EARLY STRENGTH MONITORING OF SHOTCRETE USING THERMAL IMAGING

Dr Benoît D. Jones
Director, Tunnelling and Underground Space, University of Warwick, UK
b.d.jones@warwick.ac.uk

Dr Shuangxin Li
former Research Fellow, University of Warwick, UK

Vishwajeet Ahuja
PhD student, University of Warwick, UK

Summary

Strength Monitoring Using Thermal Imaging (SMUTI) is a new method of monitoring the early strength of shotcrete using thermal imaging techniques. 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. All other methods of early strength determination are very local tests, many are not non-destructive and they introduce additional risks. This therefore represents a step-change in safety and quality control of shotcrete application. A description of the method is given, along with an example calculation using real field data, and further development work is described.

INTRODUCTION AND BACKGROUND

Concrete hardens due to a chemical reaction known as 'hydration', where water reacts with cement to form solid hydrates. As these chemical reactions take place, the solid hydrate crystal structures grow. The amount of hydration that has taken place can be described by the 'degree of hydration'. There are several subtly different definitions of degree of hydration, but basically it describes the amount of hydration that has occurred relative to the theoretical maximum degree of hydration where all the cement is hydrated.

At a critical degree of hydration, sufficient solid hydrates have formed to create a kind of skeleton. After this point has been reached, continuing reactions will gradually increase the strength of the concrete. This occurs typically at a degree of hydration of 0.1, after which the compressive strength has been found to be approximately linearly proportional to degree of hydration (Byfors, 1980 [1]), as shown in Figure 1.

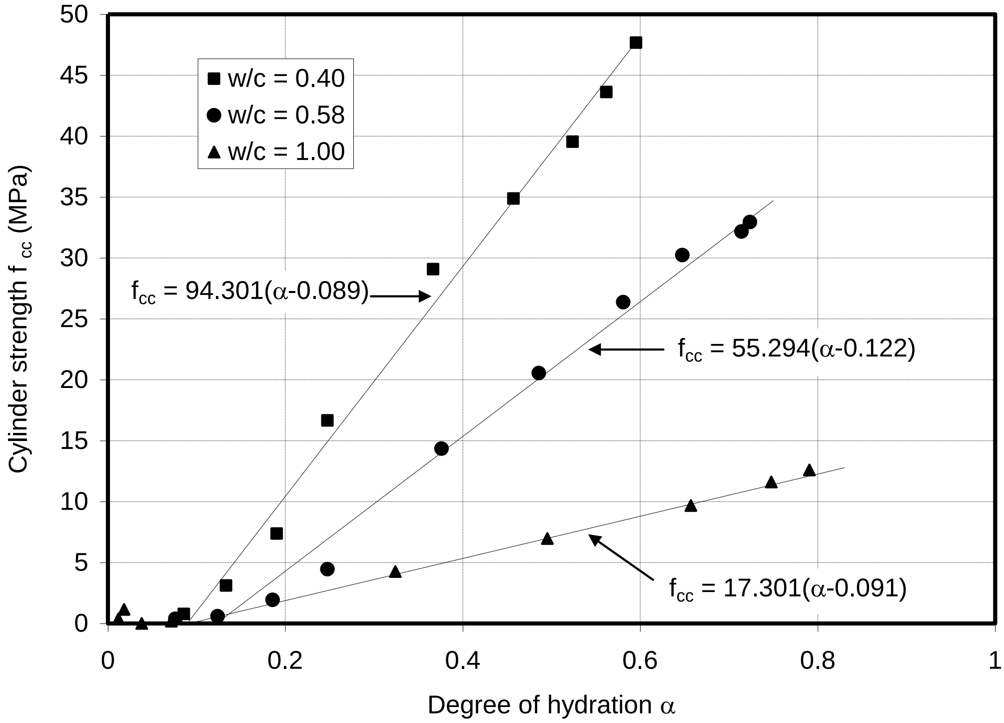

Figure 1: Relationship between compressive strength and degree of hydration (redrawn from Byfors, 1980 [1])

For a given concrete mix, the rate of hydration of concrete has long been known to be dependent on temperature and degree of hydration [1]. It follows then that the strength development of concrete is strongly dependent on its temperature history. As a rule of thumb, an increase of 10°C will double the rate of hydration, and hence double the rate of strength gain. Despite this we still specify, model or describe strength development of shotcrete as a function of time, ignoring temperature.

