Swissmetro - Tests on Air Permeability of Concrete

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Summary

Air-tightness of the concrete lining is a critical factor for a railway tunnel to be operated under partial vacuum. The testing described in this article investigates the influence on air permeability of aggregate composition (sand content, maximum grain size), type of cement, addition of steel fibers, degree of saturation of the concrete, and use of a curing compound. Laboratory testing was performed on samples taken from 18 concrete wall elements representing a range of pumped concrete mixtures. Fresh-concrete properties, compressive strength, and porosity were also measured. This report handles the first 12 concrete mixtures. Evaluation of the remaining testing is still in progress.

Keywords: aggregate composition, air permeability, curing compound, degree of water saturation, steel fibers, type of cement

1. Introduction

Swissmetro is the high-speed rail system planned for Switzerland. The system will be concentrated primarily on an east-west axis and a north-south axis. Trains up to 200m long will travel at speeds of up to 400 km/h exclusively through tunnels approximately 5m in diameter. To keep energy consumption within reasonable limits it is planned to operate under partial vacuum within the tunnels. An additional aspect of the concept is internal concrete surfaces of continuous curvature, finished as smoothly as possible.

The following variants for construction of the tunnel lining come into consideration:
(1) Concrete ring with formwork on one side.
(2) Concrete ring, as in (1), but with internal surface coating.
(3) Double-ring construction with a sealant layer between.

Variant (1) places the greatest demands for air-tightness. But even the most conservative variant (3) would require an airtight concrete lining because local leaks in a built-in membrane cannot be ruled out over the required 100-year life-span of the project.

Testing conducted for the Swissmetro project includes laboratory testing and systems testing. Laboratory testing has been carried out at Technical Research and Consulting on Cement and Concrete (TFB) in Wildegg, Switzerland. Systems testing has been carried out at the Federal Institute of Technology in Lausanne, Switzerland. Results of the laboratory testing are presented in this article.

2. General Conditions for Laboratory Testing

Considering the expected operation of the system over a life-span of 80 to 100 years, an estimated eight to ten local temperature extremes of 200°C lasting about one minute could occur [2]. Under normal operating conditions maximum temperatures should remain below 50°C. Such temperature conditions have no significant influence on the concrete properties. The testing program for laboratory investigations is therefore based on a concrete temperature of 20°C.

3. Testing Program

The laboratory testing serves to optimize the material-technological composition of a concrete with maximum air-tightness. Practical, simple concrete mixtures suitable for pumping were studied.

3.1 Main Parameters Investigated

3.1.1 Type of Cement

The effects of three types of cement were analyzed. Chosen were CEM I 42,5 (the most commonly used cement in Switzerland), CEM II/A-L 32,5R (Portland-limestone cement) recognized for good workability, and CEM II/A-D 52,5R (Portland silica fume cement) offering increased impermeability of the paste matrix through micro-silica reaction.

3.1.2 Aggregate Composition

Aggregates in the grading ranges of 0/16mm and 0/32mm were studied. For each range, a high-sand and a low-sand mixture were tested. For the 0/32mm range the sand (0/4mm) content was 45% and 32.5% respectively; for the 0/16mm grading range the sand content was 47% and 34.5%.

3.1.3 Steel Fibers

The steel fibers added to fresh-concrete mixtures indicated measured 35 kg/m^3 and 60mm in length.

3.1.4 Concrete Mixtures

The combination of the three aforementioned parameters produced a total of 18 mixtures of pumped concrete which were used to fabricate 18 wall elements (Nos. W1 through W18) measuring 570 x 600 x 200mm and aged according to paragraph 3.2.

Cement dosage for all mixtures was 330 kg/m^3. The W/C ratio was 0.46 for the high-sand mixtures and 0.43 for the low-sand. The dosage of a super-plasticizer varied between 0.40 and 0.80% of cement weight.

