# Études de cas européennes de l'imagerie thermique pour la surveillance de la résistance du béton projeté

# European case studies of shotcrete strength monitoring using thermal imaging


**Abstract**

«SMUTI» signifie Strength Monitoring Using Thermal Imaging (surveillance de la résistance à l'aide d'imagerie thermique), qui est une nouvelle méthode révolutionnaire de surveillance de la résistance initiale du béton projeté. La résistance de l'ensemble du revêtement du béton projeté peut être surveillée à partir d'une position de sécurité, aussi facilement que de prendre une photo.

A mesure qu'un tunnel en béton projeté avance, il est important de suivre l'évolution de la résistance du béton pour s'assurer que les mineurs ne risquent pas d'être accidentés par des chutes de béton et que le revêtement ait une résistance suffisante pour supporter les forces imposées par le massif. Ceci est habituellement réalisé en utilisant une combinaison de tests de pénétromètre et de cloueuse dans un panneau projeté immédiatement après le revêtement. Le plus gros problème est que ces tests sont des tests locaux sur de très petites surfaces de béton projeté, et on suppose qu'ils sont représentatifs de l'ensemble du revêtement de tunnel.

SMUTI est une nouvelle méthode pour contrôler le développement de la résistance, en utilisant une méthode de maturité sur la base de l'équation d'Arrhenius qui permet de calculer la résistance à partir d'une histoire de température mesurée. Les tests de laboratoire et d'étalonnage sur chantier sont utilisés pour fournir les paramètres du logiciel, et une caméra d'imagerie thermique est utilisée pour mesurer la température. Ce document présente trois études de cas du Royaume-Uni et en Allemagne montrant comment SMUTI a été utilisé pour réduire les risques sur le chantier.

'SMUTI' stands for Strength Monitoring Using Thermal Imaging, which is a revolutionary new method of monitoring the early strength of sprayed concrete. The strength of the whole shotcrete lining can be monitored from a safe position as easily as taking a photograph.

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 of 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.

SMUTI is 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. This paper will present three case studies from the UK and Germany showing how SMUTI has been used to reduce risks on site.

# Études de cas européennes de l'imagerie thermique pour la surveillance de la résistance du béton projeté

# European case studies of shotcrete strength monitoring using thermal imaging


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## 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. This is done to protect workers and maximise production.

This paper will describe a new method of mitigating and controlling the risks associated with inadequate strength gain, called Strength Monitoring Using Thermal Imaging (or SMUTI). Case studies will then be presented from Whitechapel Crossrail Station and Bond Street Station Upgrade in London, UK, and the ARGE Tunnel Oberau in southern Germany.

### 1.1 Early age strength monitoring

Current early age strength measurement methods, such as the needle penetrometer and stud driving tests to EN 14488-2: 2006, are primarily used for verification of conformity rather than for continuous monitoring. The actual volumes tested are very small relative to the volume sprayed, and tests are often performed on test panels, which do not experience the same conditions as the lining.

There are also issues with the repeatability of these tests, and partly this is due to the heterogeneity of concrete when testing such small volumes, and partly due to operator errors. It is easy to use the wrong cartridges or power setting on the Hilti gun, for example, or the wrong length stud. Inserting and pulling out 10 studs can also take around 15 minutes, to obtain just one strength reading. The standard penetrometer test has a limited range, realistically between 0.2 and 0.8 MPa, and the standard stud driving test can only be used from 3 MPa onwards. It is also common to misreport the time of spraying or the time of the test.

There is therefore a need for a simple, cost effective method of continuous monitoring of strength development in all parts of the shotcrete tunnel lining. This would provide much greater confidence in the extrapolation of in situ tests, and perhaps allow them to be done less often and more carefully.

### 1.2 Theoretical background to SMUTI

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 by a straight line. If this relationship is known for a given concrete mix, then concrete compressive strength ($f_c$) may be estimated if degree of hydration ($\xi$) is known.

