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Nondestructive Approach for Shotcrete Lining Strength Monitoring

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Shotcrete lining forms an integral part of conventional tunneling and is widely applied for underground excavations. Early strength gain of the shotcrete is a crucial aspect for ground support and safety of operatives. Strength requirements are dependent on various factors such as lining thickness, ground type, excavation size, and tunnel depth. The early strength gain is typically monitored using destructive tests, such as needle penetration, stud driving or coring samples for uniaxial compressive strength testing in the laboratory. Being destructive, these tests cannot be directly performed onto the lining without causing damage that must be repaired, which is a particular problem for permanent linings. For this reason and to avoid the need for operatives to work near exposed ground and/or fresh shotcrete, these destructive tests are often performed on panels, which are sprayed at the same time as the tunnel lining. All current testing methods are also very local, testing only a small part of the lining or a panel, which may not be representative because the temperature history could be significantly different. Therefore, these tests do not provide an accurate or complete picture of the lining strength gain. New testing methods that are non-destructive and can scan the whole lining remotely would be extremely desirable. This paper describes a new method, using thermal imaging techniques, that achieves these aims. It also discusses the real-time on-site application of the method, providing insight into the experience gained and conclusions derived.

Shotcrete

Shotcrete used for tunnel linings requires immediate strength development. The strength

development is a direct result of the hydration reaction of cementitious materials present in it. A progressive sequence of the hydration reaction changes it from a solid suspension (typically referred to as fresh concrete) to a solid skeleton with a porous network and thereafter into a solid with predominantly discontinuous pores (Byfors 1980). In the case of shotcrete, early strength is needed to support the self-weight and then continuing early age strength gain is required to begin to support ground loads. These strength requirements, along with other workability needs, are met by careful concrete mixture design, the use of admixtures, such as accelerator and superplasticizer (BS EN 934-5 2007), and supplementary cementitious materials, such as silica fume.

Strength Development

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 Fig. 1. If this relationship is known for a given concrete mixture, then concrete compressive strength (f_c) may be estimated if degree of hydration (ξ) is known.

Like many other chemical reactions, the rate of hydration ($d\xi/dt$) for a given concrete mixture is dependent on temperature as well as the degree of hydration, as shown in Fig. 2. Thus, it is widely accepted that the degree of hydration and, in turn, strength development is dependent on its temperature history (Byfors 1980). Various maturity functions have been developed, such as those presented in ASTM C1074 (2011), which can be used to estimate strength development

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from time-temperature histories. Out of the various available functions, the Arrhenius equation-based maturity function is the most widely accepted. This relationship between rate of hydration, temperature and degree of hydration was first demonstrated to be appropriate for concrete in works of Freiesleben Hansen and Pedersen (1977) and is formulated as shown in 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). This function is useful while the activation energy is not varying. For cement hydration, it is applicable while the reaction is propelled through exothermic heat and is not diffusion based. This means this relationship is best applied in the ranges of $0.05 < \xi < 0.5$ (Kada-Benameur et al. 2000). 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 mixture used on site.

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

Early Age Strength Determination for Shotcrete

Currently accepted early age strength tests include needle penetrometer and stud driving and are conducted on site as described in BS EN 14488-2 (2006). At very early ages, these tests cannot be directly performed on the lining due to the danger of freshly sprayed shotcrete falling down. For this reason, shotcrete panels are used for these tests and are sprayed immediately after the lining has been sprayed. 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.