Carino & Lew [2] describe the collapse of an apartment building and a cooling tower in cold weather in the 1970's, due to striking formwork before the concrete had gained sufficient strength. These failures demonstrated the dangers of extrapolating strengths measured from specimens cured under laboratory conditions to structural elements curing under very different conditions. After these events, the US National Bureau of Standards became interested in maturity methods to enable calculation of strength for any temperature-time history, and published ASTM C1074.

The hydration of cement in concrete requires the input of heat, known as the 'activation energy', which has units of Joules per mole. But concrete hydration is exothermic, meaning that when a hydration reaction occurs, more heat is released than was required to make it happen in the first place. This means that as reactions occur, more heat is made available, making more reactions possible. Therefore, from a slow start, hydration accelerates. As the degree of hydration increases, further hydration begins to be governed by diffusion of water through layers of already-formed hydrates to reach the unhydrated cement. This slows the rate of hydration until heat loss to the exterior surpasses heat generation and the temperature begins to decrease.

Originally, 'time-temperature functions' (also known as 'maturity functions'), were used to describe the effect of temperature history on strength. They used a maturity factor expressed in units of degree-hours to calculate an equivalent age. Freiesleben Hansen & Pedersen first demonstrated in 1977 that the relationship between rate of hydration, temperature and degree of hydration may be described by the Arrhenius function [3], shown in Table 1:

$\dot{\xi} = \tilde{A}(\xi)\exp\left(\frac{-E_a}{RT}\right)$	
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. It varies as a function of degree of hydration.
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 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.

Table 1: Arrhenius equation

The Arrhenius form of maturity function has been used successfully for concrete over the last 40 years [e.g. 1, 2, 4]. It works very well for early strength gain, but does not include the effect of rate of strength gain at early age on long-term strength (faster strength gain at early age usually results in a lower long-term strength).

EXAMPLE CALCULATION

An example demonstrating the effect of temperature is illustrated by the calculated isothermal strength gain curves shown in Figure 2. In this figure the temperature is held constant at either 10, 20 or 30 °C and the strength is calculated using the Arrhenius function. In order to do this, parameters have been set based on experience of shotcrete hydration, as follows:

- The activation energy E_a used is set at E_a/R = 4200 J/mol. This was the value used by Hellmich et al. (2001) [4], and is approximately the value that would be calculated using the method of Folliard et al. (2008) [5].

- The normalised affinity $\tilde{A}(\xi)$ is based on the values used by Hellmich et al. (2001) [4], based on work by H. G. Huber for his master's thesis at the University of Innsbruck in 1991. Although shotcrete has changed a lot since 1991, and although Hellmich et al. assumed the the tests were isothermal when they weren't, in the absence of better data it has been used here. Tests to determine site-specific values of normalised affinity $\tilde{A}(\xi)$ and activation energy E_a , as well as the relationship between strength and degree of hydration, are ongoing at the University of Warwick, but no results are yet available at the time of writing the paper.

- It was assumed that the immediate massive ettringite formation caused by the aluminium sulphate-based alkali-free accelerator would produce an immediate initial skeleton but little immediate strength, and so the strength was assumed to increase linearly from 0 MPa from a start point of ξ = 0.1 at time t = 0, up to 20 MPa at ξ = 0.45. Again, the testing programme underway will ascertain real site-specific values but in order to provide an example calculation for this paper, these values have been applied.

