EXPERIMENTAL RESEARCH FOR THE LINERS OF THE SWISSMETRO TUNNELS

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Abstract

Swissmetro is an innovative concept for a very high-speed underground passenger transportation system. One of its features is that the small diameter tunnels are under permanent partial vacuum. This paper presents the results of an experimental research program conducted on the behavior of concrete liners subjected to service conditions of Swissmetro tunnels. In one series of tests air flow was measured through cracked concrete subjected to a differential of air pressure. In a second series of tests, concrete elements were subjected to a large number of cycles of pressure variations under partial vacuum conditions to investigate possible degradation of the concrete surface properties.

Background

Swissmetro is an innovative concept for a very high-speed Maglev type underground passenger transportation system. One of its features is that the small diameter tunnels are under permanent partial vacuum. The partial vacuum improves the aerodynamic conditions for the moving vehicles in the tunnels in order to reduce the required tunnel diameter. Because of the innovative character of the project, a detailed feasibility study was conducted which covers the aerodynamic, electromechanical, economical and safety issues of the project. Studies were also conducted regarding the configuration and construction of the tunnels. The choice of the tunnel liner construction is very important for the economical feasibility of the project, as well as for the durability and reliability of the system. A classic "sandwich construction" was selected for further investigation because it is a technically and economically proven solution. It consists of an exterior liner of precast reinforced concrete segments, a cast-in-place interior liner, and a flexible waterproofing membrane "sandwiched" between the interior and exterior liners.

The liner of the Swissmetro tunnels will be subjected to unusual service conditions. Aside from the usual loads acting on the structure of classic railway tunnels, it will be subjected to permanent underpressure due to partial vacuum. It will also be subjected to repeated air pressure and temperature variations at the passage of the vehicles [Mossi and Bourquin 98]. The design of the interior liners therewith raises the following unusual questions :

I. What is the long-term behavior of a reinforced concrete interior liner exposed to repeated variations of pressure and temperature in permanent partial vacuum atmosphere.
II. What is the contribution of a reinforced concrete interior liner to the tunnel "air proofing".

A research program was developed to provide a basis on which to develop answers to these two questions. This paper presents this program and its main findings.

Experimental Program

The experimental program conducted at the Swiss Federal Institute of Technology in Lausanne (EPFL) is described in [Fellay and Badoux 2001]. Five large reinforced concrete specimens were built and subjected to the following two series of tests:

I. Pressure variation tests

The objective of these tests was the investigation of possible degradation of a concrete surface subjected to partial vacuum and numerous rapid pressure variation cycles.

II. Air infiltration tests

The objective of these tests was to measure the flow of air through cracked reinforced concrete specimen under varying pressure differential and varying crack width.

(These tests were complemented with a campaign of material tests conducted at the TFB to assess the influence of the concrete mix design on the permeability to gas of small uncracked concrete samples. The campaign was conducted by the Swiss Center for Research and Consulting on Cement and Concrete (TFB) and is reported in [Badawy and Honegger 00, 02]).

Test specimens

The five test specimens are reinforced concrete plate members 3.50 m long and 1.20 m high (Figure 1). The air tests are conducted on the specimen middle section which is 0.25 m thick. The longitudinal reinforcement consists of two layers of 12 mm diameter bars spaced 240 mm on center with concrete cover of 30 mm. The stirrups diameter is 10 mm and spacing is 300 mm. For practical reasons, the specimens end blocks are made of ready-mix concrete.

The concrete mix for the middle section of the test specimen is described in Table 1. The first mix is a ready mix concrete. The next four were selected on the basis of the results of the TFB's "material tests" mentioned above. They are characterized by a relatively low cement content in order to limit thermal shrinkage. Superplasticizers are used to obtain adequate workability for pumping while maintaining a low water cement ratio. The second mix is a common structural concrete. The third one is classic tunnel concrete with a filler added coarse cement. The fourth one is identical to the third except for the inclusion of steel fibers. In the fourth one a cement with silica fume was used. Specimens T1 – T4 were used for both families of tests.

