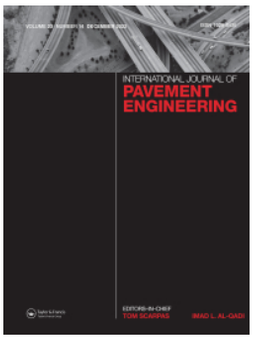

International Journal of Pavement Engineering

ISSN: 1029-8436 (Print) 1477-268X (Online) Journal homepage: www.tandfonline.com/journals/gpav20

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To cite this article: Aziz Hasan Mahmood, Ian Hampton, Eric Bescher, Louisa Pang & Arnaud Castel (2025) On-site strain and temperature monitoring of belitic calcium sulfoaluminate cement concrete airport slabs: feasibility of maturity method, International Journal of Pavement Engineering, 26:1, 2518153, DOI: 10.1080/10298436.2025.2518153

To link to this article: https://doi.org/10.1080/10298436.2025.2518153

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INTERNATIONAL JOURNAL OF PAVEMENT ENGINEERING
2025, VOL. 26, NO. 1, 2518153
https://doi.org/10.1080/10298436.2025.2518153

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On-site strain and temperature monitoring of belitic calcium sulfoaluminate cement concrete airport slabs: feasibility of maturity method

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ABSTRACT

Expedient belitic calcium sulfoaluminate (BCSA) cement concrete slabs were used to upgrade the taxiway slabs at the Melbourne Tullamarine Airport. The on-site strain and temperature profiles of the BCSA cement concrete were monitored. The datum temperature of BCSA cement was determined, and a flexural strength-maturity calibration was proposed for the concrete mix following recommendations of TfNSW T382, ASTM C1074 standards and project specifications, utilising the temperature-time factor. The correlation was tested to predict the on-site strength development of concrete slabs within a precision of ±10%, which assisted with the safe saw-cutting of contraction joints and the reopening of pavement to traffic. The strain data revealed that BCSA cement concrete slabs exhibit low shrinkage to an order of below 220 με, with the section at mid-depth shrinking relatively more than the top. This indicates that the slabs swell in a convex geometry as opposed to OPC concrete slabs, offering potential additional geometric longevity to the slab. Concrete mechanical properties confirm a rapid early-age strength development of over a target 3.1 MPa flexural strength within 4 h of placement. This work validates that the maturity method can be applied to BCSA cement concrete.

ARTICLE HISTORY
Received 28 January 2025
Accepted 5 June 2025

KEYWORDS
Maturity method; datum temperature; BCSA cement; concrete slabs; flexural strength; shrinkage; airports; low-carbon concrete

1. Introduction

Major airports continually go through critical maintenance work to continue operating safely without constraining daily operations. One of the major rehabilitation works for airport maintenance is the replacement of existing concrete slabs approaching their limited design life in the taxiway with new slabs. However, since airports cannot allow extended closures for taxiway and runway repairs from economic viability, they must be repaired quickly, often within stringent time constraints. For instance, the new concrete slabs need to reach structural flexural strength within the first 4 h of the installation for air traffic to resume the use of taxiways. Ordinary Portland cement (OPC) concrete needs days to achieve structural strength, and as such, accelerating the strength development of OPC mixes has been trialled. Unfortunately, this leads to mixes with low workability, significant shrinkage, and limited durability (Ramachandran 1996).

Belitic calcium sulfoaluminate (BCSA) cement conforms to ASTM C1600 as a very rapid hardening (VRH) cement, allows rapid concrete strength development, and is suitable for airport slab replacements. Following the works of Klein in 1962 (Alexander 1964), Ost *et al.* (1975) patented a fast-setting hydraulic cement with very high compressive strengths, marking the inception of BCSA cement by replacing the tricalcium silicate (C_3S) of hydraulic cement with calcium sulfoaluminate (CSA), or ye'elimite. As CSA forms at a lower kiln temperature than C_3S in cement manufacturing, the overall carbon footprint of BCSA is 30% lower than ordinary Portland cement (OPC) (Gartner and Sui 2018).

