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Interpretation of Pressure Cells in Sprayed Concrete Tunnel Linings

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ABSTRACT: There is a general lack of confidence amongst tunnel engineers in the U.K. in the use of pressure cells in sprayed concrete lined (SCL) tunnels. Installation defects, the complex material behaviour of sprayed concrete, temperature and shrinkage all complicate the task of interpreting pressure cell data. Typically the recorded data appear highly scattered and so are perceived to be of poor quality. At the same time, because of the dearth of other estimates of the stresses in linings, there is some uncertainty about the actual loads supported by tunnel linings, which impacts negatively on design. In this paper, using real data from a recent project, the interpretation of recorded pressures is discussed.

1 INTRODUCTION

As part of the validation of a new sprayed concrete lining (SCL) construction method termed Lasershell™, monitoring was installed for the first SCL tunnel at the Heathrow Terminal 5 works. One aspect of this monitoring programme was the installation of 2 arrays of pressure cells. Each array consisted of 5 tangential (shotcrete) pressure cells and 5 radial (earth pressure) cells.

There are various factors affecting recorded pressures, which do not affect the stresses in the lining. These were identified by Clayton, van der Berg, Heymann, Bica & Hope (2002). Corrections to the recorded pressure in the cell need to be made to obtain the stress in the shotcrete. Offsets in the readings due to crimping must be removed. Temperature variations will affect the vibrating wire sensor, and corrections for this are usually provided by the supplier. In addition, the pressure cell-shotcrete system is highly sensitive to temperature changes. Unrestrained shrinkage will increase the pressure in the cell. Finally there is the cell action factor (CAF) of the pressure cell-shotcrete system, the ratio of applied stress to cell pressure. Previous studies using an elastic solution by Coutinho (1953), and numerical modelling and laboratory studies by Clayton, van der Berg, Heymann, Bica & Hope (2002) have shown that the CAF of typical shotcrete pressure cells should be close to 1.0.

2 TEST PANEL

In addition to the 2 arrays, a test panel 1.0m x 1.0m x 0.3m containing 2 tangential cells was sprayed in the tunnel and later removed to the laboratory at the University of Southampton for testing. This provided the opportunity to observe changes in pressure in an unloaded panel due to temperature and shrinkage. The results are shown in Figure 1 and Figure 2.