New Testing Approach

The proposed approach is based on developing 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 can help determine degree of hydration and, in turn, the

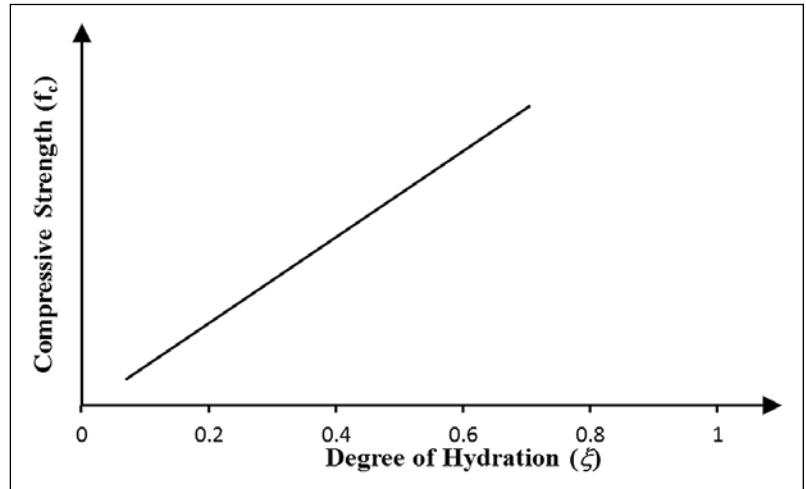


Fig. 1: Representation of linear relationship between concrete compressive strength and degree of hydration

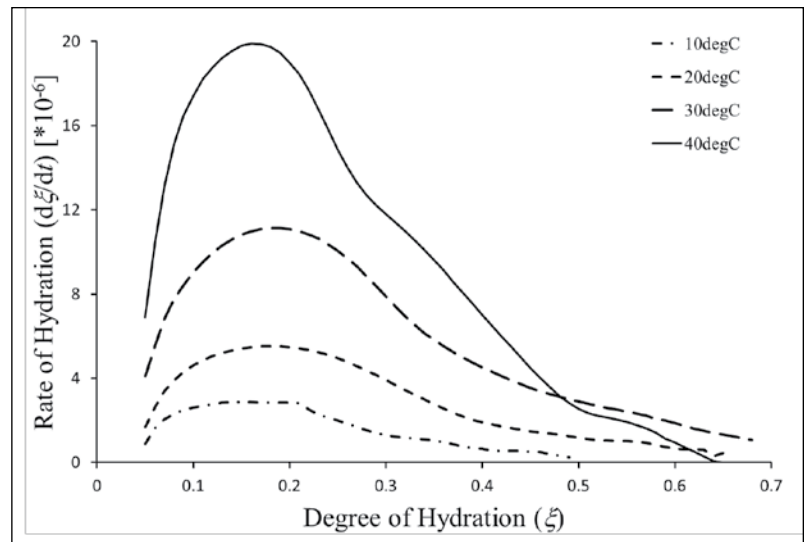


Fig. 2: Representation of change in rate of hydration versus degree of hydration development

compressive strength development. Currently, this patented approach is under further development at the University of Warwick and is being referred to as Strength Monitoring Using Thermal Imaging™ (SMUTI). Jones and Li (2013) and Jones et al. (2014) discuss various aspects of this approach in detail. Before using Equation (1), input parameters, such as $\tilde{A}(\xi)$ and E_a , are needed. Since these parameters are unique to a concrete mixture, they need to be re-evaluated if any major change is made, through lab testing such as isothermal calorimetry. Similarly, the linear relationship between f_c and ξ is also unique to a given mixture and must be determined independently for each mixture type. Due to the method of application, it is not realistic to conduct

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any strength testing inside a lab and so this requires real time field testing.

Field Application

Field trials were undertaken during primary shotcrete lining works at Whitechapel station, being constructed by BBMV, a joint venture of Balfour Beatty, BeMo Tunnelling, Morgan Sindall and Vinci Construction. The scope of field application was limited to collecting real-time thermomechanical data.

Mechanical Testing

Due to the importance of early age strength development, stringent testing criteria requiring in-situ testing, such as needle penetrometer and stud driving (BS EN 14488-2 2006), were specified. These tests were conducted separately on the panels sprayed immediately after the lining spray was finished. Table 1 describes the typical details of the testing methods used during the field testing.

Thermal Imaging

The temperature variations in the early age of concrete, mainly caused by hydrating portland cement, can be measured by thermal imaging using

a camera with the capability of detecting infrared (IR) radiations. A FLIR E60bx camera was used. Figures 3(a) and (b) show digital and thermal images, respectively, of a shotcrete lining section demonstrating how thermal imaging can measure the temperature remotely. For the shotcrete panels only the top surface was imaged whereas for the lining, surface areas of key locations such as crown, shoulders, and axis level are monitored.

