# Sprayed concrete strength monitoring using thermal imaging at Bond Street Station Upgrade.

B. D. Jones
*Managing Director, Inbye Engineering Ltd, Coventry, UK.*

A. G. Davies
*Senior Engineer, Costain Ltd, Maidenhead, UK.*

V. Ahuja
*PhD Candidate, University of Warwick, Coventry, UK*

ABSTRACT: As a sprayed concrete lined tunnel is advanced, it is important to monitor the strength development of sprayed concrete to ensure the workers are not at risk from falls of sprayed concrete, and that the lining has sufficient strength to support the ground loads and maintain stability of the tunnel. This is usually achieved using a combination of needle penetrometer and stud driving tests in a panel sprayed immediately after the lining has been sprayed. The biggest problem is that these tests are local tests on very small areas of sprayed concrete, and it is assumed that they are representative of the whole tunnel lining. This paper describes a new method of monitoring sprayed concrete strength gain, using an Arrhenius equation based maturity method that can calculate strength based on temperature history. Laboratory and on-site calibration tests are used to provide the parameters for the software, and a thermal imaging camera is used to measure the temperature.

## 1 INTRODUCTION

It is crucial to monitor the strength development of a sprayed concrete tunnel lining to ensure that the lining can support its own weight, support the ground loads and maintain the tunnel's stability, in order to protect workers and maximise production.

This paper will look at the risks resulting from inadequate strength gain of the sprayed concrete. It will then critically examine the standard methods used to mitigate those risks. The main part of the paper will describe a new method applied at Bond Street Station Upgrade in London, UK, called Strength Monitoring Using Thermal Imaging (or SMUTI).

### 1.1 *Fallouts of sprayed concrete*

King et al. (2016) analysed the potential causes of fall-outs of sprayed concrete on the Crossrail project. Although the majority of fall-outs occurred during spraying or within 15 minutes of completion of spraying the primary lining, there were some incidents of fall-outs occurring up to 2 hours later.

There are many possible causes of fall-outs, the most common of which are: high spraying rates in the crown building up layers too quickly, unfavourable geometry (e.g. filling localised overbreak), planes of weakness due to trapped rebound, laminations caused by pulsation or the presence of reinforcement, or striking young sprayed concrete with the excavator during the following advance, all of which could be considered 'workmanship'. The other main cause is insufficient strength gain.

### 1.2 *Overstressing of sprayed concrete*

Near to the face of a sprayed concrete lined tunnel, the dominant arching in the ground is from front to back, as this is usually a shorter distance than around the perimeter of the tunnel. However, as excavation progresses and the face moves forward, the arching eventually can only occur in the circumferential direction around the tunnel, resulting in higher loads. Therefore, as a sprayed concrete lined tunnel advances, more and more ground load is applied to the lining, until it reaches a short-term equilibrium.

At the same time, the sprayed concrete is gaining strength and stiffness. There is therefore an interaction between the stiffness of the sprayed concrete and the load-sharing between the sprayed concrete and the ground. There is also a need for the sprayed concrete strength to always be higher than the stress in the tunnel lining, and with an adequate factor of safety, otherwise it may fail.

### 1.3 *Standard methods of monitoring strength of sprayed concrete*

Early strength monitoring of a sprayed concrete tunnel lining is customarily achieved using a combination of needle penetrometer and stud driving tests in a test panel sprayed immediately after the lining. If early tests are passed, later stud-driving tests may be performed in the panel or in the lining itself. The biggest problem is that these tests are local tests on very small areas of sprayed concrete, and suffer poor repeatability. Testing cored samples may be more reliable, but this method is time-consuming, intact cores are difficult to obtain at early ages and it does not give immediate results.

It is also assumed that the in situ tests are representative of the whole tunnel lining, when there may be differences between the sprayed concrete in the test panel and the lining. The biggest factor is temperature, as the panel is often experiencing quite different temperatures to the lining, due to its larger surface area to volume ratio and potentially different environmental conditions.

## 2 BOND STREET STATION UPGRADE

Figure 1 gives an overview of the Bond Street Station Upgrade project. It is a £300 million pound, seven-year project, to increase capacity and introduce step-free access at the existing London Underground Bond Street station.

