Justification of the Reduction of kT Test's Maximum Duration

1. Linearity of ΔP_{ieff} vs. $t^{½} - t_o^{½}$ Plot

The formula used by the *PermeaTORR* to calculate kT is (Eq. 3.1 of the User Manual):

$$kT = \left(\frac{V_c}{A}\right)^2 \frac{\mu}{2\,\varepsilon\,P_a} \left(\frac{\ln \dfrac{P_a + \Delta P_{ieff}(t_f)}{P_a - \Delta P_{ieff}(t_f)}}{\sqrt{t_f} - \sqrt{t_o}} \right)^2 \qquad (1)$$

- kT: coefficient of air-permeability (m^2)
- V_c : volume of inner cell system (m^3)
- A : cross-sectional area of inner cell (m^2)
- μ : viscosity of air ($= 2.0\ 10^{-5}$ $N.s/m^2$)
- ε : estimated porosity of the covercrete (= 0.15)
- P_a : atmospheric pressure (N/m^2)
- ΔP_{ieff}: effective pressure raise in the inner cell at the end of the test (N/m^2)
- t_f : time (s) at the end of the test
- t_o : time (s) at the beginning of the test (= 60 s)

The scheme of the test is illustrated in Fig. 1

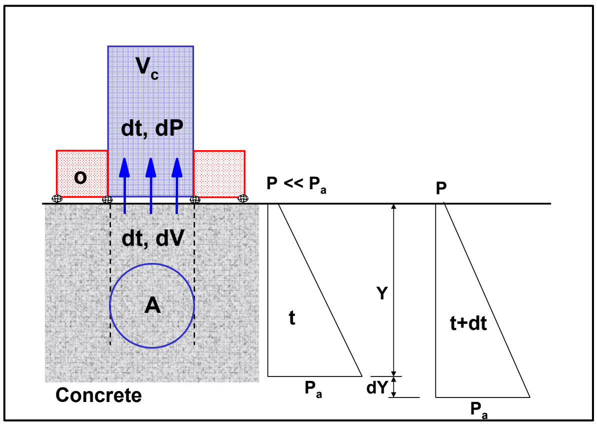

Fig. 1 – Sketch of the test and principles of the model

From (1) we can write, for a generic time t during the test (with $t > t_o$):

$$\ln [(P_a + \Delta P_{ieff}) / (P_a - \Delta P_{ieff})] = C * (\sqrt{t} - \sqrt{t_o}) \qquad (2)$$

where

$$C = P_a^{1/2} * (A / Vc) * (kT * 2 * \varepsilon / \mu)^{1/2} \qquad (3)$$

If, during the progress of the test, the permeability kT, the porosity ε and the viscosity of the air μ across the volume of the cylinder of concrete (area A and variable depth Y in Fig. 1) remain invariable, C is a constant.

Rewriting (2):

$$\ln [(1+\Delta P_{ieff} /P_a) / (1-\Delta P_{ieff} /P_a)] = C * (\sqrt{t} - \sqrt{t_o}) \qquad (4)$$

or

$$\ln (1+\Delta P_{ieff} /P_a) - \ln (1-\Delta P_{ieff} /P_a) = C * (\sqrt{t} - \sqrt{t_o}) \qquad (5)$$

The Taylor Series for ln (1+x) is:

$$\ln(1+x) = \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} x^n \quad \text{para} \ |x| < 1$$

$$\ln (1 + x) = x - x^2/2 + x^3/3 - x^4/4 + ... \qquad (7)$$

$$\ln (1 - x) = - x - x^2/2 - x^3/3 - x^4/4 + ... \qquad (8)$$

$$\ln (1 + x) - \ln (1 - x) = 2 * x + 0 + 2 * x^3/3 + 0 + ... \qquad (9)$$

therefore,

$$\ln (1+\Delta P_{ieff} /P_a) - \ln (1-\Delta P_{ieff} /P_a) = 2 * \Delta P_{ieff} /P_a + 2/3 * (\Delta P_{ieff} /P_a)^3 + ... \qquad (10)$$

but $\Delta P_{ieff} << P_a \rightarrow (\Delta P_{ieff} /P_a)^3 \approx 0$

then

$\ln(1+\Delta P_{ieff}/P_a) - \ln(1-\Delta P_{ieff}/P_a) = 2 * \Delta P_{ieff}/P_a$ (11)

Replacing (11) into first member of (5)

$\Delta P_{ieff} = C * P_a / 2 * (\sqrt{t} - \sqrt{t_o})$ (12)

Or, using (3)

$\Delta P_{ieff} = P_a^{½} * (A / Vc) * (kT * 2 * \varepsilon / \mu)^{½} * P_a / 2 * (\sqrt{t} - \sqrt{t_o})$ (13)

Therefore, if kT, ε and μ are constant, the plot of ΔP_{ieff} as function of $t^{½} - t_o^{½}$ should be linear, with a slope S equal to:

$$S = P_a^{3/2} * (A / V_c) * (kT * \varepsilon / 2\ \mu)^{½}$$ (14)

This is the basis for the solid lines displayed on the chart ΔP_{ieff} vs. $t^{½} - t_o^{½}$, during the test (Fig. 2).