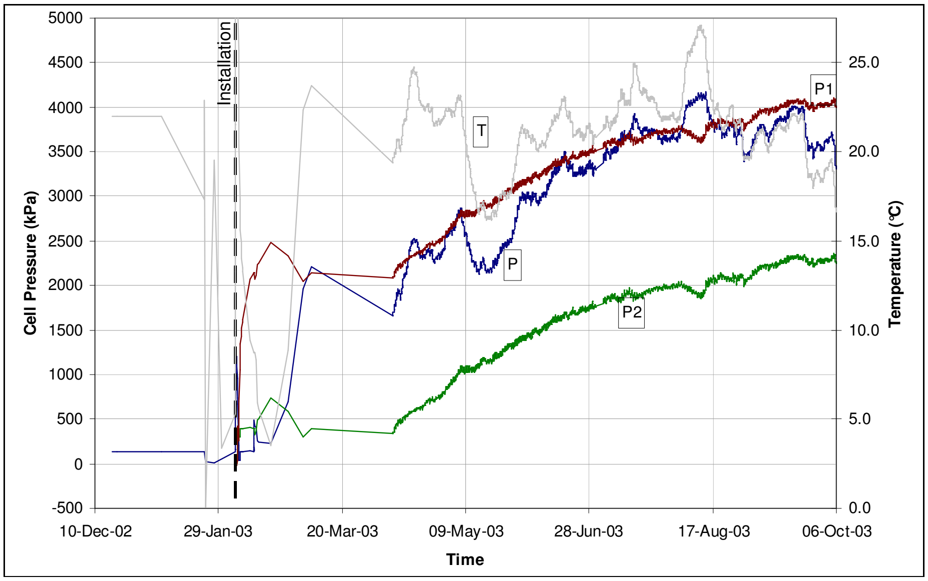

Figure 1: Read pressure and adjusted pressure for test panel pressure cell 511

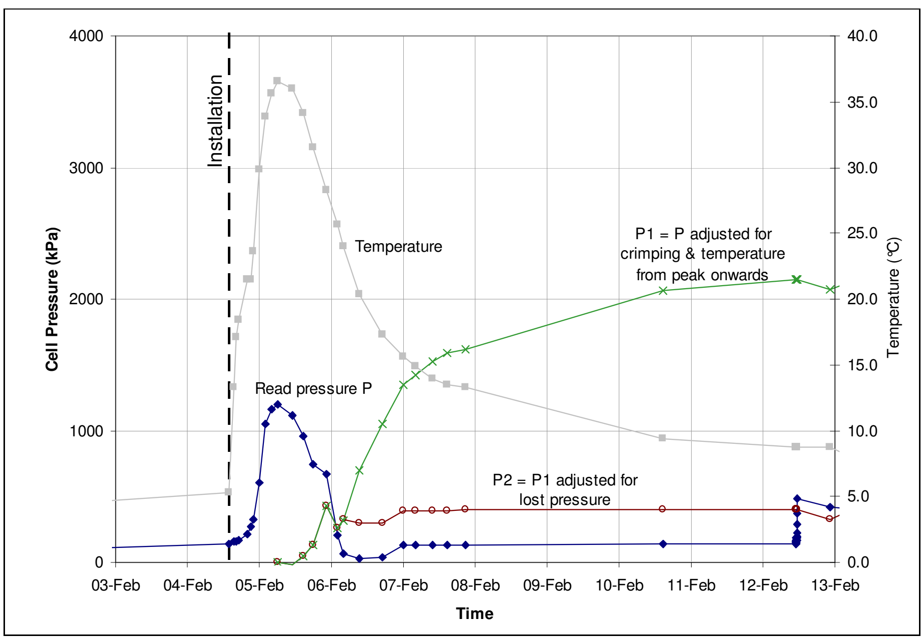

Figure 2: Read pressure and adjusted pressures in test panel pressure cell 511 at early age

2.1 *Temperature effects*

As temperature increases, the pressure in the cell also increases, and vice versa. This is because the cell has a higher coefficient of thermal expansion than the surrounding shotcrete. The 'temperature sensitivity' (TS) is defined as the change in pressure for a unit change in temperature, such that:

$$p = p_r - TS(T - T_0) \qquad (1)$$

where p is the adjusted pressure, p_r is the read pressure, TS is the temperature sensitivity dp/dT, T is the temperature at any time and T_0 is the initial temperature. TS may be estimated by plotting recorded cell pressure against temperature over a time period short enough that the effects of shrinkage may be ignored.

Pressure cells do not initially respond to increases in temperature due to hydration (Figure 2). Previously this has been attributed to shrinkage, or to temperature effects combined with the low stiffness of the young shotcrete. However, it is probable that the main cause is that the shotcrete has a higher coefficient of thermal expansion at early age, which reduces the TS. The coefficient of thermal expansion is known to decrease with age by as much as 25% in 6 months (Emanuel & Hulsey, 1977) and can be much higher at early age (Laplante & Boulay, 1994). Since there were insufficient data at early age to estimate the TS at that time, the TS adjustment was done from the peak of hydration onwards and the pre-peak rise in pressure was subtracted from all later readings (to give line P1 in Figure 1 and Figure 2). For both the test panel pressure cells TS was found to be 0.115 MPa/°C. The small amplitude fluctuations that remain are caused by the thermistor, located close to the transducer, responding to diurnal temperature variations faster than the cell-shotcrete system.