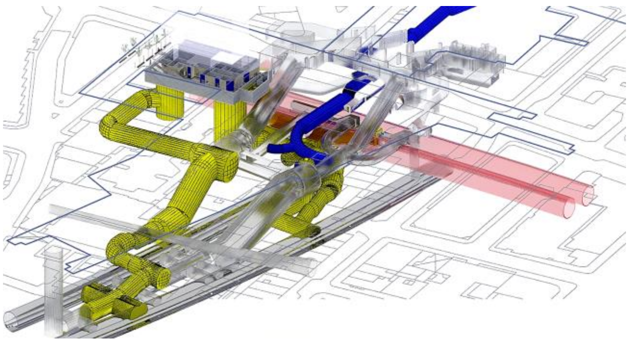

Figure 1. 3D model view of Bond Street Station Upgrade. Existing tunnels in transparent colours, new tunnels in yellow (London Underground) and blue (Crossrail link).

Having begun with civils works in 2010, the new passageways and satellite ticket hall are due for completion on-schedule in 2017. Tunnelling started in 2013, and the secondary lining (mostly sprayed concrete) was completed in May 2016. The 554m of new tunnels constructed (shown on Figure 1 in yellow and blue) had a challenging and complex geometry, often built within metres of existing operational tunnels and with a busy urban environment above.

### 2.1 *The beta-trial*

The site team were keen to improve methods of sprayed concrete strength monitoring, and having heard of the successful trials of SMUTI at Whitechapel Crossrail station (Jones et al., 2014; Ahuja & Jones, 2016), decided to apply it in what became known as a 'beta-trial'. The aim was to test the suitability of SMUTI for deployment in the production environment and to provide a case study for future projects.

SMUTI was implemented in 4 stages: (1) laboratory testing to determine the thermodynamic parameters of the sprayed concrete, (2) on-site calibration using sprayed panels, (3) training of engineers, and (4) operation and validation of the system.

### 2.2 *Laboratory testing*

Samples of the fine powder and liquid ingredients of the sprayed concrete (i.e. everything except the steel fibres, sand and aggregate) were taken to the laboratory at the University of Warwick for testing.

An isothermal calorimeter was used to test the cement paste at 10, 20, 30 and 40 °C. This allowed the determination of the activation energy using the graph shown in Figure 2.

Reactions between cement and water are exothermic, and therefore a small amount of energy (heat) is required for each chemical reaction to be initiated. Each chemical reaction then releases more heat than was put in. The activation energy may be thought of as the energy per mol required for reactions to occur. 4 tests were conducted at each of the 4 temperatures and the value of activation energy obtained was 37.71 kJ/mol.

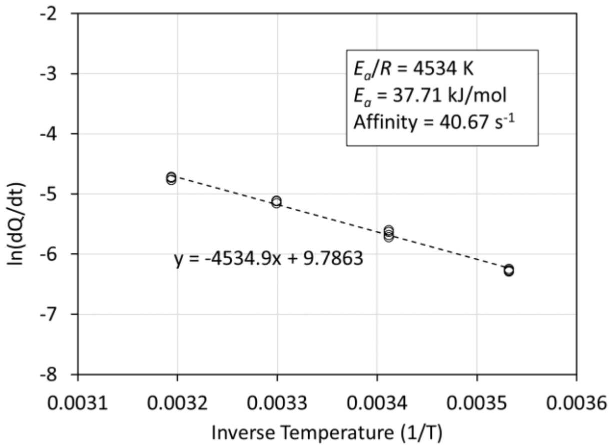


Figure 2. Activation energy determination for the BSSU cement paste

Figure 3 shows the normalised affinity plotted against degree of hydration. The degree of hydration is the proportion of reactions between cement and water that have taken place. The normalised affinity can be thought of as the driving force of chemical reactions, and its shape is a unique signature of a cement paste, dependent on admixtures, cement replacement materials, water content and the composition of the cement itself. The high initial value is the effect of the accelerator, which is followed by a short dormant period and then the long peak of the calcium silicate clinker hydration.