Table 1 Main parameters of concrete composition for wall elements W1 through W18

Type of cement	Aggregate					
	grain size 0/32 mm high-sand mixture		grain size 0/32 mm low-sand mixture		grain size 0/16 mm high-sand mixture	grain size 0/16 mm low-sand mixture
	without fibers	with fibers	without fibers	with fibers	without fibers	without fibers
CEM I 42,5	W1 W1C	W3	W7	W10	W13	W16
CEM II / A-L 32,5R	W2	W4	W8	W11	W14	W17
CEM II / A-D 52,5R	W5 W5C	W6	W9	W12	W15	W18

3.1.5 Pore Saturation

Because concrete can display various degrees of saturation due to humidity, groundwater volume and hydrostatic pressure on the tunnel, the influence of saturation level of the concrete matrix on air permeability was tested. Saturation levels of 0%, ca. 50% and 100% of the capillary-pore volume were predefined.

3.1.6 Concrete Curing

Curing influences hydration of the cement matrix and thereby affects air permeability. Due to the small tunnel diameter the use of a curing compound is a strong consideration. In order to determine the effects of a curing compound, two additional wall elements, W1C and W5C (see Table 1 for concrete composition) were prepared. These were treated with a curing compound immediately after removal of the formwork.

3.2 Fabrication and Aging of Samples

Fig. 1 Fabrication of a wall element

Permeability perpendicular to the tunnel shell is the critical issue with a tunnel under partial vacuum. Thus, samples for determining air permeability and porosity were taken and tested perpendicular to the direction of placing of the fresh concrete. A wall element was constructed for each mixture (Fig. 1) and test samples of 100mm diameter were taken from each wall element.

Concrete was placed at ca. 20°C. Aging of the cube samples, the wall elements, and the samples taken from the wall elements occurred at ca. 20°C and 70% relative humidity.

3.3 Concrete Properties and Testing Methods

3.3.1 Properties of Fresh Concrete

Consistency (measured as flow diameter) was determined in accordance with SIA Norm 162/1, Test No. 20. Samples from walls W1 through W6 were measured ten minutes after mixing the concrete and samples from walls W7 through W18 were measured at 10, 30, and 60 minutes after mixing. Specific gravity and air void content were measured in accordance with SIA Norm 162/1, Test Nos. 18 and 21, each 15 minutes after preparing the mixtures.

3.3.2 Properties of Hardened Concrete

Specific gravity and compressive strength were determined for each mixture in accordance with SIA Norm 162/1, Test No. 1 for 28-day concrete, using three test cubes measuring 150 x 150 x 150mm. Porosity of the hardened cement paste was determined under SIA Norm 162/1, Test No. 7, using six samples (100mm dia., average height H = 38mm) from each mixture.

Air permeability was measuring for each mixture using six samples (100mm dia., H = 50mm). After aging all samples for 90 days, the air permeability tests were carried out after subjecting samples to following different conditions:

- 7-day submersion under water (capillary pores 100% full with water)
- Capillary pores ca. 50% full with water (total and capillary-pore volume determined according to SIA Norm 162/1,Test No. 7)
- 14-day drying at 50°C (capillary pores containing no water, known from previous experience)

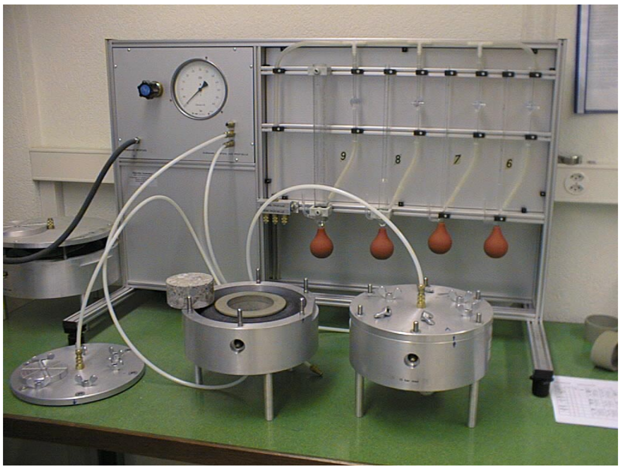


Fig. 2 Instrumentation used to determine air permeability

After determining the air permeability for the samples dried for 14 days at 50°C, drying was continued at 50°C to a total of ca. 70 days, and then further at 60°C for an additional 14 days. Air permeability was measured at the end of each of these periods. In addition, for samples W1 through W6 air permeability was measured after vacuum drying for three days at 60°C (samples completely dry). Because alteration of the pore structure of the concrete could not be ruled out initially, this method of sample preparation was not used from the beginning.