BCSA cement has a different composition to OPC and a few deviations from other rapid-setting cements like calcium sulfoaluminate cement (CSA) and belite-calcium aluminoferrite cement (Glasser and Zhang 2001, Quillin 2001, Gartner 2004, Li *et al.* 2007, Chen and Juenger 2011, Ioannou *et al.* 2014). The major BCSA cement minerals are belite (C_2S) and ye'elimite ($C_4A_3\underline{S}$) with minor additions like mayenite, gehlenite, perovskite, magnesia, and excess anhydrite (Glasser and Zhang 2001, Chen and Juenger 2011, Álvarez-Pinazo *et al.* 2012) that hydrate to form ettringite ($C_6A\underline{S}_3H_{32}$, AF_t), monosulfate ($C_4A\underline{S}H_{12}$, AF_m),

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amorphous aluminum hydroxide (AH_3) and strätlingite (C_2ASH_8) (Ding *et al.* 1995, Gastaldi *et al.* 2009, Pelletier *et al.* 2010, Berger *et al.* 2011). The hydration stages of BCSA cement initiate with a rapid reaction of calcium sulphate with water to form crystalline ettringite ($C_6A\overline{S}_3H_{32}$) and amorphous aluminium hydroxide (AH_3) (Álvarez-Pinazo *et al.* 2016, Jansen *et al.* 2017). Upon consumption of all calcium sulphate and in the presence of sufficient water, monosulphate ($C_4A\bar{S}H_{12}$) precipitates along with aluminium hydroxide (AH_3) (Álvarez-Pinazo *et al.* 2016, Gastaldi *et al.* 2016, Jansen *et al.* 2017). At a later age, belite (C_2S) hydrates in the presence of AH_3 and forms strätlingite (C_2ASH_8) (Álvarez-Pinazo *et al.* 2016, Gastaldi *et al.* 2016). However, when all AH_3 has been consumed, belite hydrates to precipitate calcium silicate hydrate (C − S − H) and Portlandite (CH), similar to OPC systems and unlike CSA systems. This differentiates BCSA from CSA cements. As a minor reaction product, iron-containing siliceous hydrogarnet may precipitate from the hydration of the ferrite (C_4AF) phases in the presence of strätlingite (C_2ASH_8).

BCSA cement concrete airport pavements have been used for nearly 30 years, mostly with rehabilitation works due to the quick turnover of assets. Major USA airports like Seattle-Tacoma International Airport pioneered and popularised using BCSA cement concrete slabs (Deo *et al.* 2022). Following the success in the USA, Australian airports, including Sydney Kingsford Smith Airport, Melbourne Tullamarine Airport, Brisbane Airport, and Avalon Airport, have seen BCSA cement concrete slabs in expedient taxiway repairs. The application of BCSA concrete has some global footprints, as rehabilitation works have been undertaken at Amsterdam Airport Schiphol and Rarotonga International Airport, as well as several airports in South and Central America (Deo *et al.* 2022).

When working with BCSA cement concrete projects, it is crucial to plan construction stages carefully and train the on-site crew, as efficient time management is critical. Monitoring the strength development in its current practice requires specimens to be cast on-site and tested within hours of specimen preparation. For instance, typical project specifications for airport concrete pavements in Australia specify a minimum flexural strength of 3.1–4.0 MPa within 4 h of placing. Similarly, TfNSW QA Specification 3201 (TfNSW 2021) for concrete supply for pavement maintenance requires high early strength (HES) 40-grade concrete to reach a minimum compressive strength of 15 MPa at 2 h or a minimum flexural strength of 2.6 MPa at 2 h. Similarly, the Federal Aviation Administration (FAA) in the United States requires a minimum flexural strength of 3.79 MPa (550 psi) to reopen pavement to traffic. This puts tremendous pressure on the concrete technicians to quickly prepare specimens and transport freshly made cylinders to preferably a nearby laboratory for demoulding, sulphur capping, marking, weighing, measuring, and testing. Often, such associated activities are difficult undertakings within early testing ages of 1–4 h. An alternative approach to saving critical time on such projects is setting up on-site testing facilities, which must go through strenuous procedures to be accredited before becoming operational. The exercise is expensive and tedious, adding extra costs to the project.

