Early Strength of Shotcrete for Tunnel Advances – New Monitoring Approach Using Thermal Imaging

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Early Strength of Shotcrete for Tunnel Advances – New Monitoring Approach Using Thermal Imaging

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ABSTRACT

Sprayed concrete (or ‘shotcrete’) is often used as a lining for tunnels, particularly where the low mobilisation cost and flexibility of geometry make segmental tunnel linings uncompetitive. The early strength gain of the shotcrete is a crucial aspect to ensure there is effective ground support and to ensure the safety of operatives. Currently, strength monitoring is achieved by needle penetrometer and stud-driving tests according to EN 14488-2 (2006). These tests are very local and hence may not be representative, they are time consuming, and to avoid the risk of falling fresh shotcrete, these tests are often performed in panels sprayed subsequent to spraying the lining.

Strength Monitoring Using Thermal Imaging (SMUTI) is a new method which allows quick and easy monitoring of the early strength of the whole shotcrete lining from a safe remote position. A thermal imaging camera is used to build up a time-temperature history of the shotcrete, from which compressive strength may be calculated using an Arrhenius maturity function. The main advantage is the ability to scan the whole surface of the shotcrete from a safe position, in the time it would take to take a photograph.

SMUTI represents a step-change in safety and quality control of shotcrete application. In this paper, a description of the method is given, along with an example calculation using real field data obtained at the Tunnel Oberau in southern Germany.

Keynotes: Early strength monitoring, thermal imaging, SMUTI, sprayed concrete

INTRODUCTION AND BACKGROUND

The chemical reactions that make the shotcrete gain strength are exothermic, i.e. when cement reacts with water to form solid hydrates, heat is produced. The strength gain in concrete is known to be linearly proportional to the amount of cement hydration reactions that have taken place (Byfors, 1980) and can be represented as shown in Figure 1. If this relationship is known for a given concrete mix, then concrete compressive strength (f_c) may be estimated if degree of hydration (ξ) is known.

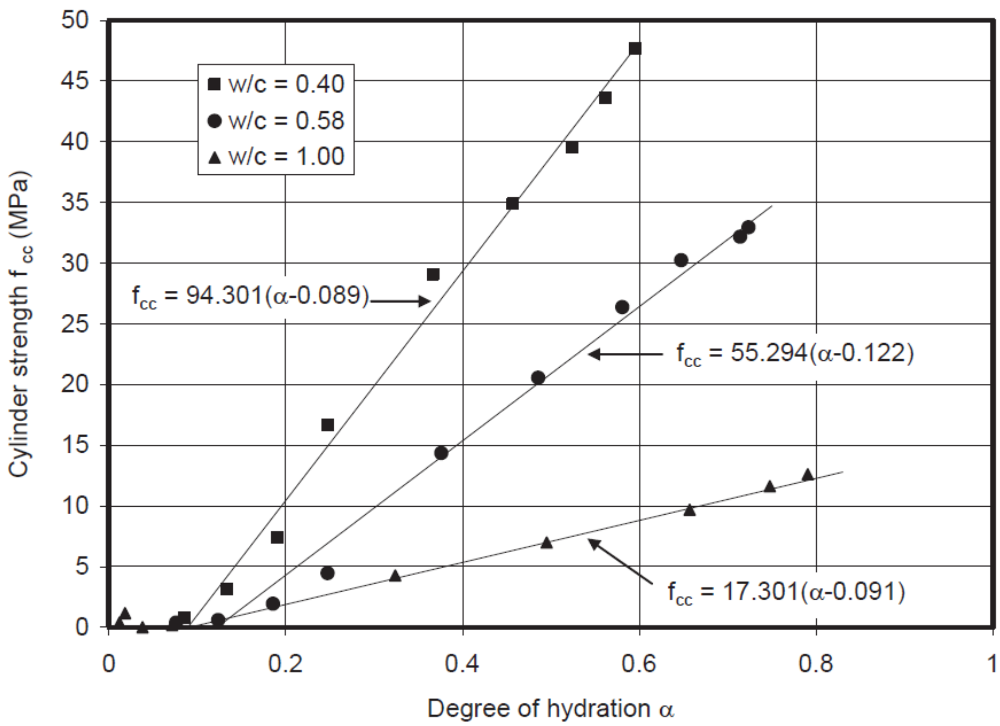

Figure 1. Relationship between compressive strength and degree of hydration (redrawn from Byfors, 1980)

The instantaneous rate of hydration ($d\xi/dt$) for a given concrete mix and, in turn, strength development, is dependent on the current temperature and the current degree of hydration. The Arrhenius function (Freiesleben Hansen & Pedersen, 1977) is widely used to describe the relationship between rate of hydration, temperature and degree of hydration and is given by:

$$\frac{d\xi}{dt} = \tilde{A}(\xi)\exp\left(\frac{E_a}{RT}\right) \qquad \text{Equation (1)}$$

where $\tilde{A}(\xi)$ is normalised affinity (s^{-1}), E_a is activation energy ($J.mol^{-1}$), R is the ideal gas constant (= 8.314 $J.mol^{-1}.K^{-1}$), and T is absolute temperature (K). The activation energy and normalised affinity are dependent on the cement type, the chemical admixtures and the supplementary cementitious materials. Therefore, they must be determined for each shotcrete mix used on site.