Table 1: Concrete mix proportions of the five specimen

Member	**Cement (content kg/m^3)**	**Admixture**	**Aggregate**	**W/C**	**Plasticizer**
T0-CI4*	CEM I 42.5 (350)	None	0/32 (mm)	0.48	1.40 %
T1-CI4	CEM I 42.5 (330)	None	0/32 (mm)	0.46	0.50 %
T2-CII3	CEM II/A-L 32.5R (330)	None	0/32 (mm)	0.46	0.50 %
T3-CII3-F	CEM II/A-L 32.5R (330)	steel fibers (35 kg/m^3)	0/32 (mm)	0.46	0.70 %
T4-CI3	CEM I 32.5 (330) with 5 % silica fume	None	0/32 (mm)	0.46	0.50 %

* Specimen made of ready-mixed concrete

Test set-up for the air infiltration tests

The test set-up used for the air infiltration test is shown in Figure 1. Two air chambers were installed, one on each face of the test specimen middle section. The upstream “atmospheric” chamber was at atmospheric pressure. A vacuum pump (capacity of 400 m^3/h) could create underpressure (minimum around 100 mbar) in the downstream chamber, which is called the “vacuum chamber”.

They chambers were designed and installed to measure air flow through a 1 m^2 test area of the plate element. Outside of the test area, the specimens were coated with a brush–applied waterproofing coating to prevent secondary sources of air leakage. An O-ring, set in a groove in the edges of the metal chambers provided air-proofing between the chambers and the test elements surface. The “atmospheric chamber” was connected upstream to six float flow meters with a reading range of 0.80 to 80,000 Nl/h (1 Nl/h = 1 litre at standard pressure and temperature per hour).

After the two chambers were bolted on the test specimen, they were placed in the tension testing bench. High precision hydraulic jacks were used to impose tensile deformations to the specimen. The controlled strain is increased in increments of 0.1 ‰. When the tensile resistance of the concrete was reached, a single through crack formed in the test area. Further strain increases mostly widened the crack. The strain in the test area and the crack width is monitored at every step of the test through an extensive network of gauges. The vacuum pump was activated and the air flowing through the crack was measured for different levels of pressure differential. This procedure was repeated for each strain increment until a crack width was reached for which the vacuum pump could not create the target pressure differential.