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, as shown in Figure 1. 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:

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

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 water/cement ratio, the chemical admixtures and the supplementary cementitious materials. Therefore, they must be determined for each shotcrete mix used on site.

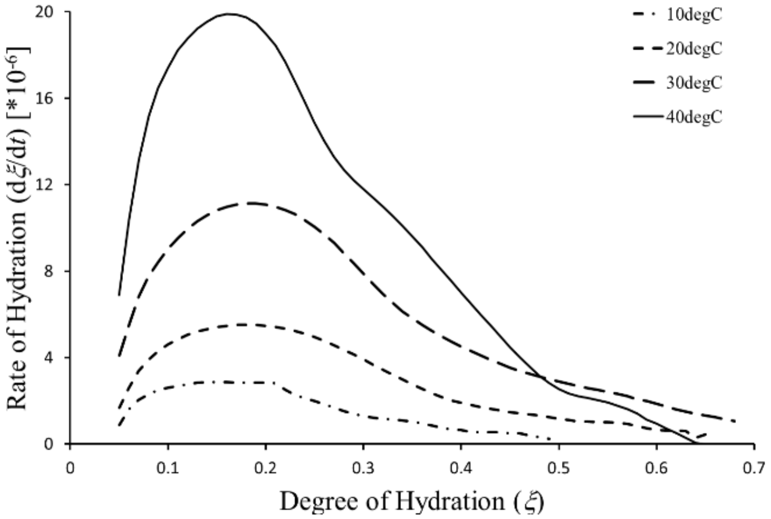


**Figure 1: Representation of change in rate of hydration versus degree of hydration development, at different constant temperatures**

SMUTI was invented and patented at the University of Warwick by Benoît Jones. The technology is now owned by Inbye Engineering Limited, where it is being continually 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), Jones et al. (2014), Ahuja & Jones (2016), 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 ($\xi$).

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.

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 are used to calculate degree of hydration.

## 2 Field application at Whitechapel Crossrail Station

At Whitechapel Crossrail Station, large caverns were being constructed in sprayed concrete, mostly in London Clay – a stiff overconsolidated clay. The use of SMUTI on this project was the subject of a previous paper (Ahuja & Jones, 2016), so the results will not be discussed in detail here.

The objective was to assess the feasibility of SMUTI to measure shotcrete strength in real conditions. All measurements were made by a PhD researcher (one of the authors - Vishwajeet Ahuja) and were therefore of high quality. The ability of the thermal imaging camera to remotely measure temperatures was assessed by comparing readings to thermocouple measurements at the surface of a sprayed concrete panel.

The method worked well on site and taking thermal images proved to be very easy. 40 sprayed concrete panels were sprayed for in situ testing and simultaneous thermal imaging. SMUTI provided very good results when compared to in situ tests.

Various improvements were made to the laboratory testing methodology and the calculation algorithm during this project, for instance the timesteps were reduced to improve accuracy. The modelling of the accelerator reaction was also improved to reduce the number of assumptions made at the start of hydration.

## 3 Field application at Bond Street Station Upgrade

Bond Street Station Upgrade involved approximately 550 m of new tunnels, again mainly in London Clay. SMUTI was deployed for the sprayed concrete secondary lining between March and May 2016. The objective was a 'beta-trial'; for the engineers on site to use the SMUTI software during construction, in order to assess its user-friendliness and reliability in a production environment.

Existing in situ test methods, consisting of needle penetrometer and stud driving tests, were used in parallel. As part of the safe system of work, the site engineers were instructed to act according to the lower strength result.

### 3.1 Laboratory 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. The value of activation energy obtained was 37.71 kJ/mol.