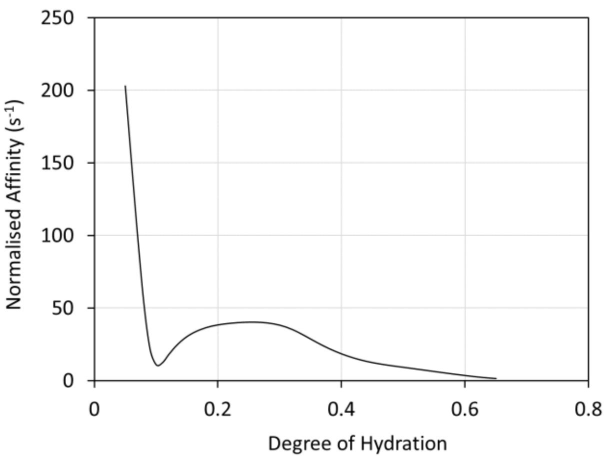


Figure 3. Normalised affinity of the BSSU cement paste

Once the activation energy and normalised affinity are known, the temperature of a cement paste, mortar or concrete can be used to determine instantaneous rate of hydration, using the Arrhenius equation, shown as Equation 1 below:

$$\frac{d\xi}{dt} = \tilde{A}(\xi)\exp\left(\frac{-E_a}{RT}\right), \tag{1}$$

where $\xi$ is the degree of hydration, $d\xi/dt$ is the rate of hydration in $s^{-1}$, $\tilde{A}(\xi)$ is the normalised affinity in $s^{-1}$, $E_a$ is the activation energy in J/mol, $R$ is the ideal gas constant 8.314 J/K.mol and $T$ is the temperature in K.

If the temperature history of the sprayed concrete is known, from the time of spraying onwards, then a time-stepping algorithm can be used to determine degree of hydration at any time. The degree of hydration is a measure of the maturity of the concrete, and will always have a better correlation with parameters such as compressive strength and Young's modulus (as well as creep, shrinkage and thermal properties) than age.

## 2.3 *On-site calibration*

The aim of the on-site calibration is to define the relationship between compressive strength and degree of hydration. This can only be done using sprayed concrete, as the compressive strength depends on all the constituents of the concrete mix (not just the cement paste), and the density, which is influenced by the placement method. Although it is possible to mix small quantities of cement paste with accelerator in the laboratory, it is not possible to mix concrete with accelerator properly except by spraying.

3 sets of 4 panels were used for the on-site calibration. Each set was sprayed from a different batch of shotcrete on a different day, as a check on repeatability.

A thermal imaging camera was used to record temperature histories of the panels, as shown in Figure 4, and the SMUTI calculation was used to determine the degree of hydration development for each panel.

At the same time, mechanical strength tests were performed on the panels according to EN 14488-2:2006, namely penetrometer tests between 0 and 1 MPa and Hilti pull-out tests above 3 MPa. We used the more powerful yellow cartridges for the higher strengths (which is not covered by the standard) and some of the later values are from coring.

A linear relationship was obtained between strength and degree of hydration, as shown in Figure 5, and this was input to the software to enable strength to be calculated.

As a check, the in situ test results are plotted against the SMUTI strength curves for each set of panels, and these are shown in figures 6, 7 and 8.