An alternative approach towards monitoring the early-age strength development of BCSA cement concrete can be determining concrete maturity following placement and relating maturity to its in-situ strength. The maturity method to predict concrete strength gained attention following incidents of under-construction building collapses and failures in the 1970s and was standardised in 1987 as ASTM C1074 as part of Federal research initiatives (Carino and Lew 1983, Carino and Lew 2001). It has since been trialled and optimised for ordinary Portland cement (OPC) concrete strength estimates. Following the work of (Carino and Lew 2001), major transport agencies in the United States have instituted procedures or are undertaking projects to investigate the feasibility of the maturity method to predict the on-site strength development of OPC concrete (Tepke and Tikalsky 2001). The US Department of Transportation (DOT) in New York, Texas, Florida, Arizona, California, and more have adopted the maturity method in their specifications. With many alternative cements being utilised in the pursuit of low-carbon cement, the reliability of the maturity method still needs to be established for alternative low-carbon binders such as BCSA cement concrete. TfNSW, the State Transport Authority of New South Wales, Australia, very recently released Test Method T 382 'Estimating compressive strength of concrete using maturity method' in December 2021, specifying a test method for high early strength (HES) mixes. This is particularly of interest in relation to BCSA cement concrete as the 'crossover' effect has been reported in the literature to limit the use of maturity methods to predict the behaviour of concrete with high temperatures at an early stage of installation (Yikici and Chen 2015). As such, this investigation has been undertaken to monitor the temporal temperature profile of very rapid hardening BCSA cement concrete, propose a strength-maturity correlation, and verify its accuracy in predicting concrete strength against lab-tested specimens prepared during supply. Moreover, considering the vigorous early-age reactions of BCSA cement, the real-time concrete strain in the first seven

days of placement has also been monitored to further advance the knowledge of the field performance of BCSA cement concrete in pavement slabs.

2. Project details

The project was designed to assist Australia Pacific Airports (Melbourne) Pty Ltd (APAM) in construct-only delivery trials of expedient concrete supply for distressed slab replacements at Melbourne Airport as part of the Melbourne Airport Pavement Maintenance Program 2.0 (MAPMP 2.0). The scope of the project included replacing end-of-life pavements – one slab on a gravel hardstand area adjacent to a taxiway apron (Off-site Trial) and four slabs on a live taxiway (On-site Trial). The scope of the project also extended to establishing a strength-maturity relationship for the BCSA cement concrete as per ASTM C1074 with provisions for testing at early ages of 2, 3, 4, 8, and 24 h. It is to be noted that this also deviates from the TfNSW Test Method T 382 test ages of 2, 4, 6, 8, and 24 h. The project specification specified the use of embedded strain gauges within the off-site trial slab to monitor the early-age shrinkage behaviour of BCSA cement concrete. This study was planned and executed as per the project specification with additional research carried out to determine the datum temperature of BCSA cement, develop the maturity calibration curve for the concrete, and apply the proposed correlation to predict the on-site strength development to determine safe windows for cutting construction joints to control cracking.

3. Materials and methods

3.1. Cement

The chemical composition of the BCSA cement, as determined by X-ray fluorescence (XRF), is summarised in Table 1; other cement properties are summarised in Table 2. The BCSA cement composition varies from ordinary Portland cement (OPC) and Australian General Purpose (GP) cement. Notably, BCSA cement has a significantly short setting time (~20 min) and low drying shrinkage (less than 250 με) compared to traditional OPC and GP cements. Also, it is characterised by the higher-than-usual but non-detrimental SO_3 content (Bescher *et al.* 2016). Moreover, the cement is much finer than OPC and GP cement, with a fineness index of over 600 m^2/kg.

Table 1. Chemical composition of BCSA cement.

Oxide composition	Results (%)
CaO	50.80
SiO_2	13.74
SO_3	15.80
Al_2O_3	15.51
MgO	0.93
Fe_2O_3	0.72
Na_2O	0.06
K_2O	0.62
TiO_2	0.78
P_2O_5	0.16
Mn_2O_3	0.03
Cr_2O_3	0.01
SrO	0.17
Total alkali content (Na_2O equivalent)	0.47
Loss on ignition (LOI)	1.30

3.2. Aggregates

The aggregates used in the concrete for this project were procured from Hanson quarries in Victoria, Australia. The stones are predominantly naturally occurring basalt and the sand is natural coarse sand. The nominal stone size was 40 mm, as specified by the project specification, and was graded following the specified target grading for combined aggregates. As such, two graded stones and sand were procured; their particle size distributions are illustrated in Figure 1(a). To conform to the Project Specification, Stone-1, Stone-2, and sand were blended at a ratio of 35:35:30 (mass %), and the combined PSD is plotted against the target in Figure 1(b). Other aggregate properties, as determined following relevant Australian Standards, are summarised in Tables 3 and 4 (courtesy of Hanson Australia). The aggregates conform to the specifications of AS 2758.1 Concrete aggregates.