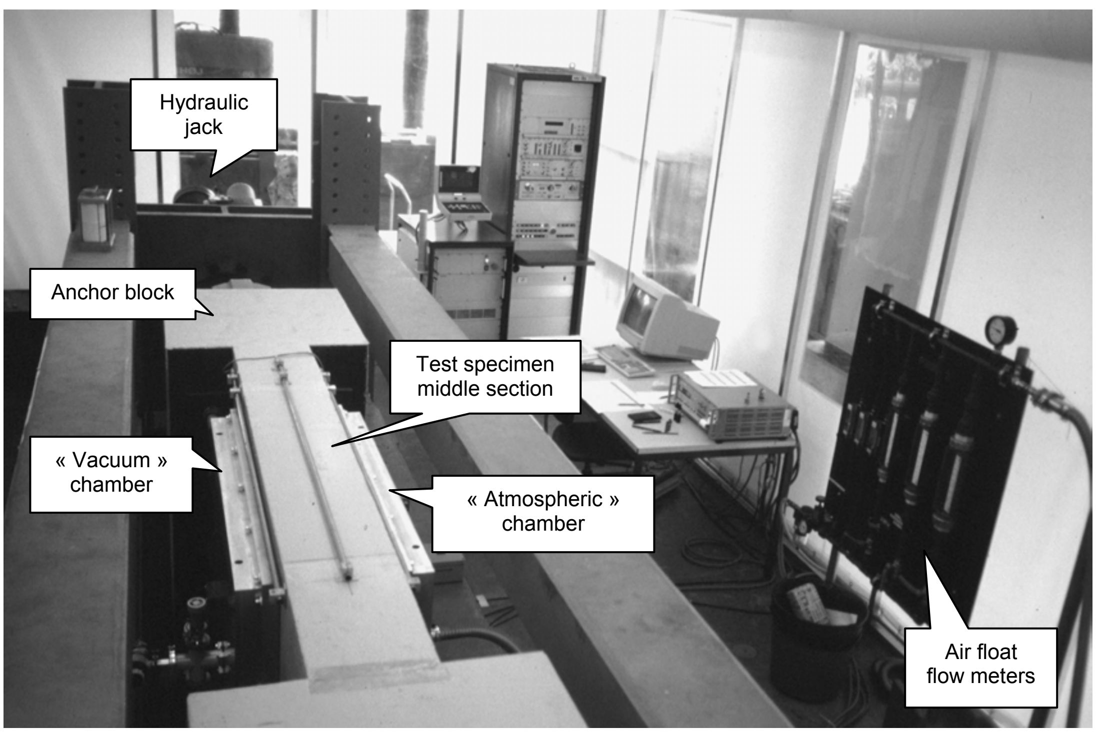

Figure 1: Test specimen T0 in the testing bench

Test set-up for the pressure variation tests

For practical reasons, the pressure variation tests were conducted in the test set-up of Figure 1 after the air infiltration tests. Before the pressure variation test, the specimens were repaired to seal the cracks in the test area. No tensile strain was applied to the specimen for these tests. The desired rapid pressure variation cycles were generated in the “vacuum chamber” by the vacuum pump. The pump and pressure release gauges were piloted by an ad-hoc automated control system.

Two amplitudes of pressure variations were applied in the “vacuum chamber”. The first amplitude is obtained by varying the pressure between 84 and 116 mbar (32 mbar amplitude). These pressure parameters were selected on the basis of studies conducted for the Swissmetro research project [Mossi and Bourquin 98] [Jufer 99]. The second amplitude is obtained by varying the pressure between 200 and 750 mbar (550 mbar amplitude). This is a very large amplitude designed to accentuate the possible concrete surface degradation mechanisms. The pressure variation rate was limited by the capacity of the vacuum producing pump: it took between 1 and 2 seconds to go through the smaller amplitude cycles and about 10 seconds for the higher amplitude cycles (most of the time spent lowering the pressure). These rates of variation are significantly slower than what is expected in Swissmetro tunnels.

Pressure variation tests

The objective of these tests was to detect a possible mechanical degradation of the surface of the five concrete specimens when subjected to repeated variations of the air pressure in partial vacuum conditions. The first 220’000 cycles had an amplitude of 32 mbar, and the next 60’000 cycles had an amplitude of 550 mbar. Specimen T4 underwent an additional 700’000 cycles of large amplitude variation cycles for a total of about 1 million cycles.

Several investigative techniques were used to monitor different concrete properties before and after the application of the pressure variation cycles. The following investigative techniques are presented below:

- Visual observations (dust, scaling, cracks …)
- Microscopic examination of thin concrete samples (concrete quality and microstructure, development of micro cracks)
- Schmidt hammer (concrete strength)
- Torrent permeameter measurements (concrete surface permeability)
- Ultrasound measurements (concrete modulus of elasticity)
- Acoustic emissions (development of micro cracks)

The results obtained with the different investigative techniques are summarized below. More detail can be found in [Fellay and Badoux 2001]. In order to account for the possible influence of time on the measured properties, the measurements were mostly made on both the test surface (in the vacuum chamber) and a reference surface (in the atmospheric pressure chamber). Generally, the determination of the absolute value of a parameter (e.g. compressive strength) is of secondary importance, the goal being to follow vaiations, i.e. trends, of the measured parameters. The specimen were aged 150 to 220 days at the start of the pressure variation tests.

Visual observations

Visual observations of the test surface after the application of the pressure variation cycles did not reveal indications of concrete surface degradation.