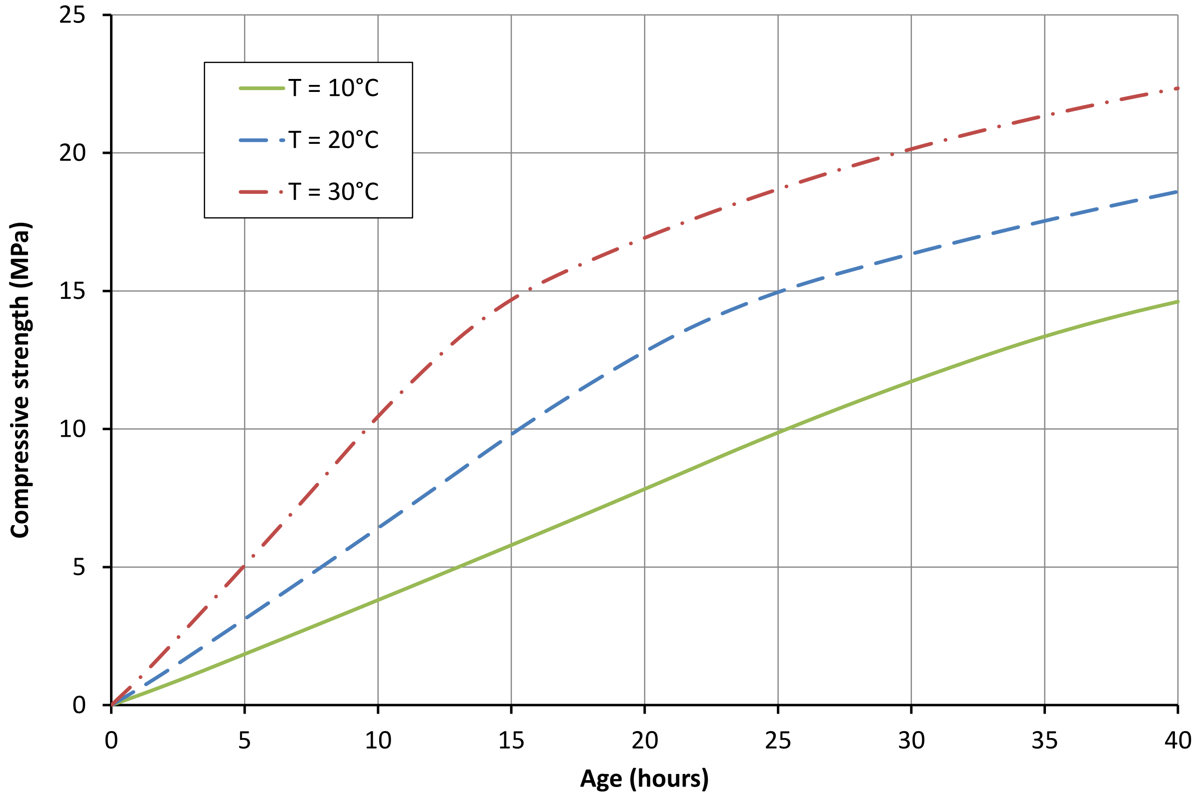

Figure 2: Isothermal (constant shotcrete temperature) strength gain curves based on the Arrhenius function

Figure 2 shows that strength development is highly dependent on shotcrete temperature. The initial temperature of the shotcrete at the time of spraying will have a big impact on the early strength gain, as well as any heat generated by the immediate ettringite formation provided by the alkali-free accelerator, which is strongly exothermic.

EARLY STRENGTH MONITORING OF SHOTCRETE

In shotcrete applications in tunnels, understanding the strength gain is of critical importance. The risk to tunnel operatives of falling shotcrete is in many cases as important as the risk of falling ground, especially where thick linings without steel mesh are being applied. In this case, it is not permitted to stand under or near the shotcrete until it has gained sufficient strength to safely support its own weight, usually specified at 0.5 or 1 MPa. Strength development beyond this point is also important, as subsequent excavation steps will incrementally increase the loads on the shotcrete lining, which must have sufficient strength to resist them with adequate factor of safety.

Early strength development of shotcrete is highly variable – this is why it has to be systematically monitored. We can't just assume that it will reach a certain strength at a certain age. Assuming that variations in composition of the mix are minimised as much as possible, Figure 2 shows that the most important factor in early strength variability is likely to be the shotcrete temperature.

The early strength development is usually measured by a combination of needle penetrometers, Hilti nail penetration and/or pull-out tests and uniaxial compressive strength testing of cores. At many sites in the UK it is now common to spray small panels (e.g. 600 x 600 x 150 mm) immediately after completion of an advance, and to perform the early strength tests (up to 12 or 24 hours) on the panel. But what happens if strength gain in the panel is different to that in the lining? Common practice is to try to mitigate as much as possible this problem using the following steps:

- The panel is usually sprayed after the lining advance has been sprayed. This means that it is younger, hence strength tests should be conservative.

- The panel is kept close to the face whenever possible so it experiences a similar ambient temperature and relative humidity as the lining.

However, there are a number of reasons why the panel may not accurately represent the lining:

- The panel is sometimes thinner and has more exposed sides than the lining, for example on one site the panels are 600 x 600 x 150, whereas the lining is 250-400 mm thick, sprayed in 1m advances with only one edge exposed to the air. This means the panels lose more heat to the exterior.

- The panel is sprayed after the lining. For spray machines with on-board compressors, the compressed air temperature may gradually increase over time, meaning that the panels may start at a higher initial temperature than the parts of the lining that are sprayed first.