Investigating air permeability was performed using an established testing method developed by the Cement Industry Research Institute (VDZ) in Germany [3]. Each test was carried out at pressures of 1.5, 2.0 and 3.0 bars.

The following equation was used to calculate the coefficient of permeability k:

$$\mathbf{k = 2.02 * 10^{-10} * \frac{Q * L}{A} * \frac{2}{(p^2 - 1)} \qquad [m^2]}$$

where:

Q = Permeated air volume [$m^3.s^{-1}$]
A = Cross-sectional area of the sample [m^2]
L = Thickness of the sample [m]
p = Absolute pressure [bars] = testing pressure + atmospheric pressure

Further testing not described here was also performed to determine the following concrete properties and to determine the influence of a curing compound on these properties:

- Sulfate resistance of concrete with CEM I 32,5 containing 4% silica fume. Testing was performed using the expansion of the samples, the dynamic E-modulus (AlpTransit Method), and the TFB Method (multiple redundancy).
- Mechanical and shrinkage properties of concrete with CEM I 42,5 and CEM I 32,5 containing 4% silica fume.

4. Test Results

The most important test results for wall samples W1 through W12 follow. Evaluation of results for samples W13 through W18 is still in progress.

4.1 Consistency of Fresh Concrete

Flow diameters for the fresh concrete measured ten minutes after mixing ranged between 370mm and 480mm for samples W1 through W6. The range of measurements for concrete without steel fibers was significantly narrower (430mm to 460mm). Flow diameters measured ten minutes after mixing the concrete for wall elements W7 through W12 ranged between 330mm and 480mm (Fig. 3). Within this group, measurements for fiber-reinforced concrete ranged between 410mm and 480mm, and measurements for non-reinforced samples ranged between 330mm and 420mm. Corresponding values measured after 30 minutes ranged between 290mm and 470mm; those after 60 minutes ranged between 280mm and 400mm, corresponding as expected with the values measured at ten minutes.