3.3. Water and admixture

The mixing water used in concrete manufacture is reticulated drinking water. An overview of the water quality indicators is presented in Table 5. A commercial high-range water-reducing admixture, MasterGlenium SKY 8100 was used as a superplasticiser, and a proprietary retarder was used as a set retarding admixture in the

Table 2. Cement properties.

Sl. No	Test/Properties	Test Method	Results
1.	Initial setting time	AS 2350.5	16 min
2.	Final setting time	AS 2350.5	20 min
3.	Normal consistency	AS 2350.3	37%
4.	Soundness	AS 2350.5	1 mm
5.	Chloride content	AS 2350.2	0.042%
6.	7 days compressive strength	AS 2350.11	55.5 MPa
7.	28 days compressive strength	AS 2350.11	60.1 MPa
8.	7 days drying shrinkage	AS 2350.13	90 με
9.	28 days drying shrinkage	AS 2350.13	220 με
10.	Fineness index	AS 2350.8	605 m^2/kg

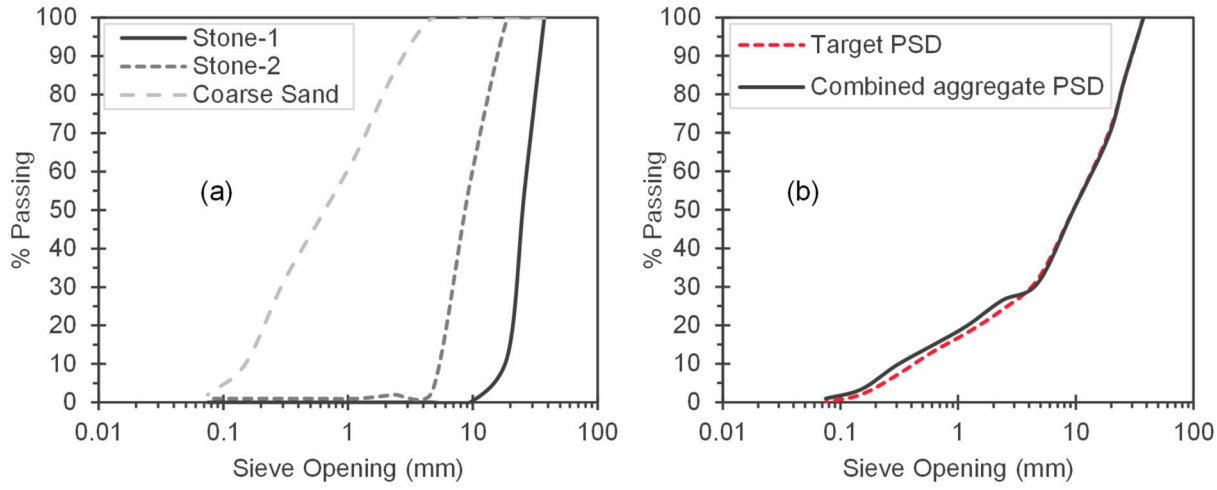

Figure 1. Particle size distribution (PSD) of (a) Stone-1, Stone-2, and Coarse Sand; (b) Combined PSD of aggregates against the Project Specification target – the proportion being 35% Stone-1, 35% Stone-2, and 30% Coarse Sand.

Table 3. Coarse aggregate properties.

Sl. No	Test/Properties	Test Method	Stone-1	Stone-2
1.	Particle density	AS 1141.6.1	2.86 t/m^3	2.87 t/m^3
2.	Water absorption	AS 1141.6.1	0.8%	1.1%
3.	Material finer than 0.075 mm	AS 1141.11.1	0%	1%
4.	Misshapen particles using a 3:1 ratio	AS 1141.14	0%	0%
5.	Wet strength	AS 1141.22	269 kN	269 kN
6.	Wet/dry strength variation	AS 1141.22	12%	12%
7.	Flakiness index	AS 1141.15	11%	14%
8.	Weak particles	AS 1141.32	0%	0.1%
9.	Soundness	AS 1141.24	0.4%	0.4%
10.	Los Angeles coefficient	AS 1141.23	11%	11%
11.	Chloride salt content	AS 1012.20	0.002%	0.002%

Table 4. Fine aggregate properties.