Site Testing

The following testing procedure was adopted for the field trials in order to validate the method (this will not be the procedure when SMUTI is used for systematic monitoring):

1. Select appropriate lining section;
2. Prepare five shotcrete panels, corresponding to lining section, for mechanical testing and thermal imaging purposes; and
3. Thermal imaging of lining section.

The shotcrete mixture design is shown in Table 2.

Results and Discussion

The following section discusses results corresponding to testing and thermal imaging of a

Table 1: Tests Performed on Shotcrete Panels

Stage	Test Type	Strength Range (equivalent cylinder compressive strength)	Time and Frequency	Typical Test Apparatus
1	Penetration needle (panels only)	14.5 to 145 psi (0.1 to 1.0 MPa)	Up to 1 hour Minutes – 15, 30, 60	Meyco Penetrometer
2	Stud driving (panels only)	290 to 2320 psi (2.0 to 16.0 MPa)	Up to 24 hours Hours – 3, 6, 12, 24	Hilti DX 450-SCT

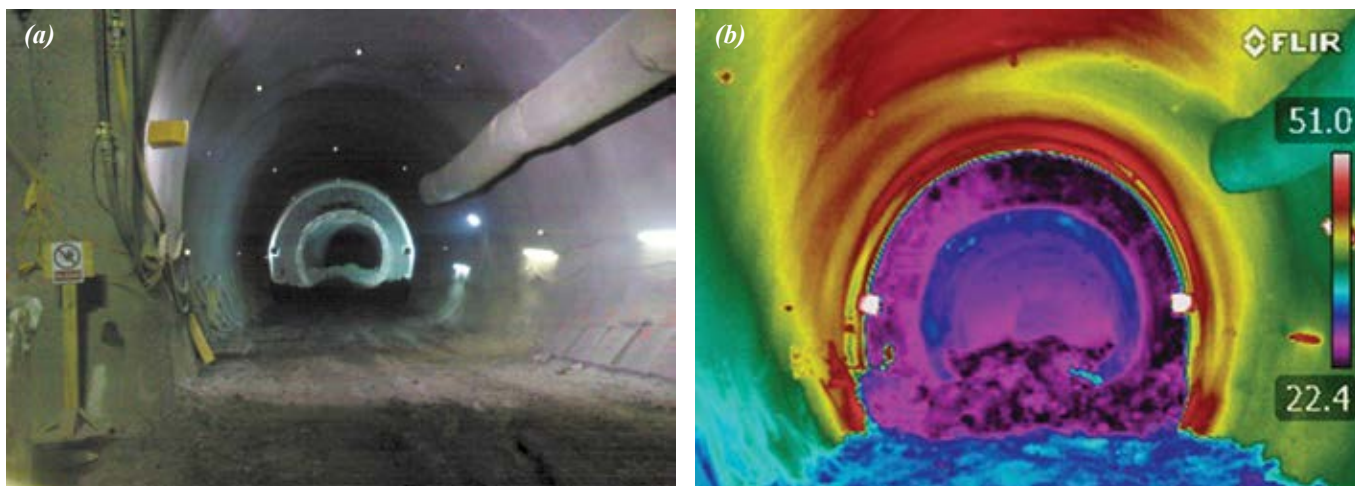


Fig. 3: (a) Digital and (b) thermal images taken during the early age of shotcrete lining demonstrating the ability of thermal imaging to measure temperatures remotely

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Table 2: Primary Shotcrete Mixture Design P1

Content	Type	Quantity, kg/m ³ (lb/yd ³)	Ratio/dosage*
Cement	CEM I 52.5 N	420 (708)	—
Water	—	173 (292)	0.41
Aggregate	Limestone (0/4)	590 (995)	—
Aggregate	Marine Sand (0/4)	590 (995)	—
Aggregate	Limestone (2/6)	505 (851)	—
Microsilica slurry	EMSAC 500 S	52 (88)	12.38%
Retarder	Pantarhol 85 (VZ)	6 (10)	1.43%
Superplasticizer	Pantarhit T100CR (FM)	4.8 (8)	1.14%
Accelerator	Gecederal F 2000 HP	Added at spray	5.50% (averaged)
Steel fibers	Steel HE 55/35	35 (59)	—

*Dosage in percentage (%) of cement weight basis

lining section in the Eastbound Rail Tunnel – West (EBRT-W) pilot tunnel.