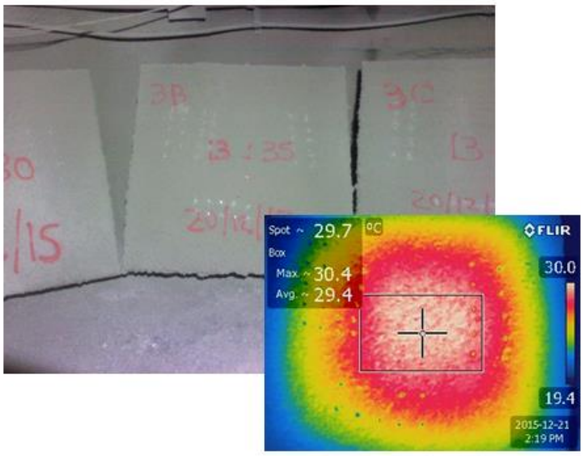


Figure 4. Calibration panels and thermal imaging

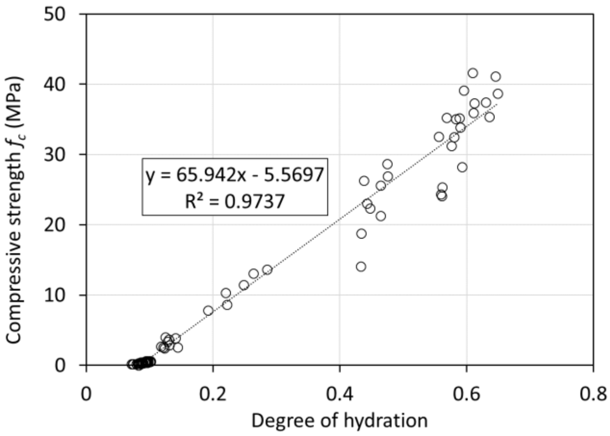


Figure 5. Relationship between compressive strength and degree of hydration

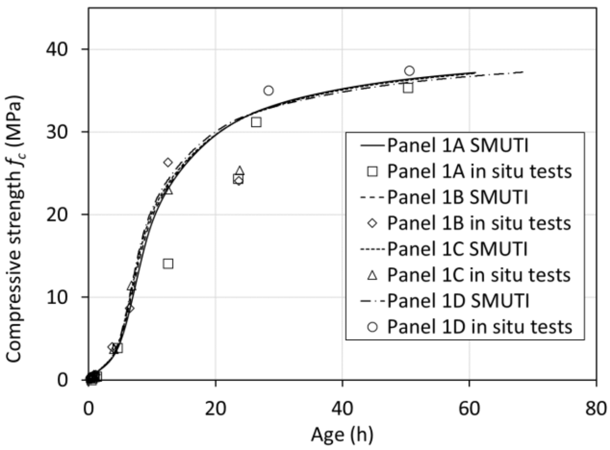


Figure 6. Calibration panels set 1

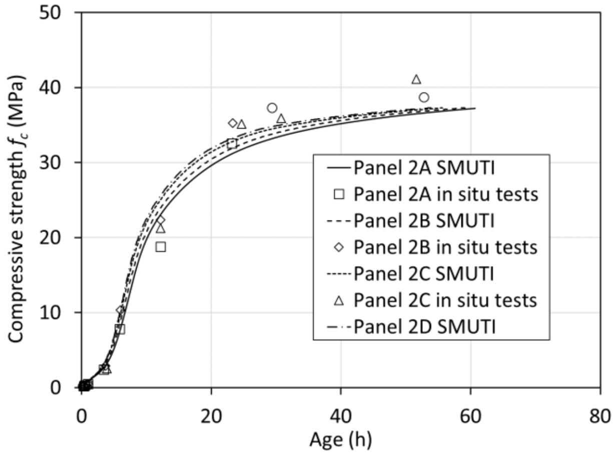


Figure 7. Calibration panels set 2

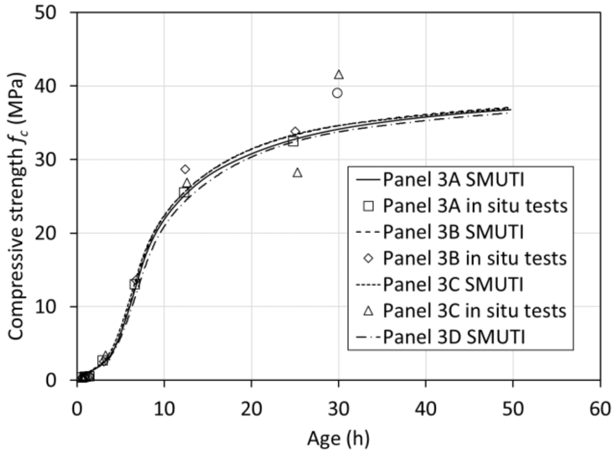


Figure 8. Calibration panels set 3

Figures 6, 7 and 8 show that scatter in the in situ strength test results is random, i.e. there are no panels where there is a clearly different trend in the in situ strengths compared to the SMUTI calculation.

## 2.4 *Training*

After the calibration stage, the aim was to get the site engineers to use the system for systematic monitoring of the shotcrete, alongside the existing in situ test methods.

Training was provided for the site engineers and shift managers, and also the foremen, nozzlemen, client and design representatives and inspectors. Each training session lasted approximately 1 hour 15 minutes and explained the background so everyone could understand how the system worked. Very little time was required to explain how to use the thermal imaging camera and the software as they are so intuitive and easy to use.

An unexpected added benefit of using the SMUTI system on site was the improved understanding of how concrete cures, upskilling the engineers and the workforce. It was also very important to ensure everyone felt part of the initiative, so that they would be motivated to put in some effort and make it work.

### 2.5 *Implementation*

The aim of the beta-trial was to assess the suitability of the method to implementation by site engineers in a production environment. A FLIR E40bx thermal imaging camera was used (Figure 9), and this proved to be surprisingly robust.