Sl. No	Test/Properties	Test Method	Coarse Sand
1.	Particle density	AS 1141.5	2.61 t/m^3
2.	Water absorption	AS 1141.5	0.7%
3.	Material finer than 0.075 mm	AS 1141.12	4%
4.	Soundness	AS 1141.24	0.5%
5.	Organic impurities	AS 1141.34	Pass (lighter than standard)
6.	Presence of sugar	AS 1141.35	Negative
7.	Chloride salt content	AS 1012.20	0.004%

mix. It is to be noted that commercially available set retarders may not be compatible with BCSA cement and trials must be undertaken prior to commercial supplies.

3.4. Concrete mix proportion and supply

A range of individual component of the concrete mix are outlined in Table 6, conforming to the mix design requirements of the project specification. The concrete was batched on-site and supplied using a fleet of seven mobile batching units (volumetric concrete mixers). Such units offer on-site concrete mixing and discharge with minimal wastage, considering the short setting time of the concrete. Prior to batching, the mixers were calibrated for each concrete component (stone, sand, cement, admixtures, and water) to ensure concrete uniformity and consistency throughout the project. On each shift, the mix water was adjusted based on the field moisture content of the aggregates to minimise instances of loss of free mix water to aggregate moisture absorption. A proprietary retarder was used to allow the on-site crew about 45 min to place, compact, and finish the concrete slabs.

Table 5. Concrete mix water (reticulated drinking water) properties.

Test	Test Method	Results
Sugar	AS 1141.35	Not Detected
Oil and Grease	APHA 5520D	< 2 mg/L
pH	APHA 4500HB	7.8
Total dissolved solids	APHA 2540C	110 mg/L
Sodium equivalent (%)	APHA 3120B	17 mg/L
Chloride ion content	APHA 4500D	3 mg/L
Sulphate ion content	APHA 4110B	7 mg/L

Table 6. BCSA cement concrete mix proportions.

Description	Unit Content
BCSA cement	400–430 kg/m^3
Coarse aggregate	1200–1350 kg/m^3
Fine aggregate	550–650 kg/m^3
Water	172–193.5 kg/m^3
Superplasticiser	200–600 mL/100 kg cement
Retarder	Proprietary

3.5. Strain and temperature monitoring

Four temperature sensors were embedded into each slab to monitor the temporal temperature profile of the slab following installation. Sourced from PCTE, INSITE Concrete Temperature and Strength Testing Sensors (loggers) were used to record concrete temperature continually, and data was retrieved from the loggers using an INSITE Pocket Reader for further analysis. The loggers are capable of measuring temperatures from −10°C to 110°C with an accuracy of ±1°C. As BCSA cement hydration is rapid, the slab temperature was recorded at 1-minute intervals to provide data on the continuous variations in its thermal behaviour.

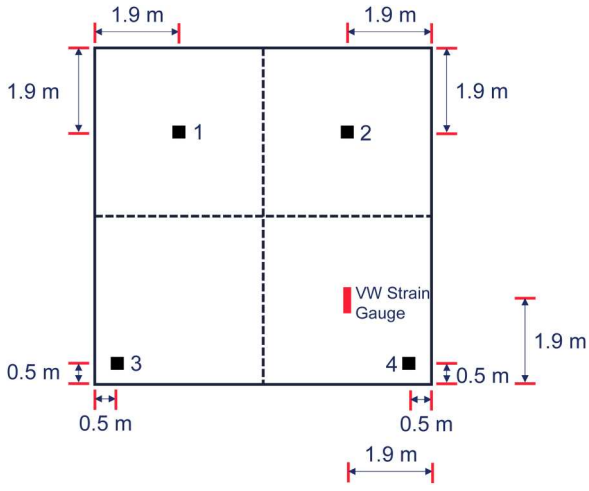

Figure 2. Schematic of locations of the temperature probes and VW strain gauges.