EBRT-W Pilot Tunnel Primary Shotcrete Lining Section

Five shotcrete panels were tested using a needle penetrometer and stud-driving as described in Table 1. Concurrently, thermal imaging was performed. Figure 4 shows real time strength (dashed lines) and temperature (dotted lines) histories. The strengths of up to 14.5 psi (1.0 MPa) were determined using the needle penetrometer while the rest were determined using standard-

method green cartridge stud-driving using Hilti DX 450 SCT as described in its operating instructions (Hilti, 2009).

It can be seen that the panels have achieved strengths of around 2180 psi (15.0 MPa) at the age of 12 hours and have approached the upper limit of the stud-driving test. Therefore, further mechanical testing was not useful. In the case of the temperature histories, a typical temperature variation pattern was observed with initial lowering of temperature, approaching 84°F (29°C), during the first hour after spraying and increasing thereafter, peaking at more than 88°F

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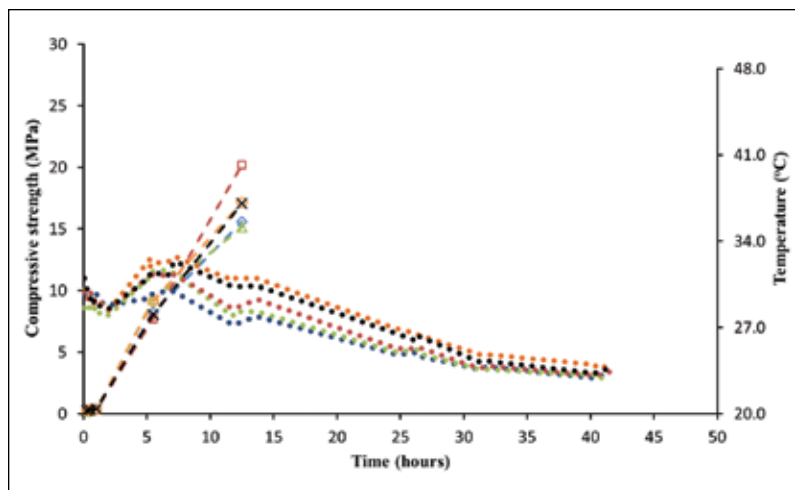


Fig. 4: Shotcrete panel strength and temperature histories for EBRT-W section

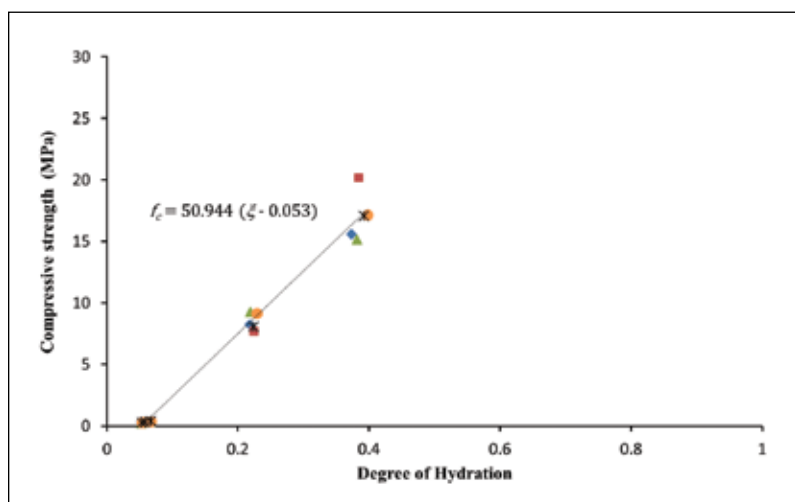


Fig. 5: f_c - ξ relationship from shotcrete panels corresponding to EBRT-W lining section

