Strength Monitoring Using Thermal Imaging

In this article, Dr Benoît Jones, Director of the Tunnelling and Underground Space MSc, and Dr Shuangxin Li, former Research Fellow, at the University of Warwick, UK, present a new method of early strength monitoring of shotcrete.

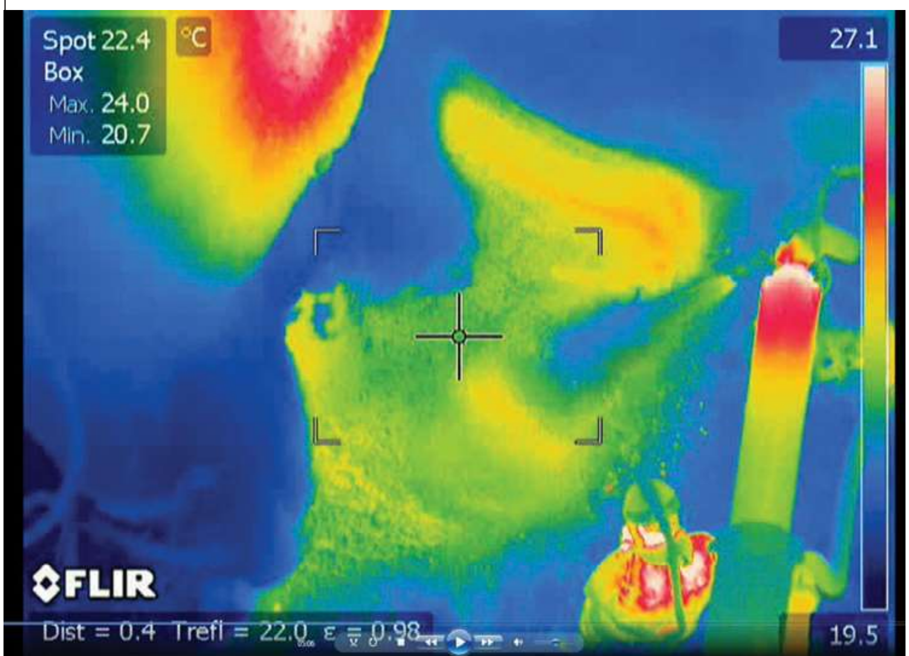


Figure 1: Screen grab from a thermal imaging video during spraying of the left bench. Just below centre you can see the immediate temperature rise due to the accelerator. The red area top left is the lower part of the top heading and shows a higher temperature due to a build-up of hydration heat.

YOU CAN'T REALLY TELL what's going on in a sprayed concrete lining just by looking at it. It all looks, well, grey (Figure 2). But if we change the spectrum and look in the infra-red using a thermal imaging camera, the shotcrete comes alive. The chemical reactions that make the shotcrete gain strength are exothermic; when cement reacts with water to form solid hydrates, heat is produced. The temperature of the shotcrete can therefore act as a kind of signature that tells us how much hydration has occurred. Figure 3 shows the rise in temperature as we retreat from the face, reaching a peak 2-4 rings back followed by a gradual decrease to ambient temperature.

Figure 4 shows an ordinary digital photo of a shotcrete lined tunnel. There is absolutely no visible difference between advances 37 and 38. However, looking at a thermal image (Figure 5), there is a distinct temperature difference.

The SMUTI vision

Strength monitoring is important for two main reasons. The first is re-entry time: Is it safe to stand underneath the shotcrete and will it stay up if shaken by excavation or drilling? The second reason is that shotcrete linings are loaded at early age as the tunnel