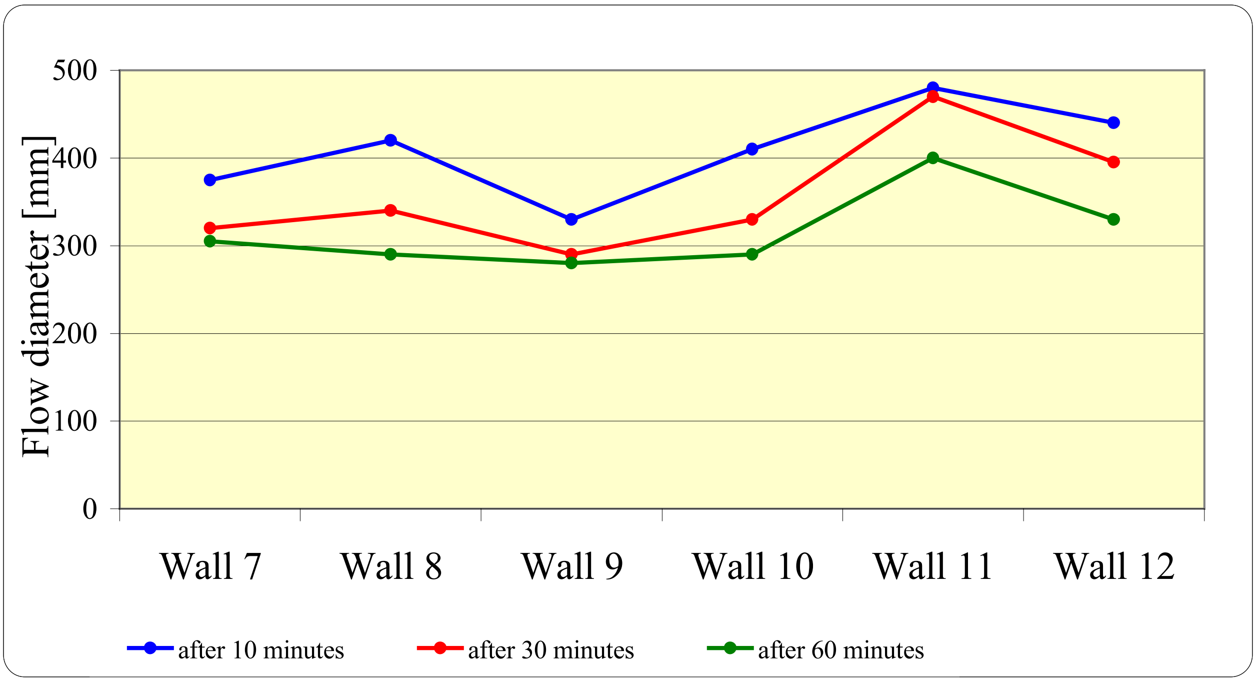


Fig. 3 Consistency of fresh concrete , wall 7 – wall 12

4.2 Compressive Strength

Compressive-strength values of the concrete mixtures tested present no problem for the intended application as a tunnel lining. 28-day test values of cubes ranged between 43 and 71 N/mm^2.

4.3 Porosity

Porosity values shown in Figs. 4 and 6 represent average values for the series of samples tested for the various walls.

4.4 Air Permeability

Air permeability was measured at three air pressures: 1.5, 2.0 and 3.0 bars (except for samples cured 7 days under water which were tested at 5 bars). Results show that air permeability decreases as air pressure increases. For this reason Figs. 5 and 7 indicate air permeability only at a testing pressure of 1.5 bars (worst case). The values shown are averages for the sample series tested, whereby extreme deviations were excluded. These were selected in accordance with known principles of statistics and based upon a 95% confidence level.

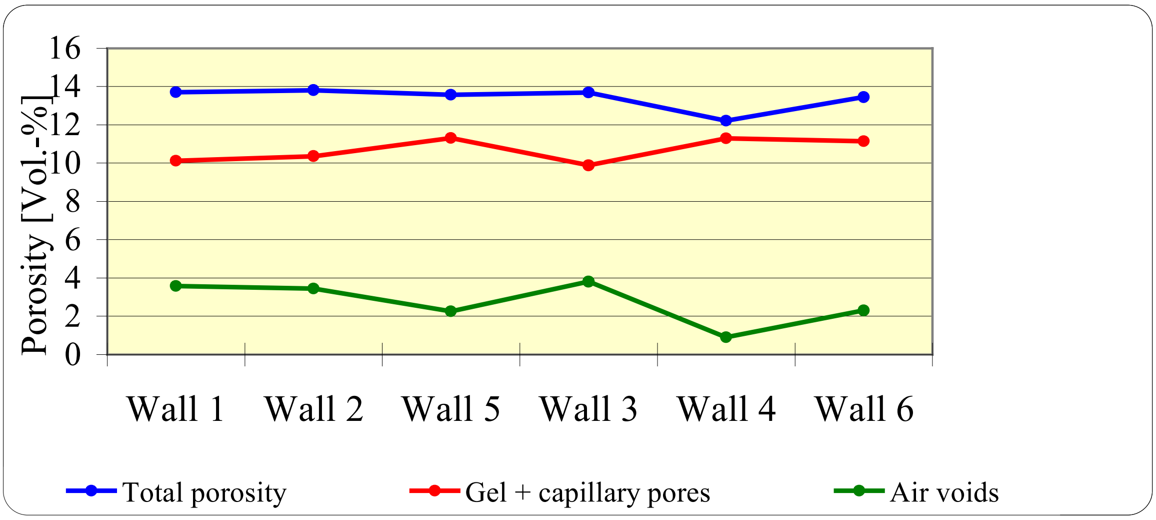
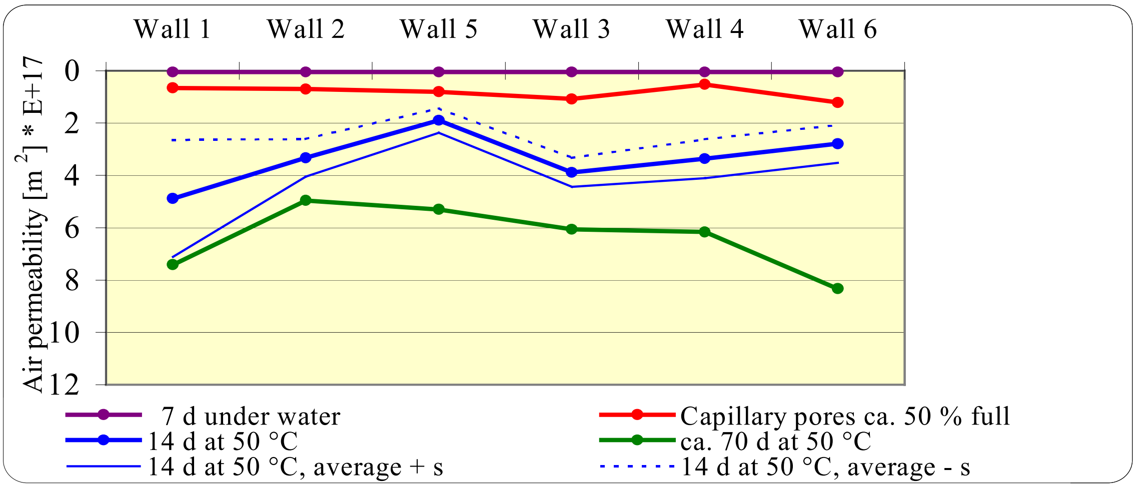