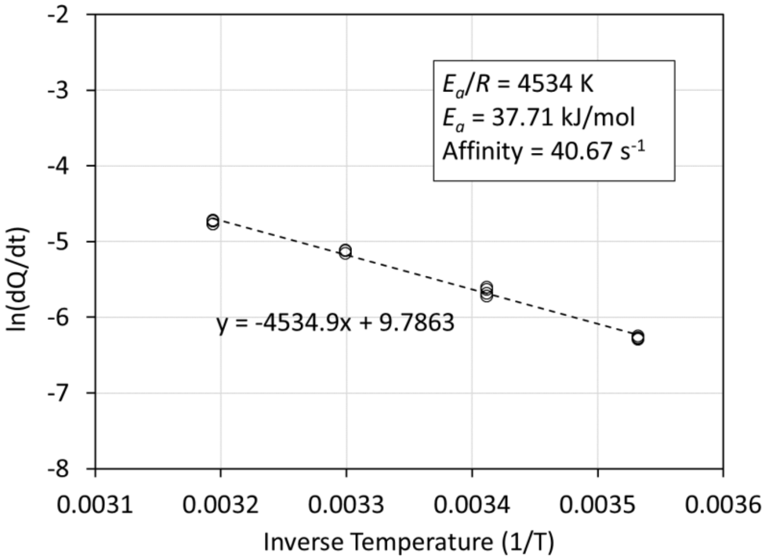


**Figure 2: Isothermal calorimetric testing of the BSSU shotcrete mix**

Figure 3 shows the normalised affinity plotted against degree of hydration. 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. Modelling the accelerator reaction was new for this project, and was enabled by a non-standard interpretation of the isothermal calorimetry along with simultaneous thermogravimetric analysis.

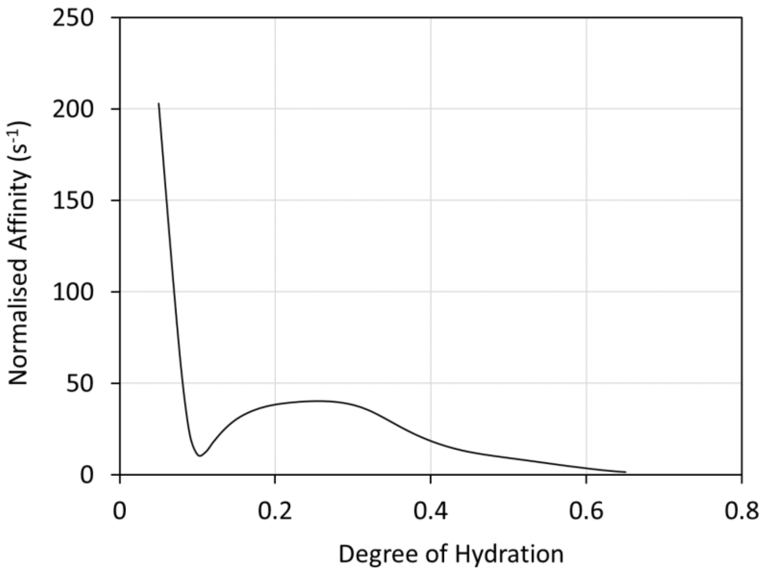


**Figure 3: Normalised affinity for the BSSU shotcrete mix**

### 3.2 On-site calibration

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.

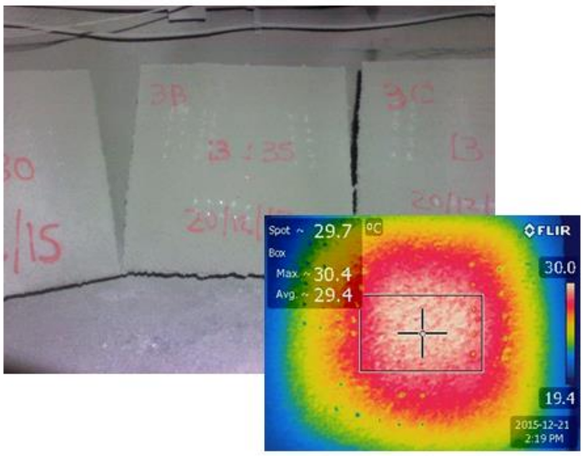


**Figure 4: Thermal imaging of calibration panels**

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.