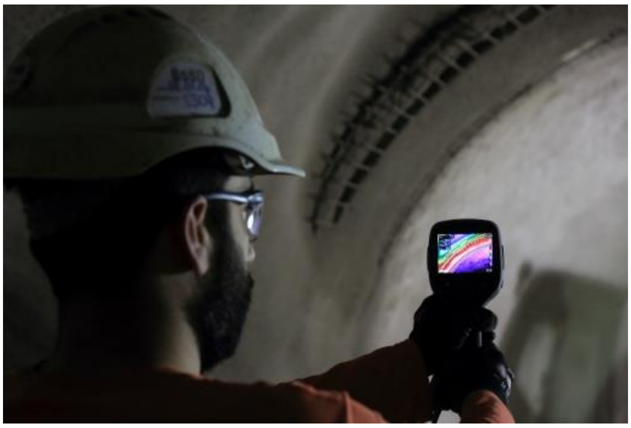

Figure 9. Site engineer using SMUTI to monitor shotcrete strength near the CONC1 tunnel headwall at Bond Street Station Upgrade

In order to record the temperature history accurately enough, temperatures were recorded for a minimum of 5 areas of each advance, at left axis, left shoulder, crown, right shoulder and right axis, at 0, 15mins, 30mins, 45mins, 1hr, 2hrs, 3hrs, 4hrs, 8hrs, 12hrs, 18hrs, 24hrs.

The site engineers found that using the system was not time-consuming, though it did require the engineers to visit the shotcrete to take readings more frequently than for existing methods. Compared to Hilti pull-out testing, which takes about 15 minutes to obtain one data point of strength, taking a temperature measurement with a thermal imaging camera, inputting it to the software and getting a result takes well under a minute.

The software is currently based on a server, and therefore can be accessed from any device with a browser and internet connection. At Bond Street Station Upgrade the tunnels had WIFI installed anyway, and tablets were being used by site engineers for accessing drawings and recording shift reports and quality assurance data, so no additional hardware was needed and temperature data could be input to the server immediately and shotcrete strength results returned immediately.

The safety benefits from the beta trial were substantial. There was increased awareness of strength differences between panels and the lining, and a better understanding amongst the inspectors and workforce of how concrete curing actually works. It also, critically, showed that it was easy to monitor safety critical areas of lining (such as the tunnel crown, see Figure 10), without being in close proximity to it.

Figure 10. Site engineer using SMUTI to monitor shotcrete strength in the CONC1 tunnel at Bond Street Station Upgrade

### 2.6 *Results from the beta-trial*

As an example of typical results, Figure 11 shows results obtained by site engineers for SMUTI and in situ strength tests in a panel. There were many more like this.

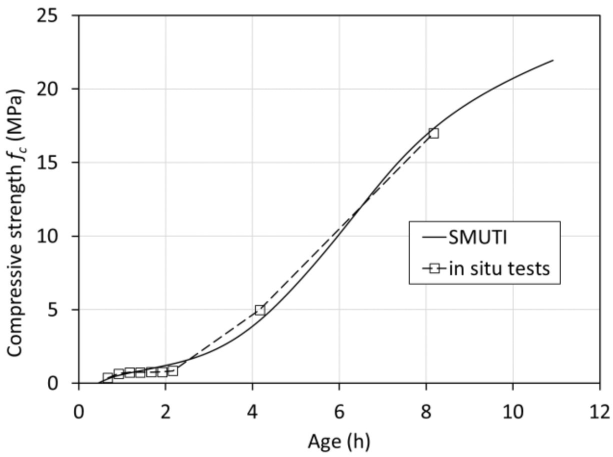


Figure 11. Strength results in Tunnel 4/209 Chainage 10

The in situ strength values up to 2hrs 15mins are from a needle penetrometer (Meyco needle), and after that, from stud driving (Hilti pull-out). The penetrometer gives a strength of 0.74 MPa at 1hr 15mins, and for the next hour barely increases, achieving 0.85 MPa at 2hrs 15mins, whereas SMUTI strengths continue to increase. This is a common problem with the needle penetrometer, where strength appears to remain virtually constant after achieving around 0.8 MPa, because it is difficult to apply any greater force to the instrument.

Figure 12 shows results from Tunnel 4/209 Chainage 33. The early tests in the panel (the crosses) were from penetrometer testing. SMUTI was also applied to the panel and to an area of the lining on the right-hand side (RHS) of the tunnel, based on the recorded temperature histories shown in Figure 13. Later in situ strength test results in the lining (circles) were from Hilti pull-out tests.