Figure 2 illustrates a schematic of the 'off-site trial' slab with the locations of the temperature sensors, while Figure 3 shows the photos of the slab captured on-site. The off-site trial slab sensors were installed at each quadrant of the 7.6 m by 7.6 m slab to avoid the contraction joint saw cuts shown in Figure 2 with dotted lines; they can be identified as – (1) Mid-depth centre (290 mm); (2) Top 100 mm centre; (3) Mid-depth corner (290 mm); (4) Top 100 mm corner. Two vibrating wire (VW) strain gauges were embedded into the off-site trial slab – one within the uppermost 75 mm and one located at the mid-depth (290 mm) of the slab to investigate differential strains within the slab section, if any. Figure 2 also shows the locations of the VW strain gauges within the slab, while Figure 3 depicts the actual photos. The VW strain gauges were left connected to a GeoLogger Linx data logger to record strain data continuously for the first week of slab installation.

However, for the four 'on-site trial' slabs, no VW strain gauge was installed, and the temperature sensors were installed at the four corners of each slab to minimise operational disruption during the pour and to accommodate design provisions for plain concrete pavements.

4. BCSA cement concrete maturity

The determination of BCSA cement concrete maturity involved three major steps – (i) determination of the datum temperature (T_o) of BCSA cement (Sections 4.1 and 5.1), (ii) formulation of calibration curve to correlate concrete maturity and flexural

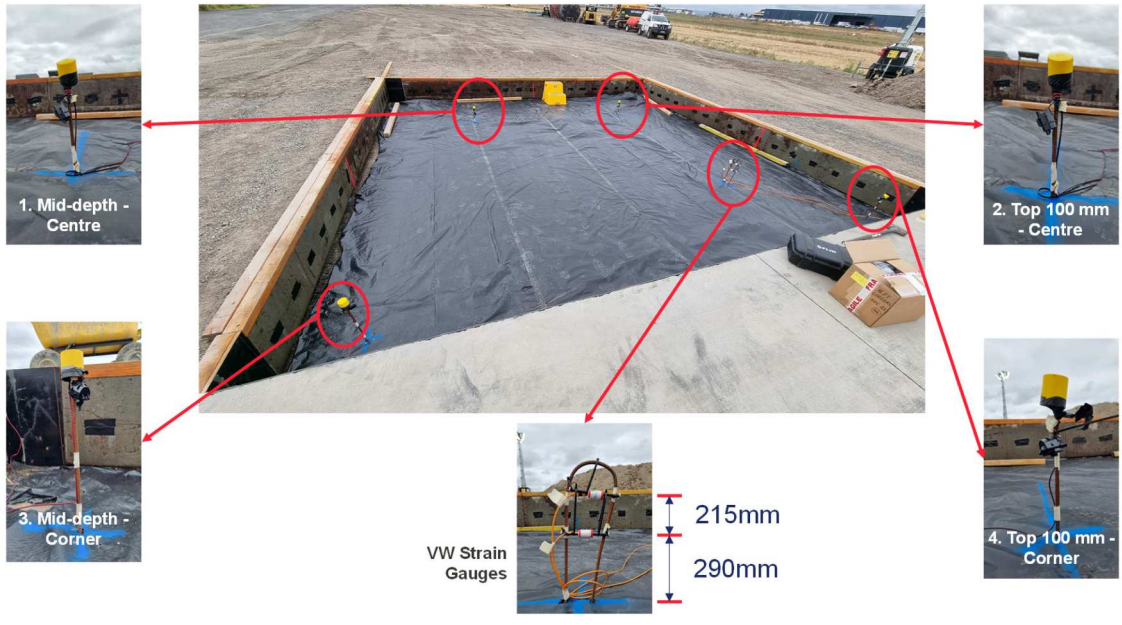

Figure 3. Actual locations of the temperature probes and VW strain gauges.