### 3.3 Beta-trial

The site engineers were trained in the use of SMUTI. Very little instruction was needed in the use of the thermal imaging camera or the software, as they are very easy to use. 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.

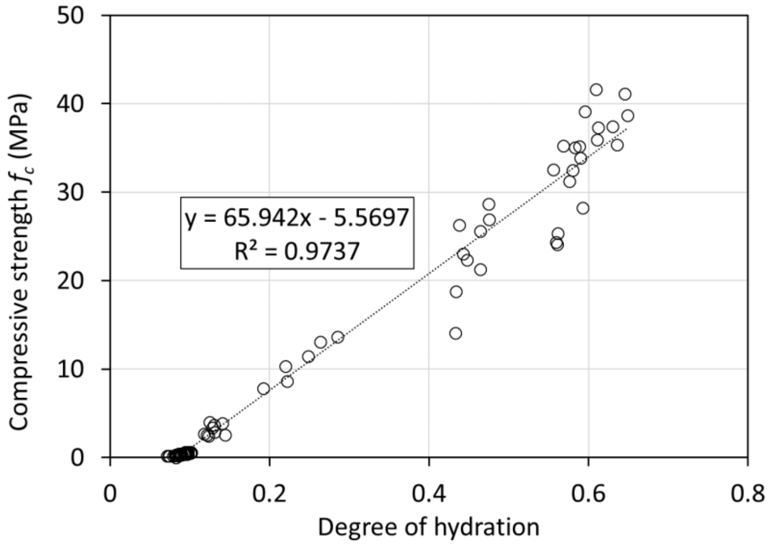


**Figure 5: Calibration relationship between compressive strength and degree of hydration**

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 stud driving tests, which take 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 a matter of seconds.

The software is currently based on a server, and therefore can be accessed from any device with a browser and internet connection. At BSSU the tunnels had WIFI installed, 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 crown, without being in close proximity to it. An example of strength development measured in a test panel is shown in Figure 6.

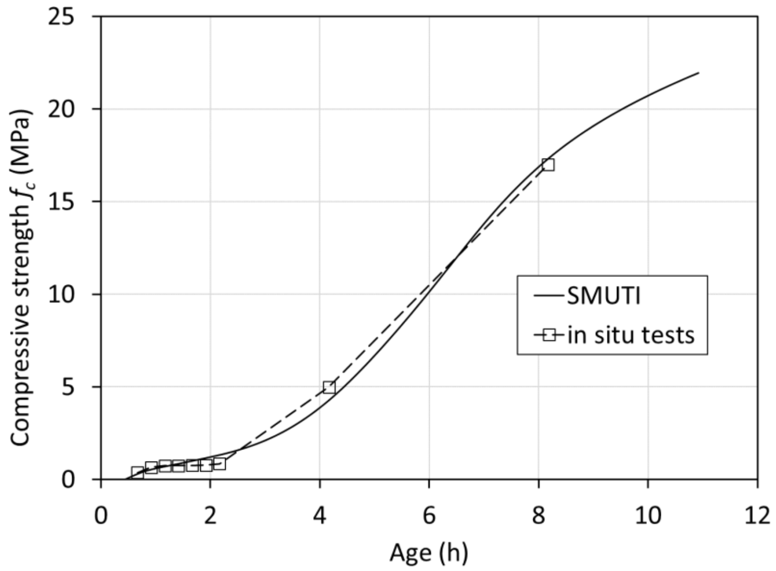


**Figure 6: Strength results in Tunnel 4/209 Chainage 10**

# 4 Field application at the ARGE Tunnel Oberau

The ARGE Tunnel Oberau is a 3 km twin bore highway tunnel in Bavaria, Germany. It is being constructed by drill and blast and shotcrete is being applied as the primary lining. The final lining will consist of cast in situ concrete. In some sections there is water inflow, which can flow down the face of the newly-sprayed shotcrete. The water is at approximately 12 °C, and hence has a significant impact on the rate of strength gain of the approximately 100 mm thick shotcrete lining.