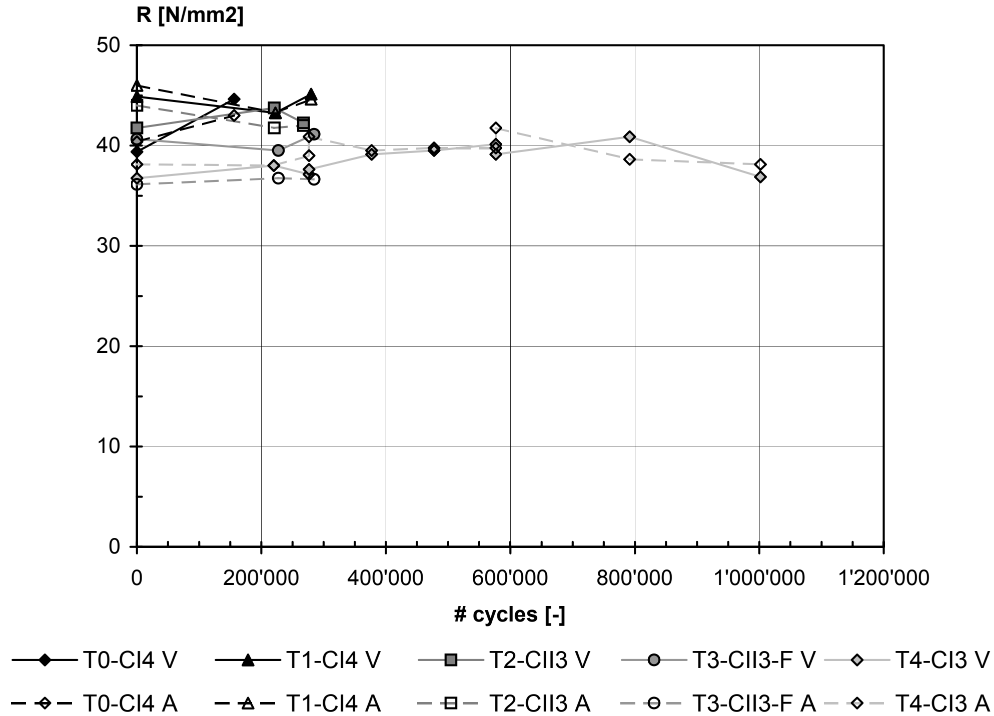

Figure 2: Surface concrete strength (Swiss hammer measurements)
(A: reference surface, V: test surface)