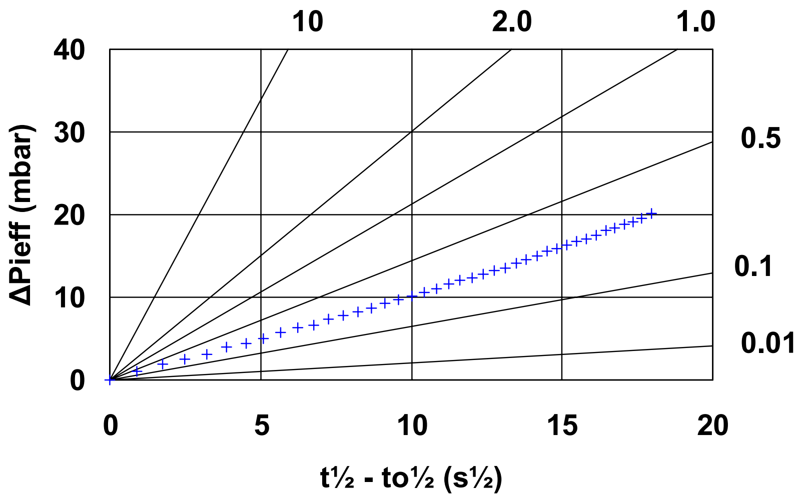

Fig. 2 – Plot ΔP_{ieff} vs. $t^{½} - t_o^{½}$ on the screen of the on the screen of the *PermeaTORR*

In fact the plot is displayed by the *PermeaTORR* to allow the user to check whether the evolution of the test is normal (linear plot) and to guess the approximate value of kT before the end of the test.

A non-linear plot indicates changes in the porosity or permeability with depth, an uneven distribution of moisture and/or temperature (affecting μ), or the presence of surface coatings, microcracks, etc.

If the plot is perfectly linear, the kT value calculated at any time of the test will be identical. This opens the way to reducing the testing time from a maximum of 12 minutes to 6 minutes.

Thanks to the very good control of the test and to the fact that the *PermeaTORR* works at pressures above the water vapour pressure, the plot ΔP_{ieff} vs. $t^{½} - t_o^{½}$ is usually quasi-linear, meaning that there should not be a significant difference between the kT value calculated at 12 min and that calculated at 6 min (called kT6).

2. Relation between kT6 and kT

Over 100 test results were analyzed in order to ascertain what changes in the coefficient of air-permeability may occur if *PermeaTORR*'s test would be shortened from 720 s (12 min) to 360 s (6 min).

The results include laboratory and site test data obtained with one *PermeaTORR* (Instrument 1) and laboratory results obtained with another *PermeaTORR* (Instrument 2). In both cases, the tests involved at least three different operators.

The results were analyzed from the files exported from both instruments, as follows:

- Only test data where the duration of the test exceeded 360 s were considered (the others will not be changed). This corresponds roughly to concretes with kT < 1.0 10^{-16} m².
- For those tests, the coefficient of air-permeability kT was calculated with Eq. 1, using the ΔP_{ieff} measured at the very end of the test (i.e. t_f between 360 and 720 s) and the value kT6 was calculated using the ΔP_{ieff} measured after 6 minutes of initiating the test (i.e. t_f = 360 s).

Tests performed with Instrument 1

Total number of tests = 109, performed between March and June 2009.

Number of tests with t_f > 360 s = 83 (76%)

The 83 test results considered correspond to:

- Tests on laboratory specimens (8)
- Tests on Dutch panels stored outdoors and tested indoors (24)
- Tests on site, on two occasions, on the walls of a Swiss tunnel (22 + 11 tests)
- Tests on site, on concrete pavement slabs in Switzerland (20 tests)

Tests performed with Instrument 2

Total number of tests = 63, performed between September and October 2009.

Number of tests with t_f > 360 s = 20 (32 %) [1]

The 20 test results considered correspond all to tests done on laboratory specimens.

[1] The low proportion of tests with t_f > 360 s is explained by the fact that this instrument was predominantly used for demonstration purposes. Hence, in order to limit the duration of the demonstration, a large proportion of concretes of high permeability were tested.

Fig. 3 presents a chart where the 103 calculated values of kT6 and kT are plotted in a log-log scale. The points signalled with arrows correspond to the results showing a maximum and a minimum kT6/kT ratio; i.e. those that depart more significantly from equality.