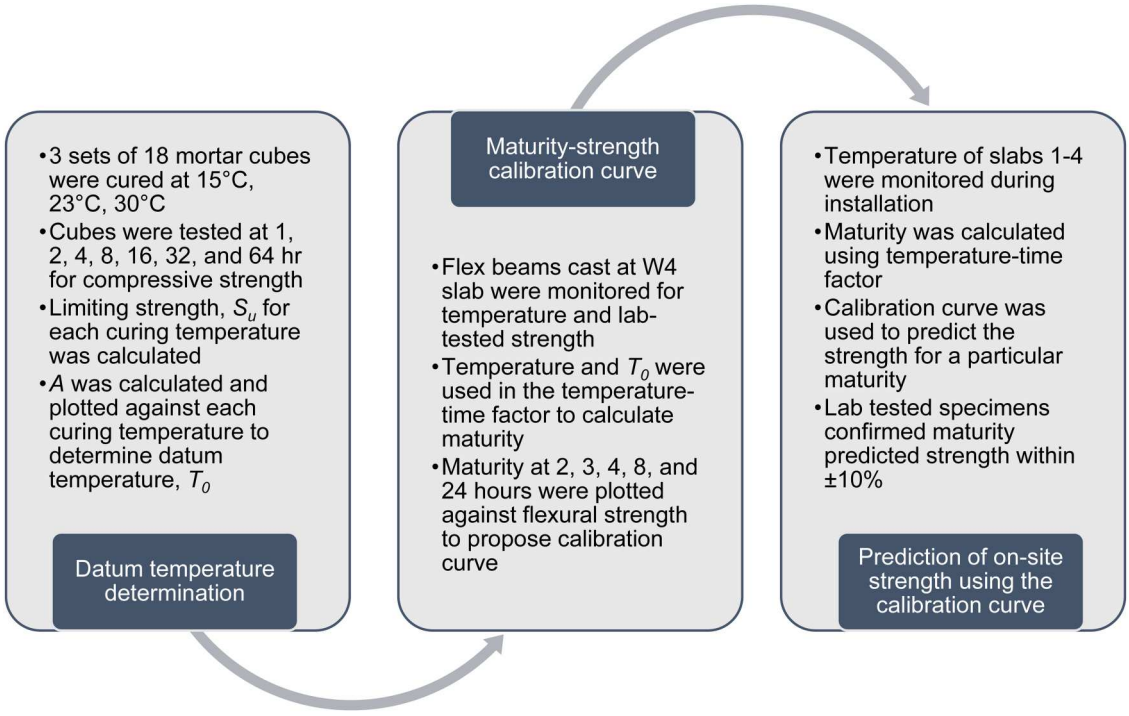

Figure 4. Flowchart of experimental methods.

strength (Sections 4.2 and 5.5), and (iii) application of calibration curve to predict on-site strength development of on-site (Sierra) slabs 1–4 (Section 5.6). Figure 4 illustrates a flow diagram of the work undertaken chronologically.

4.1. Determination of datum temperature

The maturity index of BCSA cement concrete was determined using the temperature-time factor (further explained in Section 4.2) as per ASTM C1074. As such, the datum temperature of BCSA cement was experimentally estimated following ANNEX A1 to the Standard. Mortar cubes of 50 mm were made with a sand-to-cement ratio equivalent to the gravel-to-cement ratio of the concrete mix, with the same W/C ratio and exact amounts of superplasticiser and retarder as admixtures. Three sets of standard mortar cubes were prepared following the recommendations of AS 1012.8.3, each set with 18 specimens. The specimens were cured in lime-saturated water baths at 15°C, 23°C, and 30°C. The temperature regimes were chosen to represent the lowest (15°C), usual (23°C), and highest (30°C) concrete temperatures at discharge from historical data collected over years of supplying this concrete. Two specimens were tested in compression at 1, 2, 4, 8, 16, 32, and 64 h each; the first test was done at approximately twice the final setting time. The spare specimens were cast to complement testing in case the two compression test data deviated more than 10%. The testing ages were chosen as per TfNSW T382 test method, which allows a deviation for rapid hardening cements from the ASTM C1074 procedure.

4.2. Concrete maturity estimation

To determine concrete maturity, i.e., the extent to which concrete has developed its strength, the concrete temperature, age, and strength development are correlated with an educated assumption that two samples of the same concrete mix will have the same strength at the same maturity. Based on concrete temperature measurements, ASTM C1074 provides two alternative methods for calculating the maturity index – the temperature-time factor and the equivalent age function. As defined below, the temperature-time factor has been used in this study to establish a strength-maturity relationship for BCSA cement concrete, and all further discussions will be limited to this function.

$$M(t) = \sum (T_a - T_o)\Delta t \quad (1)$$

Where, $M(t)$ is the temperature-time factor at age t, °C-hours; Δt is the time interval, hours; T_a is the average concrete temperature during time interval Δt, °C; and T_o is the datum temperature in °C. According to ASTM C1074 and Carino and Lew's study (Carino

and Lew 1983), the datum temperature is to be assumed as 0 °C; however, for other cement types and blended cements, it is recommended to determine the datum temperature experimentally. The datum temperature of BCSA cement used in this study was determined following the recommendations of ASTM C1074, as discussed in Section 4.1.