Fig. 4 Porosity of high-sand concrete mixtures, 0-32 mm, W/C ratio = 0.46, walls 3, 4 and 6 with steel fibers



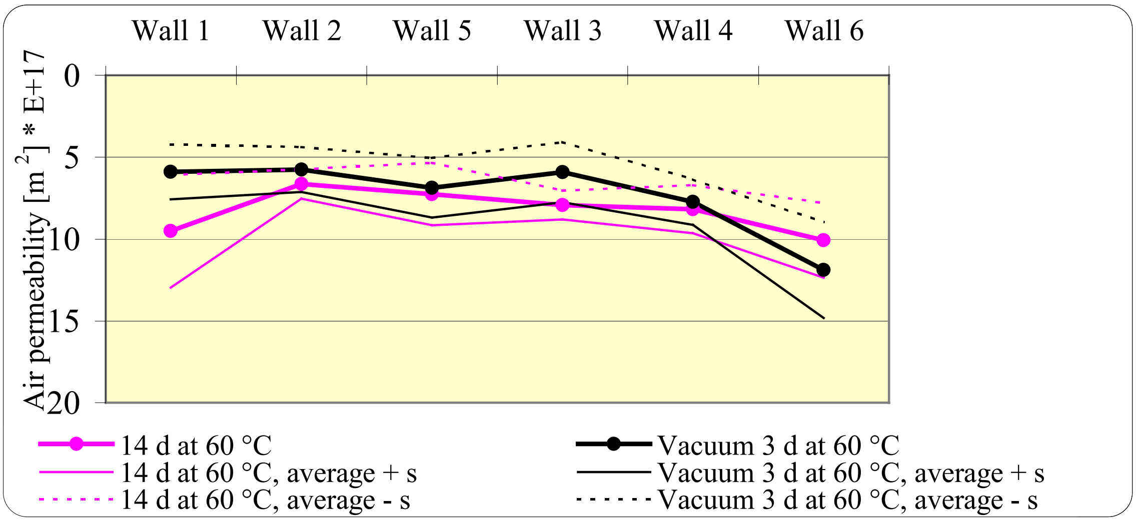


Fig. 5 Air permeability of high-sand concrete mixtures, 0-32 mm, W/C ratio = 0.46, walls 3, 4 and 6 with steel fibers, testing pressure = 1.5 bars