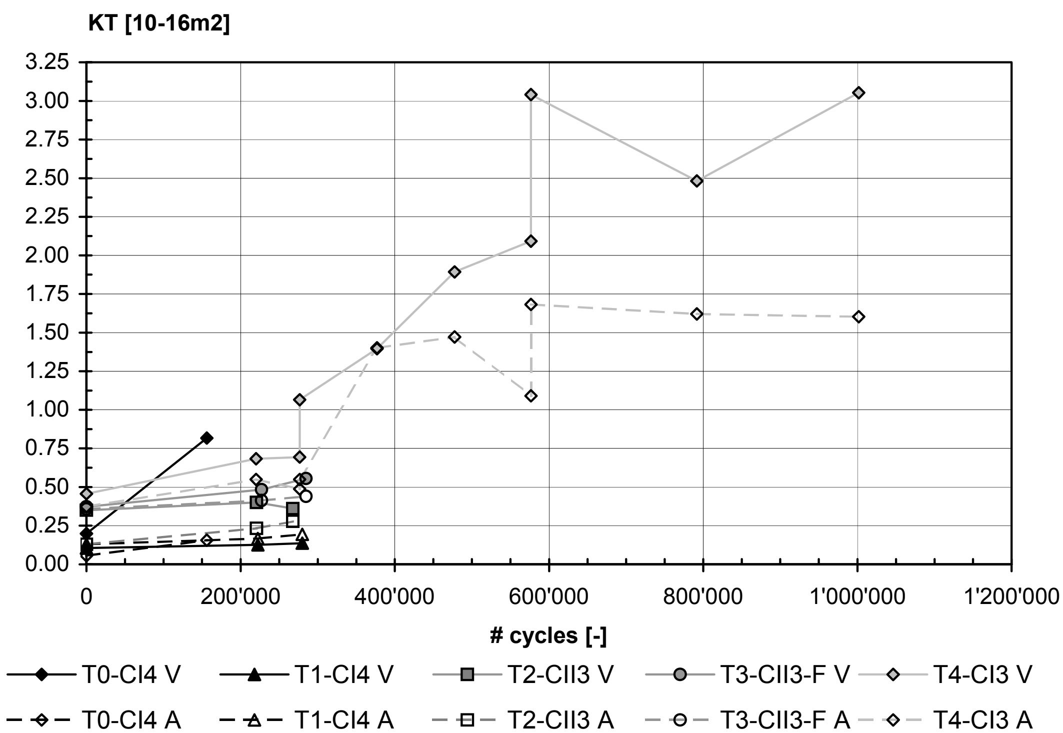

Figure 3: Air permeability measurements on the concrete surface (Torrent permeater)
(A: reference surface, V: test surface)

Microscopic examination of thin concrete samples

Thin surface concrete samples taken from specimen T4 after the pressure variation cycle application were examined under polarized light by the TFB laboratory. The comparison of the samples from the test surface with those of the reference surface indicated no significant differences in the concrete microstructure. Levels of microcracks and porosity were generally low and the observed microstructure indicated a concrete of average quality.

Schmidt hammermeasurements

Schmidt hammer measurements were conducted to monitor the evolution of the compressive strength of the concrete surface. Such measurements have low reliability for the determination of the absolute value of the concrete compression strength. However, if used systematically and with sufficient number of measurements, they give valuable indications for comparison and trends. Figure 2 shows that the measued compressive strengths were generally stable and that they evolve in similar ways for the reference and test surfaces.

Torrent permeameter measurements

Measurements were conducted on the concrete surface with a Torrent permeameter device (Figure 3). There is considerable scatter of initial measurement values because concrete porosity is very variable from one specimen to another and because of the measurement inaccuracies. As expected, the permeability increases because of the concrete drying between the beginning and end of the test. The permeability increase is generally higher in the test surface then on the reference surface. This could indicate a surface degradation, but could also result from accelerated drying of the surface in the vacuum chamber which is subjected to pressure variations (air flow).