The lowest and highest recorded shotcrete surface temperatures are shown in Figure 7. The effect of this temperature difference on the strength development is shown in Figure 8. This large range in strength development was also found by in situ testing of the lining and panels and further demonstrates the importance of temperature to strength development.

The software was improved for the ARGE Tunnel Oberau project by including German language, improving the presentation of results, and an offline version of the software has been developed because the tunnel does not have an internet connection and is too long for engineers to exit the tunnel to obtain a strength result. The device will then synchronise with the database on the server whenever it has an internet connection available.

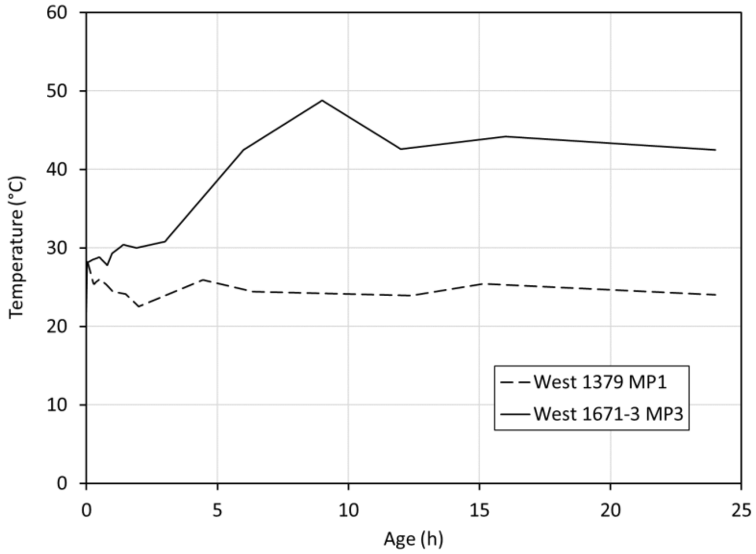


**Figure 7: Extremes of shotcrete surface temperature measured in the ARGE Tunnel Oberau**

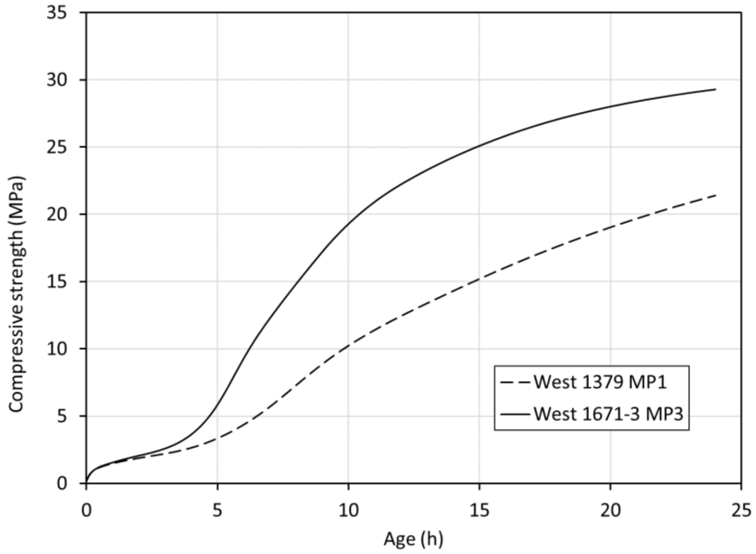


**Figure 8: Extremes of strength development measured by SMUTI in the ARGE Tunnel Oberau**

## 5 Conclusions

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 very good agreement with in situ tests up to 24hrs. Unfortunately, from 0-2hrs it is not currently possible to fully validate the method at present due to shortcomings of the penetrometer test. 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.

The SMUTI software provides rich, 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.

Future developments will aim to integrate SMUTI into other technologies to provide a complete solution for the tunnel engineer at the face of the tunnel. There will also be a continued focus on validation of the first 2 hours of strength development.

## 6 Acknowledgements

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