EARLY STRENGTH MONITORING OF SHOTCRETE

Currently accepted early age strength tests include needle penetrometer and stud driving and are conducted on site as described in EN 14488-2 (2006). At very early ages, these tests should not be directly performed on the lining due to the danger of freshly sprayed shotcrete or loose ground falling onto the operator. For this reason, shotcrete panels are often used for these tests and are sprayed immediately after the lining. Assuming that the shotcrete for both the lining and the panels is placed in identical conditions, the lining strength development may be assessed. This indirect assessment approach, though widely accepted, does not present a complete picture since the panel and the lining may have a very different temperature history due to the different size, time of spraying and environmental conditions (see Figure 2).

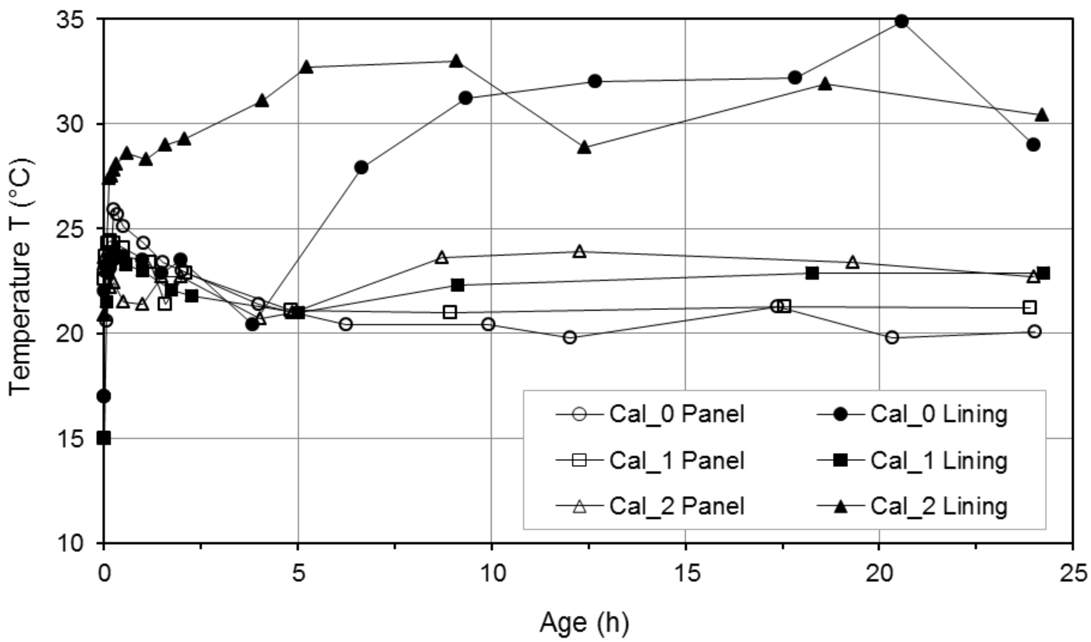

Figure 2. Temperature histories for tested panels and lining sections.

In the following a new method called SMUTI is presented, which is currently being used for strength monitoring of the shotcrete lining in the Tunnel Oberau (B2) connecting Eschenlohe and Garmisch-Partenkirchen in southern Germany.

SMUTI was invented and patented at the University of Warwick by Benoît Jones. The technology is now owned by Inbye Engineering Limited, where it has been further developed. The method is based on recording temperature histories for the shotcrete lining using on-site thermal imaging. These histories can be applied to the maturity function, as shown in Equation (1), and a stepwise calculation is used to determine degree of hydration and, in turn, the compressive strength development. In Jones & Li (2013) and Jones et al. (2014), various aspects of this approach are discussed in detail. The basic steps in implementing SMUTI on a tunnelling project are:

1. Laboratory testing of the cement paste to determine the thermodynamic properties of the shotcrete mix – the normalised affinity $\tilde{A}(\xi)$ and the activation energy E_a.

2. On site calibration using sprayed panels to determine the relationship between compressive strength (f_c) and degree of hydration (ξ).

3. The software is then set up with the operating parameters and site engineers are trained in how to take readings using a thermal imaging camera and how to input these readings into the software.