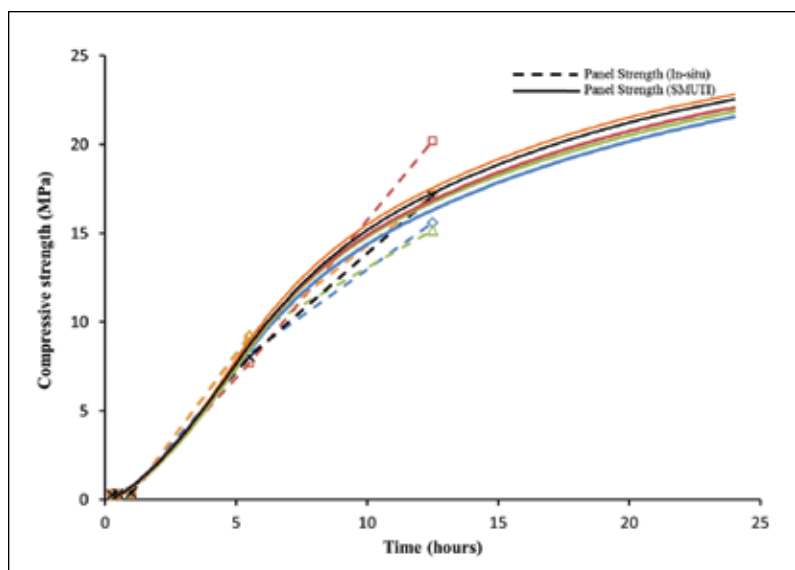


Fig. 6: Panel strengths—in-situ measurements and SMUTI estimation

(31°C). Afterwards, a consistent decrease was observed, stabilising at around 73°F (23°C) at the age of 40 hours.

The panel temperature histories in conjunction with Equation (1) were used to estimate the degree of hydration and are correlated to the strength histories. The input parameters for the rate of hydration equation were determined by isothermal calorimetric testing using an I-Cal 4000, manufactured by Calmetrix. The detailed results will be published in later publications. In the analysis, it was assumed that the shotcrete had achieved initial degree of hydration of 0.05 by the end of spray and started gaining strength immediately.

Figure 5 shows the f_c - ξ relationship deduced from the panel strength and temperature histories.

Using the f_c - ξ relationship shown in Fig. 5, the panel strength development was obtained from the calculated degree of hydration. Figure 6 provides a plot comparing strengths measured by in-situ tests and the strengths calculated using SMUTI. The average error between the in-situ and calculated strengths was approximately 7% while the maximum error was less than 17%. This may be due to the variability of the in-situ strength tests rather than inaccuracy of the SMUTI calculation. The maximum error occurred for the panel achieving the strength of 2900 psi (20 MPa). Since this strength was measured beyond the limit of the stud-driving range, it may not be reliable.

Next, the lining hydration was calculated using its temperature history. Figure 7 and Fig. 8 are comparative plots showing temperature histories and calculated degree of hydration, respectively, for the panels and lining section. It can be observed that as the temperature histories of the panels and the lining section were very different, so were the hydration developments. Further, the lining strength development was estimated using the f_c - ξ relationship and calculated degree of hydration shown in Fig. 5 and Fig. 8, respectively. These estimates are shown in Fig. 9, which is a comparative plot for strength histories of the five panels and three key locations of the lining (calculated using SMUTI).