- Accelerator dosage may be different for the panel and certain parts of the lining.

- Due to variability of shotcrete quality or spraying quality, the panel may not be representative of the lining in terms of homogeneity, composition and compaction.

This may be illustrated by Figure 3, which shows surface temperature data from 5 areas of a pilot tunnel lining advance immediately followed by the spraying of Panels A to E. All the data was obtained by a thermal imaging camera. This shows that the panels in this case, although stored near the face of the tunnel in similar ambient temperatures to the lining, experienced a markedly different temperature history.

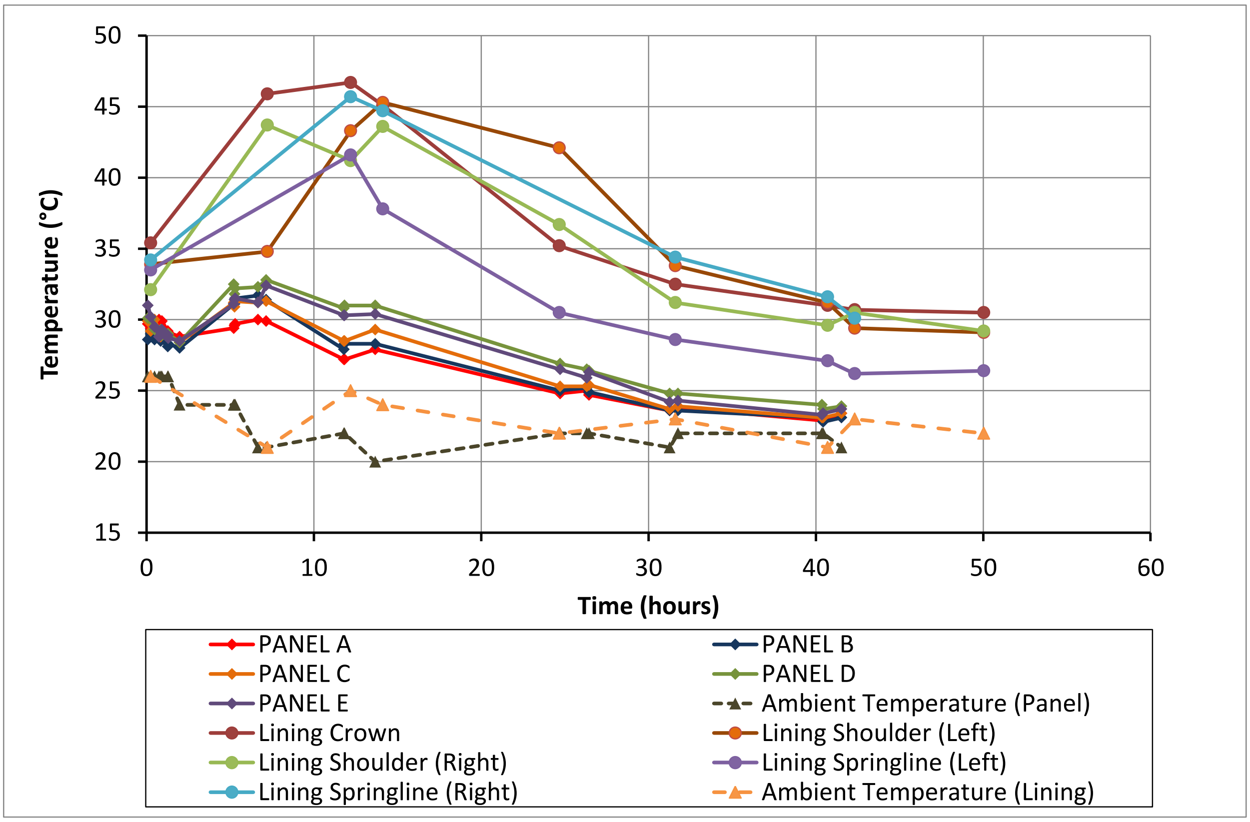

Figure 3: Temperature histories of five panels A-E and five areas of lining, all sprayed at the same time

It is easy to see from Figure 2 and Figure 3 that the strength gain would be markedly different for the panels and the lining, with the lining gaining strength more quickly in this case. 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. The immediate massive ettringite formation caused by aluminium sulphate-based alkali-free accelerators is strongly exothermic and provides an initial increase in temperature, and the by-product of this reaction $Al(OH)_3$ is a catalysing accelerator, which should be expected to reduce the activation energy (Myrdal, 2011 [7]).