4. Monitoring of any area of the sprayed concrete lining can now be undertaken by site engineers using a thermal imaging camera to obtain a temperature history.

FIELD APPLICATION

To derive a relationship between degree of hydration and compressive strength, it is not possible to cast cube or cylinder samples, because a chemical accelerator needs to be mixed into the concrete. Proper mixing of accelerator, and proper compaction of the concrete, can only be achieved by spraying at high velocity using compressed air. Therefore, for the calibration, panels are sprayed on site and early strength tests to EN 14488-2 (2006) are used to determine the compressive strength and temperature measurements used to calculate degree of hydration.

In order to get representative results three panels were used for the calibration, each panel sprayed at a different time from a different batch of shotcrete. For comparison, sections of the tunnel lining sprayed at the same time were also tested. Figure 3 shows the temperature histories of the panels and the tunnel lining sections conducted within the calibration phase at the Tunnel Oberau. In this case the lining surfaces were generally warmer than the panel surfaces (see Figure 3), which means the lining experienced higher rate of hydration in its early age than the panels. Thus, the strength gain would be markedly different for the panels and the lining, with the lining gaining strength more quickly in this case as illustrated in Figure 4. The early strengths of up to 1.0 MPa were determined using the needle penetrometer while the rest were determined using stud driving tests.

This may not always happen, and it is easy to imagine situations where the panels may experience warmer temperatures than parts of the lining, either due to the position of the ventilation, varying shotcrete delivery temperatures or other inputs. The shotcrete temperature once sprayed is also dependent on the action of the accelerator. Thus, a thermal imaging camera can also be used qualitatively for on-site quality control and safety. The main aim is to verify that the chemical reactions in the shotcrete are occurring as expected. For example, a cold patch could indicate a problem with the accelerator dosage resulting in a volume of retarded shotcrete in the lining. This would be quickly spotted and could save lives.

In Figure 4 the in situ compressive strength testing data is plotted against degree of hydration. The latter is calculated from the temperature history using the parameters determined from the laboratory testing. Additional the linear relation between compressive strength and degree of hydration obtained by regression is shown for all data.

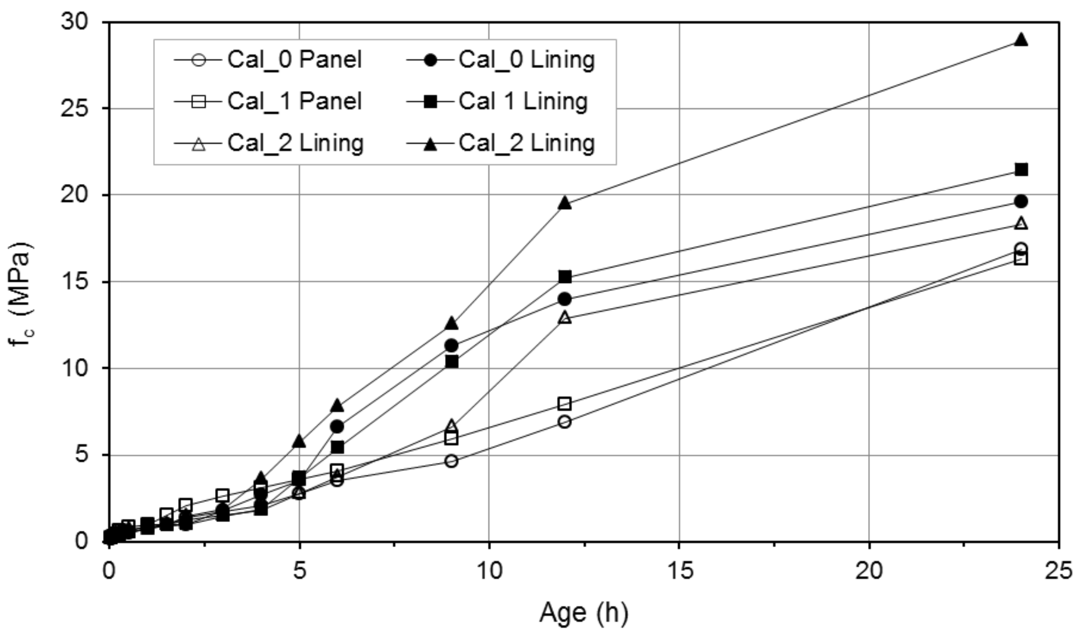

Figure 3: Compressive strength for tested panels and lining sections.