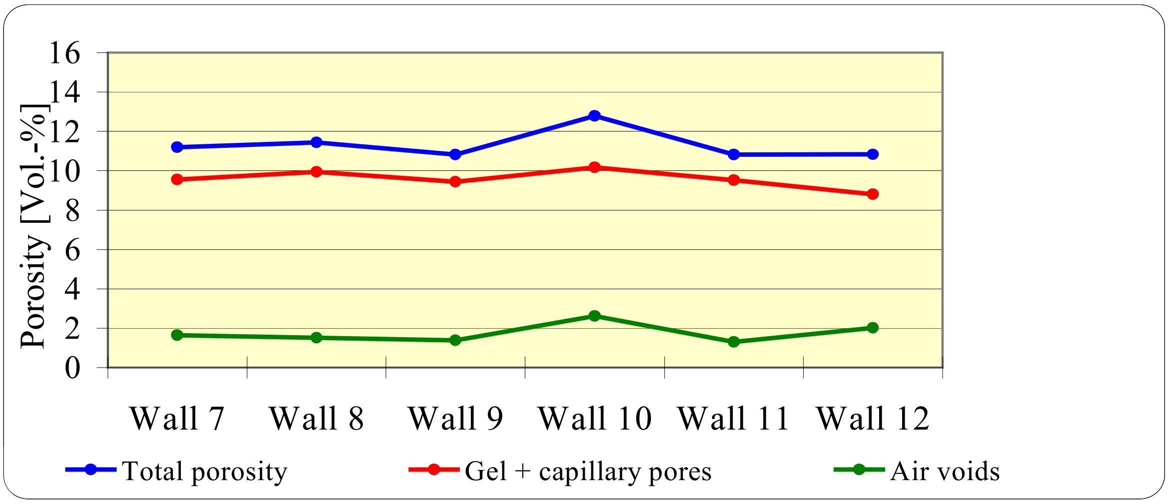


Fig. 6 Porosity of low-sand concrete mixtures, 0-32 mm, W/C ratio = 0.43, walls 10, 11 and 12 with steel fibers