It is clear that a strength monitoring method that takes account of temperature is desirable, even if it is only used to ensure that extrapolating early strength tests on panels to the lining is a safe assumption, i.e. that the lining is always warmer than the panels used for early strength testing.

Figure 4 shows a preliminary attempt at strength calculation using SMUTI. The thermodynamic model is as described earlier in the paper and is completely uncalibrated. As mentioned previously, tests are ongoing to determine site-specific values of normalised affinity $\tilde{A}(\xi)$ and activation energy E_a , as well as the relationship between strength and degree of hydration. Also shown on Figure 4 are the in situ strength tests performed on the panels. These are using a needle penetrometer for values below 1 MPa and Hilti penetration and pull-out test for values above 1 MPa.

Panels D and E in Figure 4, which had higher temperatures on average than the other panels (c.f. Figure 3), have higher strengths as measured by SMUTI and the standard in situ tests than the other panels, so a preliminary conclusion is that temperature history does appear to have a noticeable effect on shotcrete and this can be measured by a thermal imaging camera.

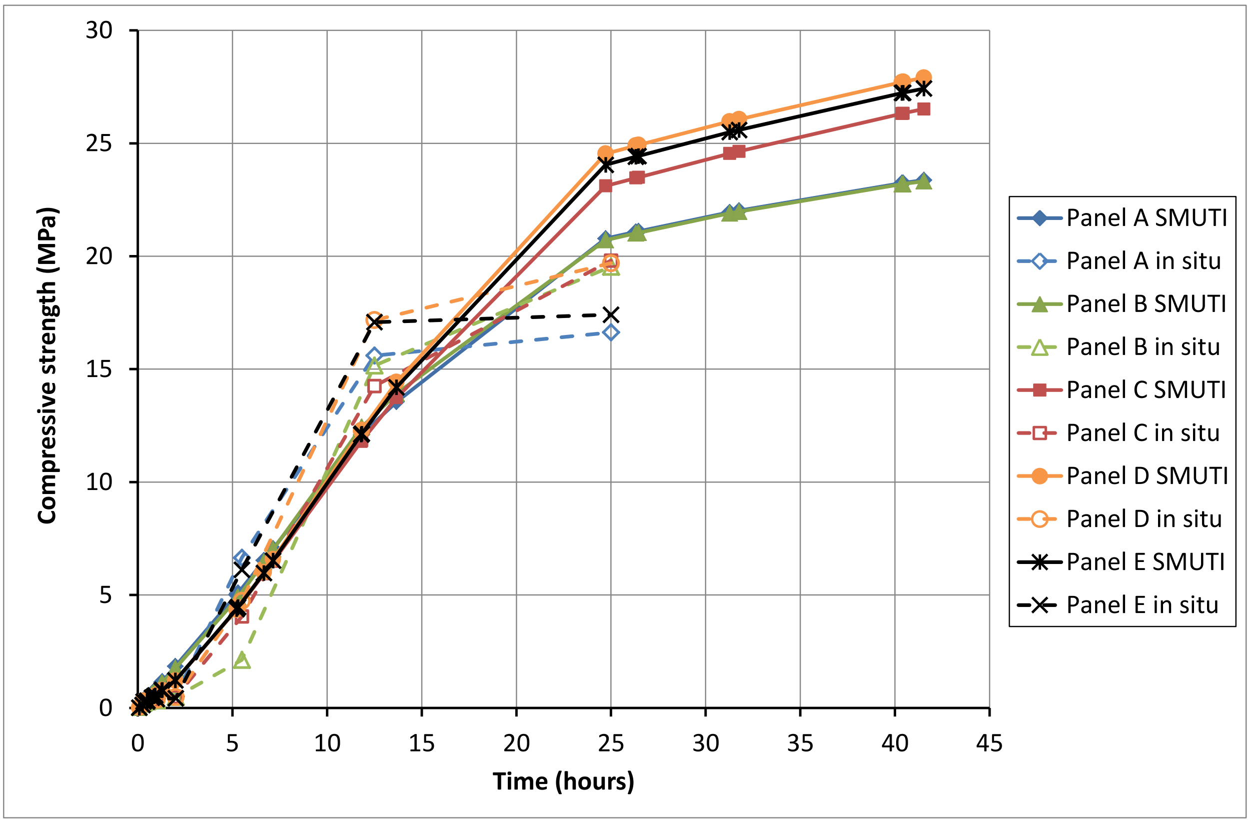

Figure 4: Compressive strength development with time for shotcrete panels A to E calculated using SMUTI and standard in situ tests

A thermal imaging camera measures surface temperature. This will always be lower than temperature in the interior of the shotcrete, therefore the method is conservative in this respect. In comparison, penetrometer and Hilti nail tests also measure only the strength of the shotcrete close to the surface. However, they are indirect tests calibrated to cylinder compressive strength tests on cored samples, and it could be argued that the derived strength depends on the thickness of the panel that was used for the calibration, and the influence of different temperature histories at different depths on the results of cylinder strength tests. For this reason, penetrometer and Hilti nail tests may not be as conservative as they first appear.