2.2 *Lost pressure*

After the peak the hydration temperature decreased towards ambient temperature (with higher temperature sensitivity). When the cells reached zero pressure, they lost contact with the shotcrete, and ceased to read further changes in temperature or stress (see Figure 2). A correction based on the temperature was made to obtain curve P2 in Figure 1 and Figure 2, but some stresses that may have acted on the pressure cell before it was crimped on 12^{th} February may have been lost.

2.3 *Shrinkage*

The remaining P2 curve in Figure 1 is due to shrinkage of the shotcrete increasing the pressure. If environmental conditions are constant, shrinkage stress may be approximated by a hyperbolic curve, similar to the ACI formula for shrinkage strain (ACI, 1992)

$$p_{shr} = \frac{t}{B+t} \cdot p_{\infty} \qquad (2)$$

where p_{shr} is the cell pressure due to shrinkage, t is time in days, B is a constant that will adjust the curvature and p_{∞} is the ultimate shrinkage pressure. For both test panel cells, B was 55 days.

3 PRESSURE CELLS IN THE TUNNEL

Due to the combination of access restrictions and the lack of a datalogger, infrequent readings were taken from the tunnel pressure cells compared to the test panel cells.

3.1 *Identifying poorly performing cells*

Poor installation of pressure cells will make their data unreliable; therefore it is important to be able to identify those that do not have a good contact with the shotcrete. This can be done by calculating the TS. For example, cell 508 had a near-zero TS, which meant it was not in contact with the shotcrete. Cell 509 was not crimped enough. As the temperature decreased, the read pressure decreased to zero and did not respond to further decreases in temperature.

3.2 *Stresses measured in the tunnel lining*

The results from the radial cells show that the average ground pressure acting on the shotcrete lining is 185 kPa, which is 46% of the full overburden pressure. The results from the tangential cells are shown in Table 1. The values of stress at the shoulders may be higher because there is more drying shrinkage (Golser, Schubert & Rabensteiner, 1989) or more vertical load.

Cell	Position	Lining thickness (mm)	P_1, adjusted pressure for temperature, crimping and pre-peak pressure (MPa)	P_2, = P_1 adjusted for lost pressure (MPa)
506	Left knee	450	1.69	0.26

507	Left shoulder	355	1.92	1.92
509	Right shoulder	435	2.57	1.99
510	Right knee	320	2.51	1.28

Table 1: Adjusted tangential pressure cell readings after 9 months

4 CONCLUSIONS

Pressure cells in tunnels should be attached to a datalogger reading at least every 10 minutes for the first week and at least every hour from then on to supply sufficient detail to calculate temperature sensitivity. The cells should be crimped whenever the read pressure appears to be approaching zero to prevent loss of data. This is likely to occur while the temperature is decreasing after the peak of hydration or during periods of low temperature. Detailed crimping records must be kept. Poorly performing pressure cells can be identified by their low or near-zero temperature sensitivity as well as by a poor response to crimping.

TS may be assumed constant, although this may introduce errors in the first 2-3 months when it may be lower than the long-term value and gross errors in the first few hours, when the TS is much lower. If data is sparse and it is not possible to calculate the development of temperature sensitivity before the peak of hydration, then only pressure changes from the peak onwards may be interpreted. Low TS at early age is partly due to the lower stiffness of the shotcrete, but is mainly because the coefficient of thermal expansion of the shotcrete is higher.

Pressure cells are highly sensitive to temperature and can detect very small changes in temperature or stress. Once corrected for temperature sensitivity, the cells experience only small fluctuations from a smooth curve as the thermistor responds to diurnal temperature changes faster than the pressure cell or the shotcrete.

Once temperature effects have been removed, shrinkage in the unloaded test panel may be approximated by a hyperbolic curve. Further work is required to calculate the pressure induced by shrinkage in a cell installed in a tunnel lining.

By performing the relatively simple corrections outlined above, meaningful results can be obtained from apparently scattered data. This opens the way for reliable measurement of the loads in sprayed concrete tunnel linings.

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