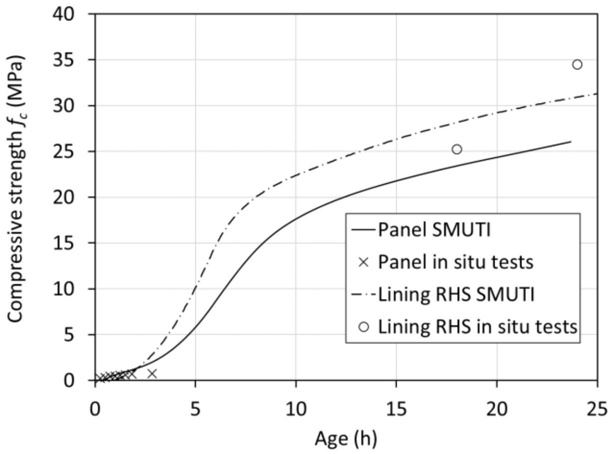


Figure 12. Strength results in Tunnel 4/209 Chainage 33

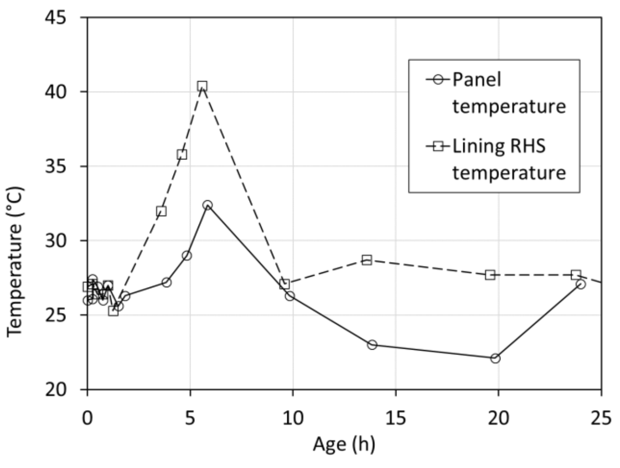


Figure 13. Temperature histories for Tunnel 4/209 Chainage 33 panel and lining RHS area

The difference between the two SMUTI curves in Figure 12 illustrates that the different temperature histories of the panel and the lining (the lining experiencing generally higher temperatures), results in a very different strength development. The Hilti pull-out test on the lining at 18hrs in Figure 12 used green cartridges, and therefore may have underestimated the strength as the test is not recommended for use above 16 MPa. The test at 24hrs used yellow cartridges.

Figure 14 shows a more detailed view of the needle penetrometer tests and SMUTI strength results in the panel from Chainage 33. Again, it shows how the needle penetrometer appears to flatline at 0.75-0.8 MPa. It also overestimates very early strengths compared to the SMUTI calculation. Partly this is due to some conservative assumptions in the SMUTI algorithm and parameters, but it is also because the penetrometer is measuring a kind of shear strength, which at very low strengths will include an important frictional component. SMUTI, being based entirely on chemical reactions in the cement paste, only relates to cohesion.

An alternative explanation is that at very early age, the relationship between degree of hydration and strength shown in Figure 5 may not be linear. This could happen because the products of hydration at very early age might not contribute to strength in the same way as the later silicate hydration. This is the subject of ongoing research.

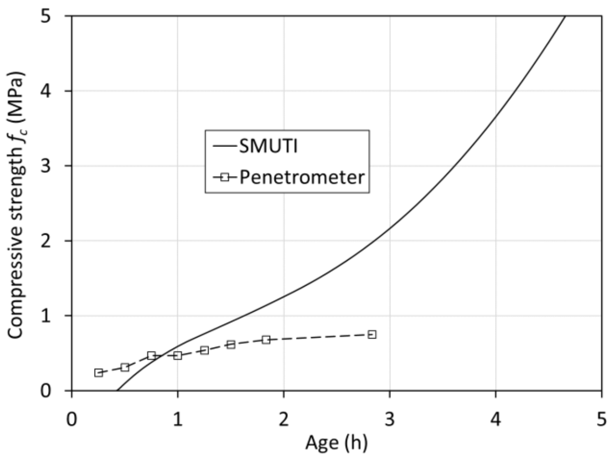


Figure 14. SMUTI and needle penetrometer results from Tunnel 4/209 Chainage 33, first 5hrs only

In order to prove beyond doubt that the later penetrometer results are unrealistic, Figure 15 shows all early age in situ compressive strength data plotted against degree of hydration, which was calculated from the individual temperature histories using the Arrhenius function.