DISCUSSION AND CONCLUSIONS

Some comments on the thermodynamic parameters

- It is possible to adjust the thermodynamic parameters to make SMUTI fit the strength development measured by penetrometer and Hilti nail tests, and to do it much better than shown in Figure 4. However, since these parameters represent real physical quantities that can be measured relatively cheaply, it is preferable to measure them directly.

- The Arrhenius function is highly sensitive to the chosen value of activation energy E_a. For example, changing the value from 4200 J/mol to 4000 J/mol makes a big difference to the calculated strengths. Therefore, this parameter needs to be measured with care using calorimetry on the mix of cement, other binders and additives to be used on site.

- The calculation is less sensitive to the chosen values of normalised affinity as a function of degree of hydration, $\tilde{A}(\xi)$, but there is a dearth of data for shotcrete so at present we have little idea of its possible range of values.

- The relationship between compressive strength and degree of hydration needs to be found for accelerated shotcrete, rather than an unaccelerated base mix, since the accelerator provides some initial strength through the formation of ettringite and this will also affect the critical degree of hydration of the cement. The massive ettringite formation, as well as the accelerated hydration of the cement clinkers, will affect the microstructure of the cement paste and hence will have an impact on the later strengths.

- Testing accelerated shotcrete in the laboratory is problematic because it is difficult to manually mix accelerator into samples and obtain the same homogeneity and compaction. Therefore, samples retrieved from panels sprayed on site will be used. This may mean that the early strengths are measured using existing in situ testing methods such as the penetrometer and Hilti nail tests, and samples for degree of hydration testing are scraped from the panels on site and ground in alcohol in situ to arrest hydration, before being transported to the laboratory in sealed containers for testing.

Comments on practicalities

- It is very possible that SMUTI is more accurate than existing methods. However, this will be difficult to prove. For practical purposes, if the strength can be determined within an error of ± 20%, this will be sufficient.

- SMUTI has the potential to provide huge benefits to shotcrete tunnelling, with a step-change in safety and quality control. The whole lining can be scanned from a safe position and without the need for a scaffold or mobile elevated working platform. Cold areas can be quickly identified as areas of concern.

- SMUTI is a truly non-destructive testing method. It is as quick and easy to take readings as taking a photograph.

- Practicalities such as the minimum specification for the thermal imaging camera, the minimum frequency that readings should be taken, how to identify areas and annotate the data and training of shift engineers to take the readings correctly are the subject of current development work.

Future development work

- Current and future work on several sites will build up a database of thermodynamic parameters for shotcrete mixes, enabling better understanding of mix design.

- The influence of accelerator on the early stages of hydration needs to be better understood. Thermodynamic tests such as adiabatic and isothermal calorimetry are excellent tools for improving understanding of these effects and this will be an interesting by-product of this research.

- SMUTI will eventually be integrated into the surveying systems for setting out and monitoring convergence of the tunnel. This will enable the thermal imaging camera to know the temperature history of what it is pointing at, allowing a real-time calculation and colour contour plot of strength to be produced on a screen.

- Using laser scanning or photogrammetry, the thickness and profile of the lining can be known, as well as its convergence. A thermochemomechanical back-calculation model could then be used to calculate stresses in the lining. Unlike previous implementations of the thermochemomechanical model, site-specific thermodynamic parameters will be known from laboratory testing, and the temperature history of the lining will be known, minimising the errors. Knowing both the stress and the strength, a real-time calculation of factor of safety is possible. This has been called 'SMUTI level 3' [8].

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INTELLECTUAL PROPERTY RIGHTS

Using thermal imaging techniques to calculate the strength of a shotcrete lining is subject to a patent held by the University of Warwick. 'SMUTI' is a trademark of the University of Warwick. A spin-out company called 'Inbye Engineering' has been set up in order to bring to market and further develop SMUTI.

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