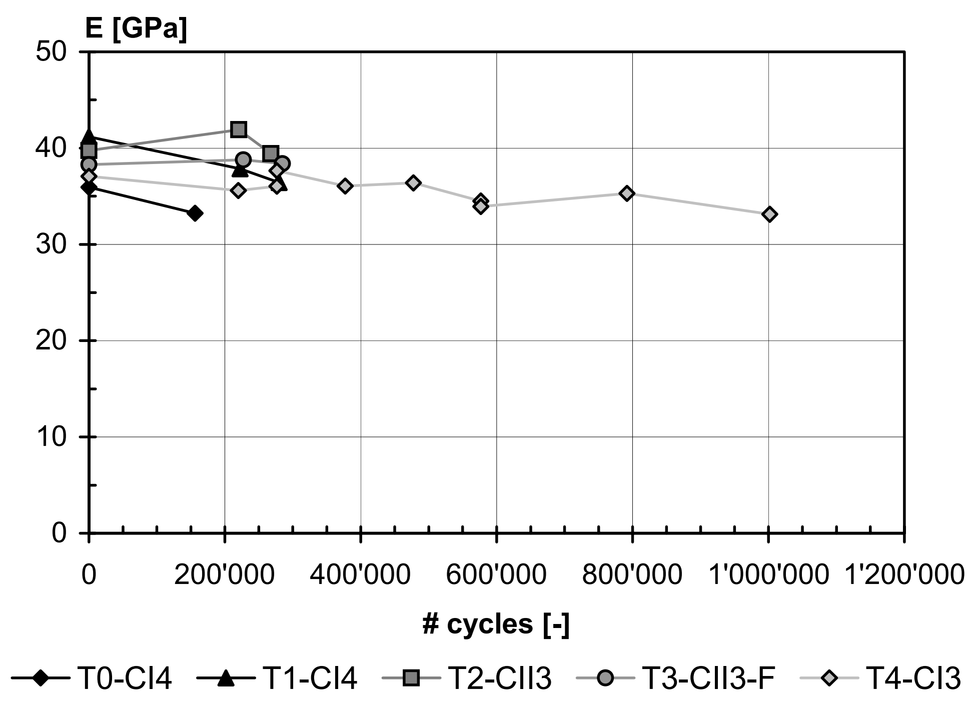

Figure 4: Ultrasound measurements of concrete modulus of elasticity (secant) for 5 specimens

Ultrasound measurements

The ultrasound measurements can be used to estimate the modulus of elasticity of the concrete. The test results are presented in Figure 4. The value of the measurement is in the evolution of the modulus with the application of the pressure cycles (rather then absolute value of the modulus). There is a scatter of trends, but the general indication is of stable to slightly decreasing values of the E-modulus. This could be indicative of a surface degradation since a slightly increasing E-modulus would be expected. An alternative cause could be drying shrinkage and resulting internal stresses which can lead to cracking and therefore to a reduction of the E-modulus. (It must be noted that the value of these measurements for spotting surface degradation is limited because the measured E-modulus is an average value for the entire thickness of the concrete elements, rather then for the concrete cover area).

Acoustic emission

Acoustic emission measurements were conducted on specimen T3 during the application of the pressure variation cycles. The goal was to track the initiation and growth of possible concrete cracks. No acoustic event pattern typical of crack formation was recorded. Acoustic events were recorded at each cycle of pressure increase. These events were very regular and are likely linked to background noise (due to the air pumping) rather the formation of concrete cracks.

Interpretation of the results of the pressure variation tests

The results of the measurements with a number of investigative techniques showed no clear evidence of a significant degradation of the mechanical properties of the concrete surface. This also applies to specimen T4 which was subjected to large number (1 million) of large pressure variations in partial vacuum.

Air Infiltration Tests

Air infiltration tests were conducted on plate test specimens T1 to T4. The air flow through the test area of the plates was measured for three levels of underpressure in the vacuum chamber, i.e. for three levels of pressure differential. The crack width was increased incrementally. The flow was measured for crack widths between 0.1 and 0.9 mm .

The test results and their use for the development of a new expression for the determination of the friction coefficient for the air flow through a concrete crack are presented at this conference in a companion paper [Badoux 02].

Conclusion

The experimental tests produced quantitative results which can be used in the design of reinforced concrete liner systems for Swissmetro type tunnels. Findings include the following:

- Numerous rapid variations of the air pressure under partial vacuum conditions does not seem to negatively affect the concrete. Visual observations and microscopic examinations, as well as measurements with Schmidt hammer, torrent permeameter, ultrasound equipment and acoustic emission equipment, did not give clear indication of surface degradation. Cementitious liners seem well adapted for the unusual service conditions of the Swissmetro tunnels.
- The air infiltration measurements on large scale specimen gave good results. The relationship between air flow and crack width was measured accurately for a wide range of crack width and for a range of very low pressure differentials. A new expression for the friction coefficient for air flow in a concrete crack was developed [Badoux 2002]. The determination of an acceptable level of cracking for reinforced concrete liners on the basis of target air leakage rates is possible.

Outlook

The industrial development of the Swissmetro concept will require extensive additional research. Regarding the tunnel liners, it will be necessary to conduct tests on full scale pilot sections. The objective will be to test the system performance and durability of the liners in realistic service conditions, including more abrupt pressure variations and more realistic temperature conditions. Several types of concrete liners should be tested, including innovative solutions using high performance cementitous materials (such as reactive powder concretes). Such solutions might make possible significant reductions of liner thickness and associated tunnel excavation volumes.

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