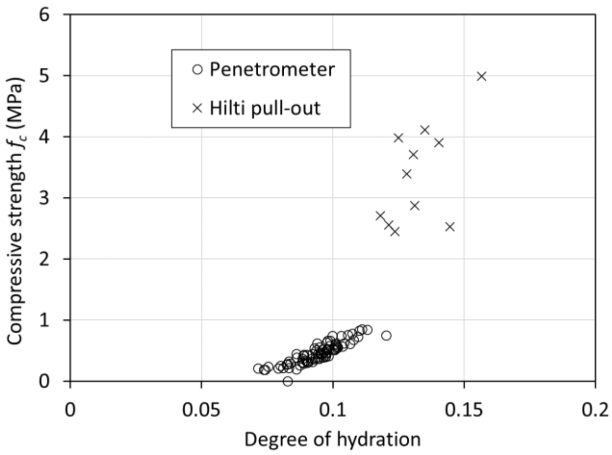


Figure 15. All early age in situ compressive strength test data (calibration and beta-trial) vs degree of hydration

Figure 15 clearly shows that a jump from a compressive strength of <1 MPa to around 2.5 MPa would be required, with very little increase in degree of hydration. This is simply not credible. Therefore, we consider that the SMUTI curves are more likely to be representative of the true strength gain, but of course it is not possible to validate this at present. Research is ongoing to find a better in situ test for the 0-3 MPa range.

## 3 CONCLUSION

SMUTI allows the strength of the whole shotcrete lining to be monitored continuously in real time from a secure position, bringing huge benefits to safety, quality control and productivity.

Strength results have excellent agreement with Hilti pull-out tests and coring results from 2-24hrs, and beyond.

From 0-2hrs it is not currently possible to fully validate the method due to shortcomings of the penetrometer test. However, the authors believe that the SMUTI results are plausible and are likely to be representative of the true strength. There is a real need for an in situ test to be developed that works reliably in the 0-3 MPa range to corroborate this.

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. There is widespread dissatisfaction with current strength monitoring methods, which suffer from poor repeatability and even poorer reproducibility – especially for the needle penetrometer.

The SMUTI software provides richer, more accessible and traceable data. It is intuitive and easy to learn how to use. Users have unique ID's, and any accidentally deleted data can be recovered from the server.

SMUTI doesn't need to replace traditional strength monitoring methods to be beneficial. When SMUTI 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.

On future projects it may be possible to replace some of the in situ testing with SMUTI. In the meantime it is providing very useful additional information that helps engineers at the tunnel face to make better decisions.

## ACKNOWLEDGEMENTS

Thank you to London Underground and Costain Laing O'Rourke JV for their support. Thanks also to everyone on the Bond Street site who helped make it work, with special thanks to Steve Nuttall, Paul Guider, David Terry, Francisco Gallego and Anita Wu.

SMUTI is patented and is also a registered trademark of Inbye Engineering Limited.

## REFERENCES

Ahuja, V. & Jones, B. D. (2016). Non-destructive approach for shotcrete lining strength monitoring. *Proc. of the World Tunnel Congress*, San Francisco, 22nd - 28th April 2016. Englewood, Colorado, USA: SME.

EN14488-2 (2006). *Testing sprayed concrete – Part 2: Compressive strength of young sprayed concrete*. Brussels: CEN – European Committee for Standardization.

Jones, B. D., Li, S. & Ahuja, V. (2014). Early strength monitoring of shotcrete using thermal imaging. *Proc. 7$^{th}$ Int. Symp. Sprayed Concrete, - Modern Use of Wet Mix Sprayed Concrete for Underground Support* (eds Beck, T., Woldmo, O. & Engen, S.), Sandefjørd, Norway, 16-19 June 2014, pp.245-254. Norway: Tekna & Norsk Betongforening.

King, M., St John, A., Brown, M. & Comins, J. (2016). Sprayed concrete lining falls and exclusion zone management. In: *Crossrail Project: Infrastructure Design and Construction – Volume 3*, pp.147-162. London: ICE Publishing and Crossrail.