Discussion

Figure 7 shows the lining surfaces were warmer than the panel surfaces, which means the lining experienced higher rate of hydration in its early age than the panels. Thus, the degree of hydration of the lining is always greater than that of the panels, in this case. This higher degree of

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hydration is shown in Fig. 8. It can be observed that the panels have an average degree of hydration of 0.12, 0.24, 0.38 and 0.49 at the ages of 3 hours, 6 hours, 12 hours, and 24 hours, respectively. On the other hand, the lining areas achieve an average degree of hydration of 0.15, 0.29, 0.44, and 0.61 at the ages of 3 hours, 6 hours, 12 hours, and 24 hours, respectively. The lining also experienced faster strength gain as while the panels had an average compressive strength of 16.6 MPa at 12 hours, the average lining strength was 2860 psi (19.7 MPa).

Additionally, with an average degree of hydration of 0.61 at 24 hours, the lining had achieved an average compressive strength of 4120 psi (28.4 MPa). It must be pointed out that from the f_c - ξ relationship shown in Fig. 5, it could be asserted that the shotcrete can achieve an average long-term strength of more than 6960 psi (48 MPa). This relationship was reasonably verified as the mean 90-day strength of the lining cores was determined to be 6860 psi (47.3 MPa).

Conclusions and Future Works

From the results shown in the previous section, the following can be concluded:

1. The Arrhenius equation-based temperature-sensitive maturity function is a useful tool to estimate shotcrete strength through the remote and nondestructive approach adopted in SMUTI.
2. With an average variation of 7% between the measured and calculated panel strengths, SMUTI appears to provide useful estimates that are in close agreement with the in-situ tests.
3. The f_c - ξ relationship deduced from the panel testing was reasonably verified by available 90-day lining core strengths averaging to 6860 psi (47.3 MPa).

While a promising step has been taken, further laboratory testing and on-site application is the most logical next step. This will improve understanding of degree of hydration development of shotcrete, especially when various admixtures, such as accelerator and superplasticizer, are key participants in its application. It will also enable the reliability of the method to be assessed.

SMUTI has the potential to provide the strength gain of the whole shotcrete lining (as against local tests on a panel) from a remote location. This is a step-change in safety and quality control of shotcrete tunneling.

As a final remark, the authors envisage that integration of the thermal imaging capability into tunnel setting out and convergence monitoring survey systems will further simplify the workflow

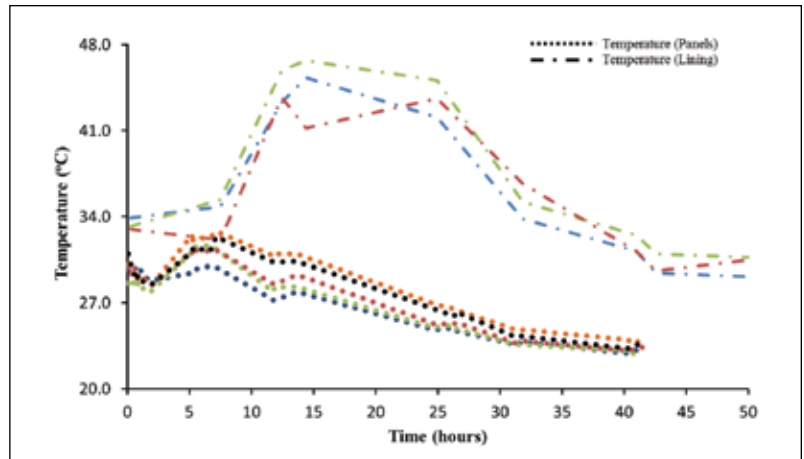


Fig. 7: Temperature histories for tested panels and corresponding EBRT-W lining section