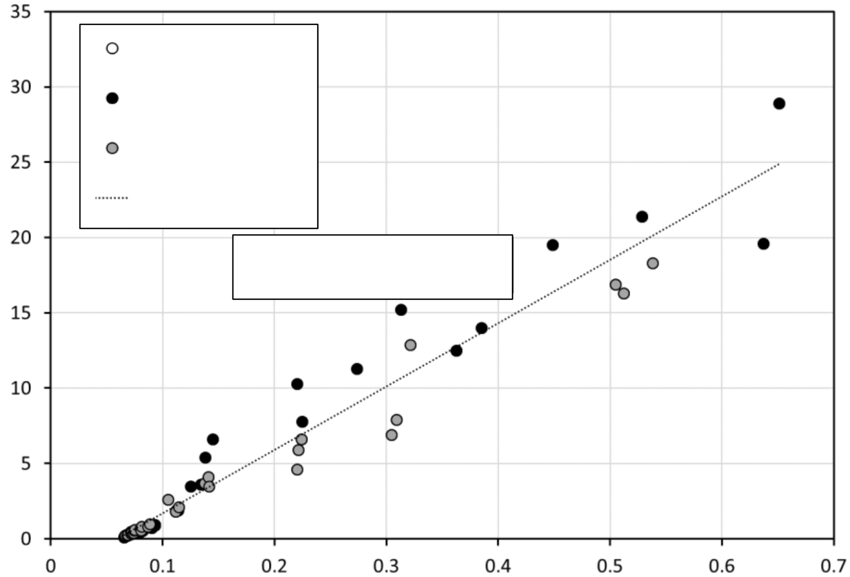

Figure 4: Calibration of compressive strength and degree of hydration relationship.

The next step is the application of SMUTI for monitoring the strength development of the tunnel lining. This will be done at 5 locations around a top heading – left axis, left shoulder, crown, right shoulder and right axis, but any other areas of concern, or where temperatures differ significantly, can be added as an additional point. Figure 5 shows a digital and thermal image, respectively, of a shotcrete lining section, demonstrating how thermal imaging can measure the temperature remotely.

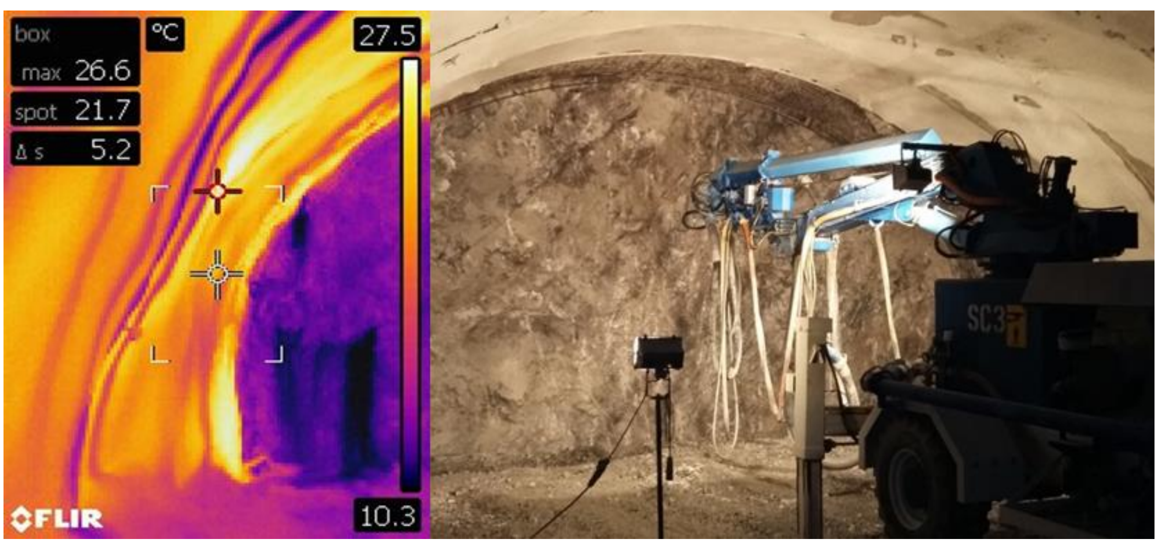

Figure 5: Digital and thermal image respectively, of the shotcrete lining.

CONCLUSIONS

SMUTI allows us to monitor the strength gain of the whole shotcrete lining (as against local tests on a panel) from a safe and remote position. There is no other method or technology that can achieve this; it represents a step-change in safety and quality control of shotcrete tunnelling. SMUTI assists in the mitigation of key hazards within the sprayed concrete tunnelling environment. SMUTI is easier, safer and quicker than existing methods, which are time consuming, involve safety risks themselves and may not be representative of the whole lining.

SMUTI doesn't need to replace traditional strength monitoring methods to be beneficial. When it is used in parallel with existing methods, it provides increased confidence in the extrapolation of test panel strengths to the lining and helps engineers and operatives understand the strength development better. It provides richer, more accessible and traceable data.

ACKNOWLEDGEMENTS

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