity, E_c [MPa], was determined cf. [6] as:

$$E_c = \frac{1.2F_r}{\pi D^2 \varepsilon_3} \quad (1)$$

where F_r [N] is the max. compressive load, D [mm] is the diameter of the specimen and ε_3 is the longitudinal strain of the specimen when $F = 0.3F_r$.

Table 1 shows the compressive strength, the modulus of elasticity and the ultimate compression strain after 7 days and 28 days.

Table 1 Compressive strength f_c , modulus of elasticity E_c , and ultimate compression strain ϵ_u after 7 days and 28 days.

Cement content [%]	7 days			28 days		
	f_c [MPa]	E_c [GPa]	ϵ_u [%]	f_c [MPa]	E_c [GPa]	ϵ_u [%]
4	2.61	6.74	0.98	6.24	14.7	0.64
5	7.48	17.5	0.63	12.3	22.8	0.41

3.2 Frost Resistance of Specimens

Potential freeze-thaw damages were evaluated in three different ways, besides from visual assessment. The change in mass was recorded and found to be insignificant. The maximum change in mass was a reduction of 0.5%. Likewise, there was no sign of scaling during the visual assessment of the condition of the specimens. The compressive strength was determined after 20 cycles and after 56 cycles for the specimens exposed to freezing-thawing and for their reference which had been water stored at room temperature during the tests. Fig. 5 shows the compressive strengths for specimens with a cement content of 4% and 5%. The reference values are an average of the reference compressive strengths after 20 and 56 cycles, since no significant difference was observed. It should be kept in mind that the frost tests were conducted on specimens measuring 10 x 10 x 10 cm.

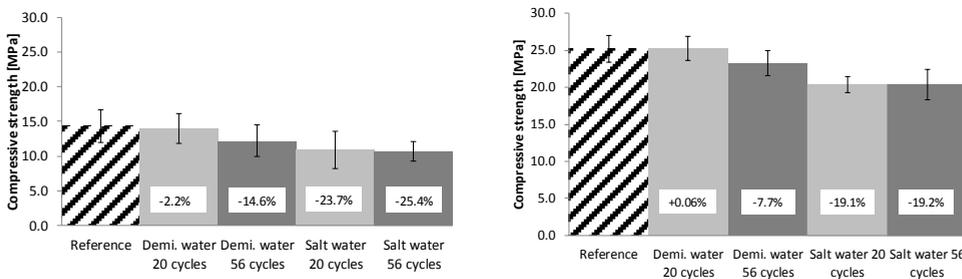


Fig. 5 Compressive strength of 10 x 10 x 10 cm specimens with 4% cement (left) and 5% cement (right) exposed to either 20 or 56 frost cycles and reference value corresponding to no frost cycles. White boxes show relative difference from mean reference value.

Moreover, the change in ultrasound wave speed was used to detect potential internal damages. The European standard [8] does not approve evaluation of frost resistance by use of ultrasound wave speed, however according to the American standard [9] the durability factor is a reliable indicator of distress due to freezing and thawing. The durability factor, DF, is calculated as:

$$DF = \frac{PN}{M} \quad (2)$$

where P [%] is the relative dynamic modulus of elasticity at N cycles, N is the number of cycles at which P reaches the specified minimum value which is here chosen as 60% or the number of cycles at which the test is to be terminated, and M is the number of cycles at which the exposure is to be terminated. The dynamic modulus of elasticity is based on measurements on specimens which have not been dried out. This will influence the measurements and give an incorrect value of the dynamic modulus of elasticity, however, since the relative modulus is evaluated, this is not considered any further. Table 2 shows the durability factors for all specimens.

Table 2 Durability factors, DF, for specimens exposed to 56 freeze-thaw cycles. % C = % cement content.

	4% C demi. water	4% C salt water	5% C demi. water	5% C salt water
DF [%]	8.6	1.4	29.9	3.2

3.3 Liquid Water Permeability and Water Vapour Permeability of Specimens

The moisture transportation in the specimens can be considered as a combined capillary suction and water vapour diffusion, cf. [10]. Menisci are formed inside the specimen due to the specimens containing a certain amount of cement and due to their underside being in direct air contact. The very low pressure under the menisci will result in capillary condensation and water flow through the material. At the same time vaporization from the surface of the menisci occurs due to the moisture content in the climate chamber being different from the moisture content in the menisci.

The position of the vapour front is calculated from [10] and Darcy's Law is used to calculate the liquid water permeability coefficient, K [s], as:

$$K = q \cdot \frac{L_C}{\Delta P} \quad (3)$$

where q [kg/(m²s)] is the stationary water flow, L_C [m] is the capillary suction length and $\Delta P \approx -P_2$ [Pa] is the pressure below the menisci. The water vapour permeability coefficient, δ_v [s], is given by:

$$\delta_v = q \cdot \frac{L_V}{\Delta p} \quad (4)$$

where L_V [m] is the water vapour diffusion length and $\Delta p = p_1 - p_2$ [Pa] where p_1 and p_2 are the vapour pressure in the vapour front and in the climate chamber, respectively.