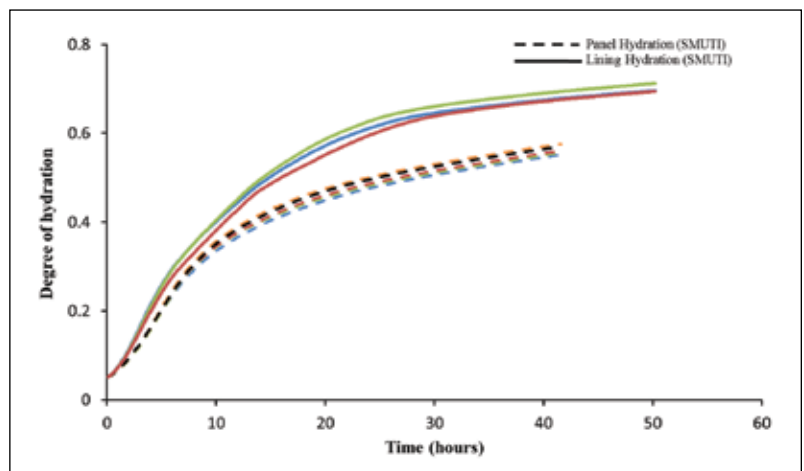


Fig. 8: Degree of hydration determination using temperature histories of EBRT-W section

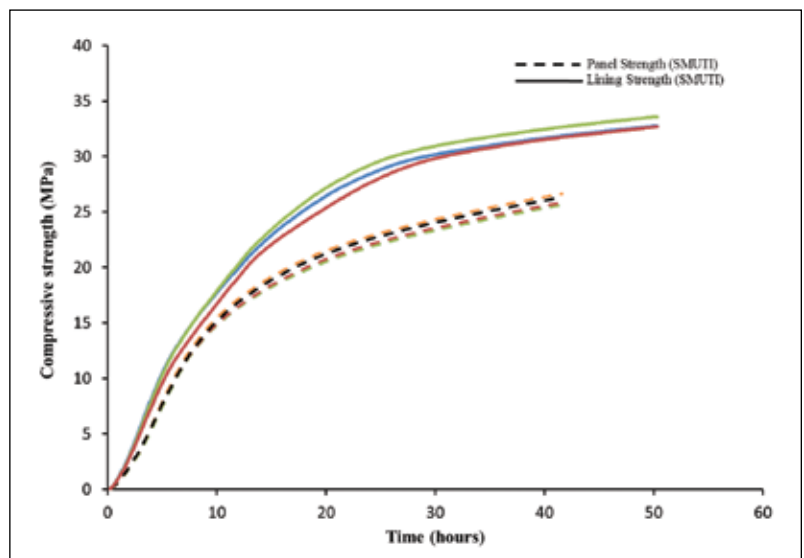


Fig. 9: Comparative plot showing in-situ panel strength and estimated strength for EBRT-W lining section

and provide an integrated and powerful tool for the engineer to make informed decisions about the safety of the tunnel.

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Vishwajeet Ahuja holds a wide array of experience in NATM/Conventional Tunneling. He has worked on a variety of railway and road tunneling projects, such as Crossrail, Dulles Metrorail, and Rohtang, involving both the soft ground and hard rock conditions while working for consultancies such as Atkins, Dr. Sauer Corp., Gall Zeidler Consultants, and SMEC. He is associated with various technical societies and groups, such as the American Society of Civil Engineers, American Concrete Institute, Institution of Civil Engineers, ITA WG20, and the Tunnelling Association of India. Currently, he is pursuing his PhD in engineering at University of Warwick, Coventry, UK, with a focus on early-age strength development of shotcrete for tunnel lining.



Benoit Jones has worked for 15 years in the tunneling industry for Mott MacDonald, Morgan Sindall, OTB Engineering, and until recently, the University of Warwick, where he retains a position as an Honorary Fellow. He has worked on major projects such as Heathrow Terminal 5 tunnels, High Speed 1, Crossrail, King's Cross Underground Station Redevelopment, and Tottenham Court Road Station Upgrade. In 2007, he received his engineering doctorate for research on stress measurement in sprayed concrete linings and numerical modeling of tunnel junctions. He has won the ICE's Telford Premium Award for a paper on the interpretation of tunnel monitoring, has twice given the prestigious ICE Geotechnical Engineering Lecture, and has written a large number of popular articles on advances in tunneling. He is the inventor of Strength Monitoring Using Thermal Imaging (SMUTI) and is Managing Director of Inbye Engineering, a spin-out company of the University of Warwick set up to enable the adoption of SMUTI by the tunneling industry. The patent and trademark for SMUTI are owned by Inbye Engineering.