Figure 2: View of a tunnel lined with shotcrete

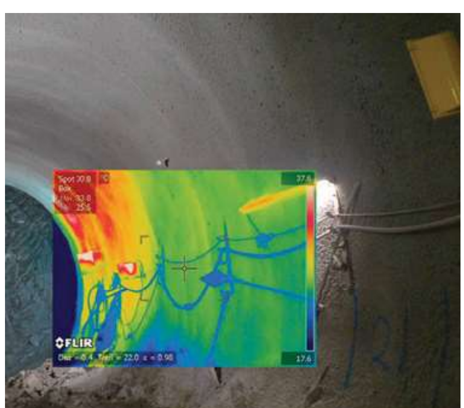


Figure 3: Same view as Figure 2, with an inset infra-red image

Figure 4: A normal digital photograph of a shotcrete lined tunnel

Figure 6: Digital image of enlargement top heading advance 1

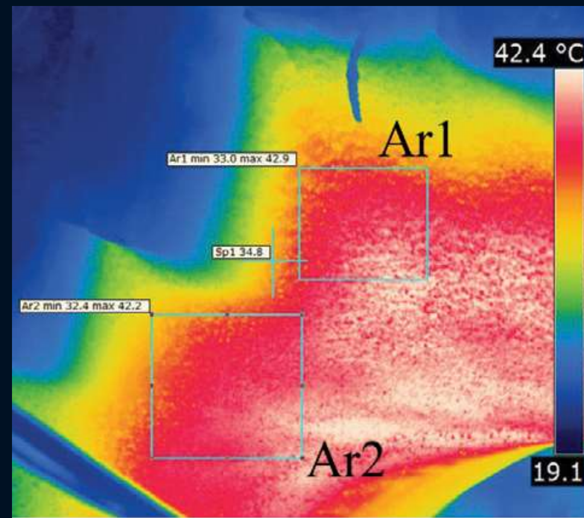


Figure 7: Thermal image of enlargement top heading advance 1, at around 15 hours after spraying.

advances, and it is important that the shotcrete gains strength at a rate corresponding to the rate of loading, so that an adequate factor of safety is maintained at all times and the lining is not overstressed. Overstressing can cause failure, but at lower levels of stress where the factor of safety against failure is greater than 1.0 but stresses are higher than the serviceability limit state, the lining may be damaged or cracked, which is a crucial issue for a permanent shotcrete lining. Strength monitoring is also an important aspect of quality control, where strength is used to verify the conformity of the concrete.

The development of Strength Monitoring Using Thermal Imaging (SMUTI) was driven by dissatisfaction with current methods of monitoring strength development of sprayed concrete. Mostly this is done using needle penetrometers and Hilti DX450 nail guns, followed by testing of cylinders cored from the lining or from a panel sprayed at the same time as the lining. The main drawback with these methods is that they are very local, they are destructive, they introduce additional risks, and some also produce hazardous waste. Checking the early strength of the shotcrete in the crown is particularly difficult and possibly dangerous using current methods.

So what if the whole lining could be scanned remotely, swiftly, safely, without damaging the lining and without special access requirements? This is what SMUTI offers.

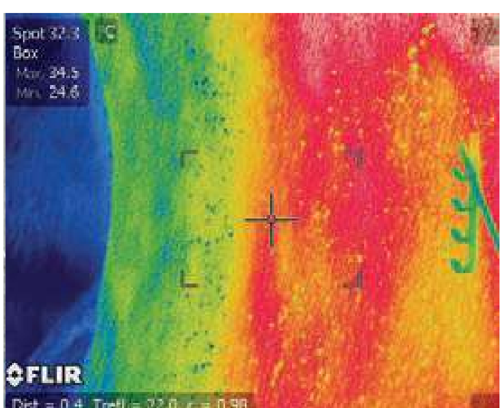


Figure 5: Thermal image of the same shotcrete lined tunnel in Figure 4

How it's done

Thermal images of the shotcrete are captured to build up a time-temperature history of the shotcrete. The images should be taken as early as possible after spraying, if not before and during, and should continue to be taken regularly for as long as early strength monitoring is required.

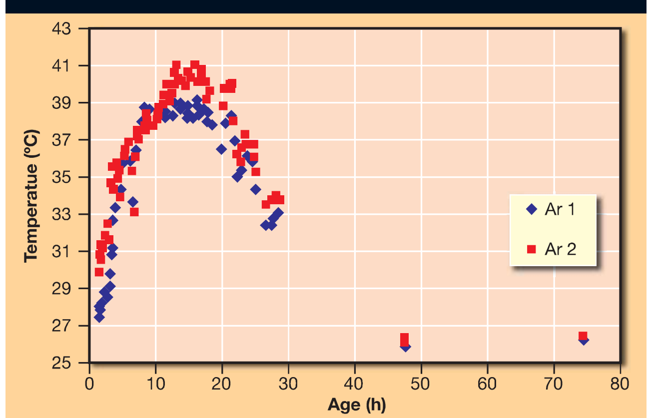
An example for an enlargement top heading advance just leaving a piled box at Bond Street is shown in Figure 6 and Figure 7. In Figure 7 two areas have been marked on the image, within which average temperatures will be determined to build a time-temperature history.

The time-temperature histories for areas Ar1 and Ar2 are shown in Figure 8. This is a typical shape of curve for a sprayed concrete, with a peak temperature at around 15 hours. This is the surface temperature, and we are going to use it to determine the surface strength. Surface strength is what is measured by all common methods of early strength testing.

Within the section, the temperature will be higher, hence the strength will be greater, therefore the calculation is conservative. If you know the coefficient of thermal conductivity and specific heat capacity of the shotcrete and ground, you can also determine the temperature profile across the section, but this introduces considerable complexity to the calculation without adding much value.