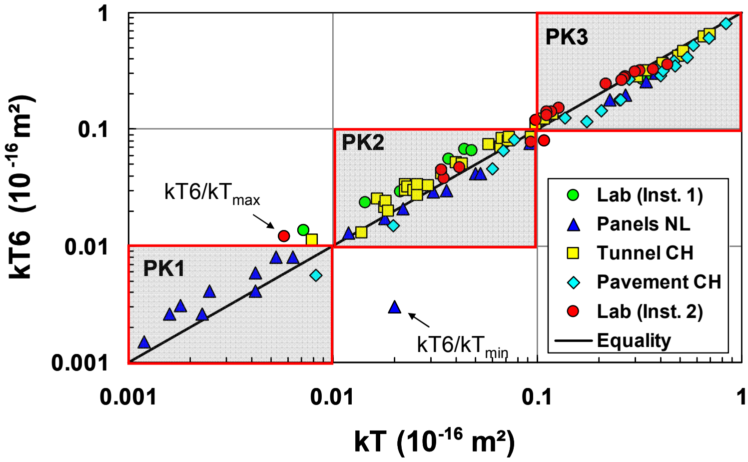

Fig. 3 – Relation between kT6 and kT for the 103 results analyzed

Fig. 3 shows that the results tend to align along the Equality line, i.e. that there are not significant differences between kT6 and kT. It seems that, for kT values below 0.01 10^{-16} m², the values of kT6 tend to be higher than those of kT, whilst the opposite seems to be true for kT values above 0.1 10^{-16} m². This has to do with the shape of the ΔP_{ieff} vs. $t^{½} - t_o^{½}$ plot. If it is linear, kT6 would be equal to kT; if it has a negative curvature is kT6 > kT and if it has a positive curvature is kT6 < kT. Fig. 3 shows that in only 7 out of 103 cases, the permeability class PK attributed by kT6 differs from that attributed by kT.

Fig. 4 presents the ΔP_{ieff} vs. $t^{½} - t_o^{½}$ plots for three cases. One plot corresponds to the case where the maximum kT6/kT= 2.0 was recorded (red circles); the second to that where the minimum of kT6/kT= 0.15 was recorded (blue triangles) and the third to a case where a value close to the average (kT6/kT= 1.08) was recorded (yellow squares).

The plot for the minimum ratio is quite unusual, as is the kT6/kT ratio (see Figs. 4 and 3) and has to be attributed to some special conditions of the test.

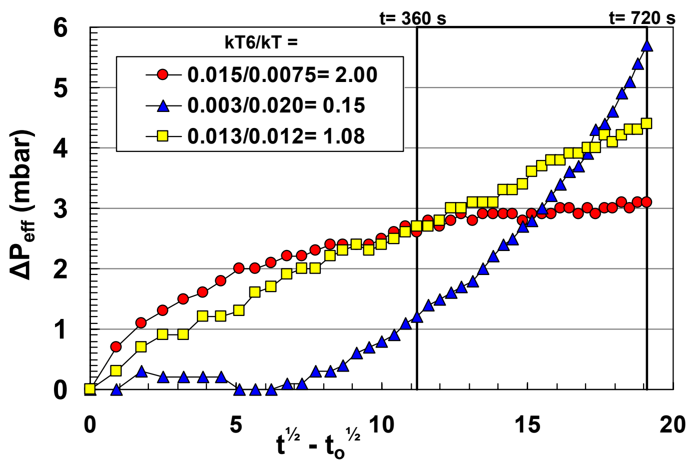

Fig. 4 - Pressure evolution of samples with extreme and average values of kT6/kT

The statistical distribution of values of the ratio kT6/kT is presented in Fig. 5; the average value for the 103 tests was kT6/kT = 1.07.

Fig. 5 – Histogram of the ratio kT6/kT for the 103 test results analyzed

It can be seen that the distribution is similar for both instruments and that over 80% of the results fall within a kT6/kT range of 0.75 – 1.50.

The shortening of the test will have an effect, albeit moderate, on the penetration L of the vacuum front, calculated with the following equation:

As the time will be halved and kT will remain basically the same, the value of L6 (t_f=360 s) will be reduced by a factor of $2^{-½}$ with respect to that determined for the maximum extension of the test (t_f=720 s).

3. Conclusion

The conclusion of this study is that it is feasible to shorten the test duration of the PermeaTORR, from 12 to 6 minutes, without affecting significantly the accuracy with which the coefficient of air-permeability of concrete is measured. In particular:

- The change will only affect tests for which kT < 1.0 10-16 m², i.e. concretes with moderate, low and very low permeability (PK Classes 1 to 3). The results of the more critical classes PK 4 and 5 (kT > 1.0 10-16 m²) will not be changed since, for these concretes, tf < 360 s
- The results that will be changed will, in average, be increased by less than 10%
- More than 80% of the results that will be changed will be affected by a factor within the range 0.75 – 1.50. This is acceptable, given the very wide range of kT values found in practice, spanning 5 orders of magnitude
- The penetration of the test will be reduced to 70% of that reached after 720 s, which is reasonable. A further reduction of t_f below 360 s is not advisable as the test may become “too superficial”

- The proposed modification of limiting the test duration to 6 min will almost double the productivity of the instrument, which clearly justifies the change proposed
- The acceptance of the kT6 value is always at the discretion of the user. In case of evident departure from linearity of the plot ΔP_{ieff} vs. $t^{½} - t_o^{½}$ plot or a wish to continue the test till its natural end, the test may be allowed to run beyond the 6 minutes

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