Assuming that the relative humidity in the vapour front is 98% the water and vapour permeability coefficients given in Table 3 are found.

Table 3 Liquid water permeability coefficient K , and water vapour permeability coefficient δ_v .

Cement content [%]	K [$\cdot 10^{-13}$ s]	δ_v [$\cdot 10^{-11}$ s]
4	1.36	5.77
5	0.71	3.58

4 Discussion

The addition of 1%-point extra cement is seen to significantly influence the compressive strength and stiffness of the specimens. From Table 1 it is seen that the 7-days compressive strength and stiffness were increased by 187% and 160%, respectively, by increasing the cement content from 4% to 5%. The corresponding 28-days strength and stiffness were increased by 97% and 55%, respectively. This implies that the addition of 1%-point extra cement has particular big influence on the compressive strength and stiffness in the early hydration. Furthermore, the ultimate compression strain is seen to decrease with 36% by increasing the cement content from 4% to 5%. This decrease is found both after 7 days and after 28 days.

The presence of salt ions has a significant influence on the compressive strength of the specimens exposed to freezing-thawing. The impact is greatest for specimens containing 4% cement compared to 5% cement with the compressive strength decreasing 25.4% and 19.2%, respectively, after 56 cycles compared to the reference specimens. When demineralised water is used the compressive strength of specimens containing 4% cement decreases 14.6% while it decreases 7.7% for specimens with 5% cement after 56 cycles. For all specimens exposed to salt ions the decrease in compressive strength after 20 cycles is in the same order of magnitude as the decrease in compressive strength after 56 cycles. Hence, the major part of the deterioration takes place in the early frost period. The same tendency is not observed for the specimens exposed to demineralised water where a significantly bigger reduction in compressive strength is observed after 56 cycles compared to 20 cycles. After 20 cycles the specimens with 5% cement exposed to demineralised water have not experienced any change in compressive strength compared to the reference specimens. For a cement content of 4% this change is also minor. Overall, the results indicate that addition of 5% cement compared to 4% cement increases the frost resistance of cement stabilized gravel with respect to compressive strength.

This result is supported by the durability factors. The durability factors for specimens with 5% cement is 247% higher for demineralised water and 129% higher for salt water than the corresponding durability factors for specimens with 4% cement. Moreover, the durability factors for specimens exposed to salt ions are significantly lower than when no salt ions are present. The salt ions decrease the durability factors by 84% and 89% compared to specimens containing 4% cement and 5% cement, respectively, exposed to demineralised water. The durability factors are strongly affected by the choice of M in Eq. (2) and a better point of comparison is the relative durability factor (here relative

to the durability factor of 5% C demi. water) by which M is eliminated. These values are shown in Table 4 and the negative influence of salt ions and lower cement content is directly seen.

Table 4 Relative durability factors (DF_{rel}) for specimens exposed to 56 freeze-thaw cycles. % C = % cement content.

	4% C demi. water	4% C salt water	5% C demi. water	5% C salt water
DF_{rel} [%]	28.7	4.8	100	10.8

The liquid water permeability coefficient decreases by approximately 50% when the cement content is increased from 4% to 5%. The water vapour permeability coefficient decreases by 38% when the cement content is increased from 4% to 5%.

5 Conclusion

Cement contents of 4% and 5% of the dry material were tested because it was expected to accommodate the requirements to the compressive strength of the filling material while also considering the economical perspectives of the Pearl-Chain Bridge Technology. An increase in cement content from 4% to 5% was seen to significantly influence the compressive strength and stiffness of the specimens. The 7-days compressive strength of the specimens was increased from 2.6 MPa to 7.5 MPa and the 28-days compressive strength from 6.2 MPa to 12.3 MPa. The corresponding modulus of elasticity was after 7 days increased from 6.7 GPa to 17.5 GPa and after 28 days increased from 14.7 GPa to 22.8 GPa. Specimens containing 4% and 5% cement were seen to be sensitive to freeze-thaw damages. However, the specimens containing 5% cement showed better frost resistance than the specimens containing 4% cement. This was observed for specimens being saturated with demineralised water as well as specimens being saturated with a 3% NaCl solution. The tendency was clear from compressive tests and from comparison of durability factors. The presence of salt ions was found to significantly reduce the frost resistance of the specimens after 20 frost cycles. The liquid water permeability coefficient was decreased by approximately 50% when the cement content was increased from 4% to 5% and the corresponding water vapour permeability coefficient was decreased by 38%.

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