Using a series of isothermal strength tests or an on-site calibration, you can determine the linear relationship between degree of hydration and compressive strength. The most important thing to remember is that for a given concrete mix, the rate of hydration at any time is dependent only on the temperature at that time and the degree of hydration. This can be described by the Arrhenius equation:

Figure 8: Time-temperature history for areas Ar1 and Ar2



$$\dot{\xi} = \tilde{A}(\xi)\exp\left(\frac{-E_a}{RT}\right)$$

ξ	degree of hydration
$\dot{\xi}$	rate of hydration in s^{-1}, where $\dot{\xi} = d\xi/dt$
$\tilde{A}(\xi)$	normalised affinity in s^{-1}. This can be thought of as the driving force of chemical reactions
R	ideal gas constant = 8.3144 J K^{-1} mol^{-1}
T	temperature in K
E_a	activation energy in J mol^{-1}. This is the minimum energy required to make a chemical reaction between 1 mole of cement and water occur. It describes the sensitivity of the rate of hydration to temperature.

The normalised affinity function and the activation energy need to be obtained from calorimetric tests on the specific shotcrete mix to be used on site. Investigation of exactly what tests are required in order to estimate the values with sufficient accuracy, while taking account of the effect of the accelerator on the shotcrete, is part of ongoing research. None of the (fairly) standard tests we are considering require particularly expensive equipment. The values thus obtained for normalised affinity and activation energy are intrinsic and can then be used throughout the life of a project, unless the composition of the mix or the properties of the cement change.

The Arrhenius equation enables us to calculate degree of hydration and hence strength from a time-temperature history. To illustrate how the calculation works in the absence of site-specific values, we are going to use published values of normalised affinity of a shotcrete, taken from Hellmich et al. (1999) and shown in Figure 9, who calculated them from isothermal strength tests performed by H. Huber at the University of Innsbruck in 1991 (though actually the temperature varied in the first 24 hours from 16°C to 28°C to 23°C, so it wasn't strictly isothermal). We are also assuming the activation energy divided by ideal gas constant, Ea/R, is equal to 4200K.

From the time-temperature history shown in Figure 8, a stepwise calculation can be performed where you take the degree of hydration and the temperature at time step 1 and use it to calculate the rate of hydration. This then gives you the degree of hydration at time step 2 and so on and so on. Here's one I made earlier: the calculated degree of hydration is shown in Figure 10.

The next step is to use the relationship between degree of hydration and compressive strength to calculate the

The SMUTI system

Strength Monitoring Using Thermal Imaging (SMUTI) can be deployed on site in one of three ways:

- **SMUTI Level 1: A thermal imaging camera is 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. 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. For an example, watch the video at http://www2.warwick.ac.uk/fac/sci/eng/staff/bdj**
- **SMUTI Level 2: A thermal imaging camera is used to produce a time-temperature history of the shotcrete lining, from which strength is calculated. This requires some simple laboratory tests to determine the normalised affinity function, the activation energy and the linear relationship between degree of hydration and compressive strength. The use of SMUTI Level 2 is subject to a patent held by the University of Warwick (IPO, 2013).**
- **SMUTI Level 3: Full factor of safety monitoring of the shotcrete lining. The strength of the shotcrete is determined using SMUTI Level 2 and in addition, strain or displacement monitoring is used to back-calculate stress using a thermochemomechanical model. Note that because temperature is measured and the thermodynamic behaviour verified by testing, this vastly improves the accuracy of the calculation compared to current implementations of this model.**

Figure 9: Normalised affinity curve approximated from Hellmich et al. (1999).

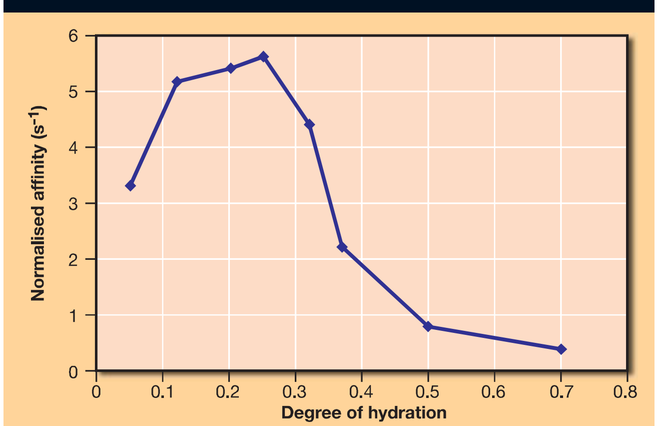
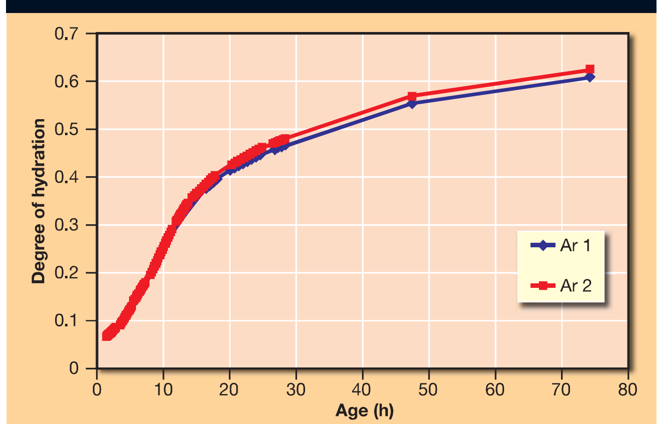