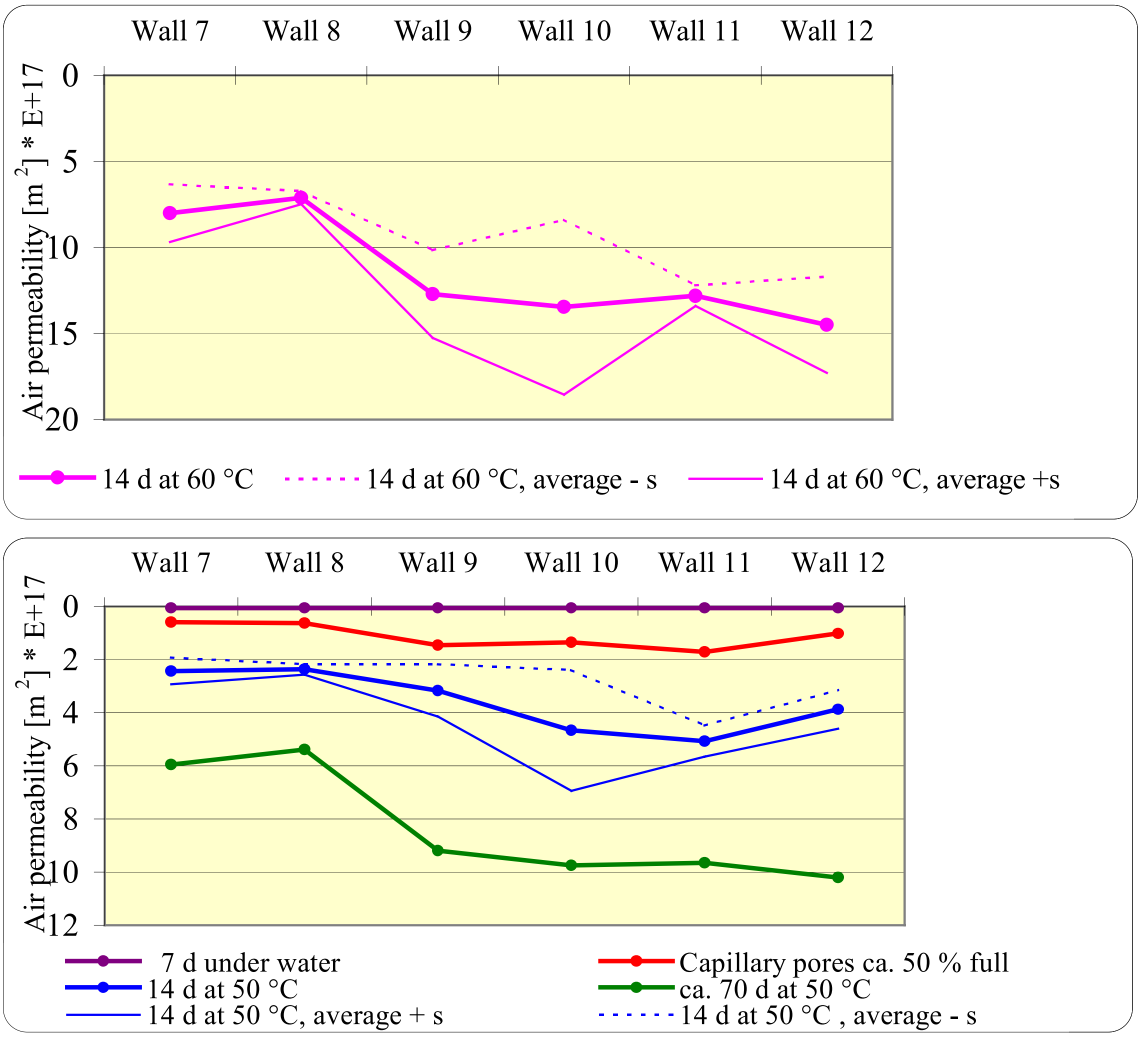


Fig. 7 Air permeability of low-sand concrete mixtures, 0-32 mm, W/C ratio = 0.43, walls 10, 11 and 12 with steel fibers, ***testing pressure = 1.5 bars***

5. Conclusions

- Under the test conditions, air permeability is higher at lower air pressures than at higher air pressures (see equation in paragraph 3.3.2). Measurement at lower air pressures therefore provides better test resolution.
- Complete drying of samples for determining air permeability through aging at 50°C or 60°C requires much time and is therefore unsuited for monitoring quality. With vacuum drying (3 days at 60°C) the capillary pores are drained much faster and more completely. Test results for vacuum-dried samples show a good correlation to results for samples cured for ca. 3 months at 50 to 60°C.
- Results show that degree of saturation has a crucial influence on air permeability. Completely vacuum-dried samples (walls W1 through W6) displayed air permeability measuring about ten times higher than for samples whose capillary pores were saturated to ca. 50%.
- The addition of steel fibers to high-sand mixtures (W/C = 0.46) produced no definite reduction in air permeability of the concrete, but produced an increase with low-sand mixtures (W/C = 0.43). Furthermore, in spite of the lower W/C ratio, air permeability is comparatively greater with low-sand steel-fiber concrete.
- Comparing the results for wall elements without steel fibers, high-sand (W1 and W2) and low-sand (W7 and W8) concrete mixtures using CEM I 42,5 or CEM II/A-L 32,5R, reveals roughly similar air permeability. Note here that the W/C ratio for samples W7 and W8 is lower than the rest (W/C = 0.43 compared to 0.46). This uniformity is not recognizable for wall elements W5 (high sand) and W9 (low sand), both mixed using cement type CEM II/A-D 52,5R. Apparently the stiffer concrete consistency of sample W9 is a decisive factor (flow diameter of 330mm measured ten minutes after mixing concrete).

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