Figure 10: Degree of hydration calculated from time-temperature history.

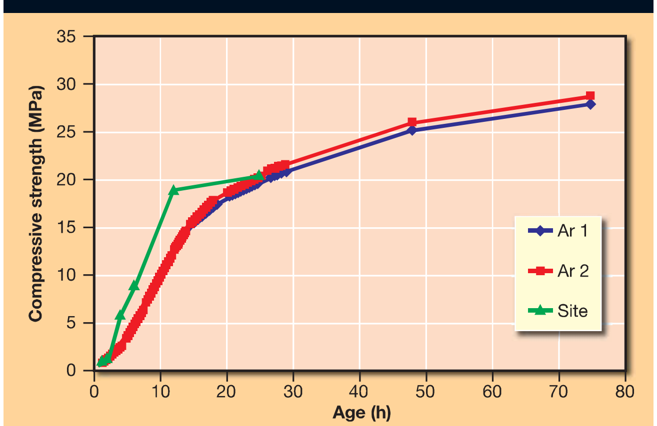


"In the future the thermal imaging camera will be linked into the surveying network. It will know the temperature history of whatever it is currently pointing at and will display a real time picture of strength, as well as temperature"

strength development of the shotcrete. The appropriate tests have not been performed for this specific shotcrete, so for the purposes of this illustration I've assumed that the strength begins to increase linearly from a degree of hydration of 0.05, and reaches 20MPa at a degree of hydration of 0.45.

The resulting strength development curves for areas Ar1 and Ar2 are shown in Figure 11. Also shown are the average strengths measured on site for a number of advances at around the same time. The 24 hour strength is approximately the same because we fixed it that way in the previous paragraph at 20MPa. The strength development we've just calculated from the thermal imaging data is lower than the site data from 4 to 12 hours because site specific values of normalised affinity and activation energy have not been used. In particular, if the accelerator is working as a catalyst we would expect the activation energy to be reduced in the first few hours, because that's what catalysts do.

Figure 11: SMUTI and conventional measurements of compressive strength.



Conclusions

- A revolutionary method of monitoring the strength development of shotcrete tunnel linings has been described, and preliminary trials presented. SMUTI represents a step-change in safety and quality control.
- The measurements can be made remotely from a safe position. The strength of the whole lining can be monitored.
- Without performing any calculations, areas of shotcrete where hydration is unexpectedly retarded can be seen very clearly using a thermal imaging camera during or after spraying (SMUTI level 1).
- The SMUTI level 2 calculation is relatively simple, as the example presented shows, and can be done in a spreadsheet.
- Initially, tests are required on the shotcrete mix to determine the relationship between compressive strength and degree of hydration, and to define the normalised affinity function and the activation energy.
- Once these parameters have been determined, they are intrinsic and will not change unless the shotcrete mix or cement type changes.
- In the future the thermal imaging camera will be linked into the surveying network. It will know the temperature history of whatever it is currently pointing at and will display a real time picture of strength, as well as temperature.

A presentation including thermal imaging videos shot during and after spraying can be found at http://www2.warwick.ac.uk/fac/sci/eng/staff/bdj

Further work

We believe at this stage that the method is feasible and will yield excellent results. In order to develop and improve the method, we are doing site trials and research in the following areas:

- The most efficient and effective method of determining the relationship between compressive strength and degree of hydration, the normalised affinity function and the activation energy.
- Site trials to determine the accuracy and reliability of the method.
- Linking the thermal imaging camera into the surveying network.
- Development of full factor of safety monitoring (SMUTI level 3).

REFERENCES

Hellmich, C., Ulm, F. –J. & Mang, H. A. (1999). Multisurface chemoplasticity I: a material model for shotcrete. J. Engrg Mech. ASCE 125, No. 6, June, 692-701.

Intellectual Property Office (2013). Patent application no. GB1312750.1 - Apparatus & method for monitoring strength development of concrete. http://www.ipo.gov.uk/p-ipsum/Case/ApplicationNumber/GB1312750.1 [last accessed 21/11/13].

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