To establish the maturity-strength calibration curve, while the off-site trial slab was being installed, 150 mm × 150 mm × 550 mm flexural beams (and 150 mm × 300 mm cylindrical specimens) were concurrently batched on-site for laboratory testing. Two beams were instrumented with temperature loggers within ±15 mm of the centre of the specimens halfway along the length. These beams, instrumented with the loggers, accompanied the test beams and were stored in the same environmental conditions until the age of testing to eliminate variations in maturity and strength from environmental factors. Specimens were tested at 2, 3, 4, 8, and 24 h, and the corresponding maturity at a specific age was determined using equation (1). A plot of the concrete maturity, i.e. the temperature-time factor against flexural strength provided the strength-maturity correlation under flexure. The correlation was later utilised to predict the on-site flexural strength of BCSA cement concrete using the temperature data collected within the slabs as outlined in Section 3.5 and verified against laboratory-tested specimens collected during the installation of each on-site slab.

5. Results and discussions

5.1. Determination of datum temperature of BCSA cement

The compressive strength of the mortar cubes was tested at the specific ages of 1, 2, 4, 8, 16, 32, and 64 h, and the strength development is plotted in Figure 5 for each curing temperature of 15, 23, and 30°C. The reciprocals of the strengths corresponding to 8, 16, 32, and 64 h were plotted against the reciprocal of the ages as illustrated in Figure 6(a) to determine the limiting strength S_u for each curing regime. The inverse of the vertical axis intercepts of the linear trendlines is the corresponding S_u.

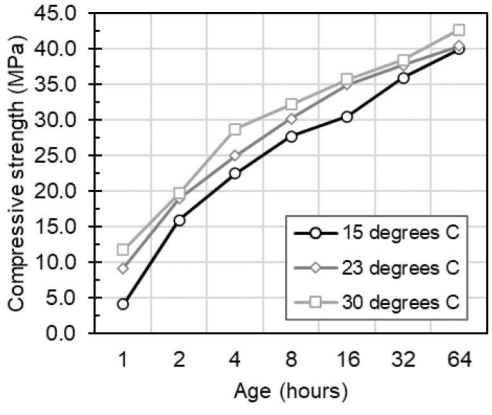

Figure 5. Compressive strength development of BCSA cement mortars under different curing temperatures.

The S_u was then utilised to calculate A as per equation (2) for each testing age and curing temperature. The S in the equation corresponds to the average strength at the four earliest testing ages of 1, 2, 4, and 8 h.

$$A = \frac{S}{S - S_u} \tag{2}$$

The A values, when plotted against the corresponding ages as shown in Figure 6(b), indicate linear correlations. The slopes of the straight lines are taken as the k-values for each curing regime and have been plotted against the temperatures in Figure 7. The intercept of the linear trendline of these data plots on the horizontal axis (temperature) is the datum temperature $T_0 = -27.1°C$ of BCSA cement intended for this application.

5.2. Concrete fresh and hardened properties

The concrete slump was measured throughout the supply from different volumetric mixers per AS 1012.3.1 and Table 7 summarises the slump for the slabs. A consistent trend in the slump can be identified within the nominated slump of 100 ± 20 mm.

The early-age development of flexural and compressive strength of BCSA cement concrete measured as per AS 1012.11 and AS 1012.9, respectively for the first 24 h of discharge are illustrated in Figure 8. The minimum 4-hour target flexural strength of 3.1 MPa was achieved within three hours of placement and a progressive development of both flexural and compressive strength in the first 24 h is observed. Minor deviations in strength for different slabs are also noticed. This is possibly from the variations in weather conditions (all supplies were scheduled for night shifts), bulk supply of aggregates, and minor adjustments of the mix on site. Also of note is the fact that specimens did not receive curing until 3–4 h of casting.

5.3. Strain measurements

The strain data was recorded using the VW strain gauge from 7:30 pm on 27 Feb 2023 until 8:30 pm on 7 Mar 2023 to monitor the dimensional change of the off-site slab in the first week of installation. Figure 9 illustrates the strain

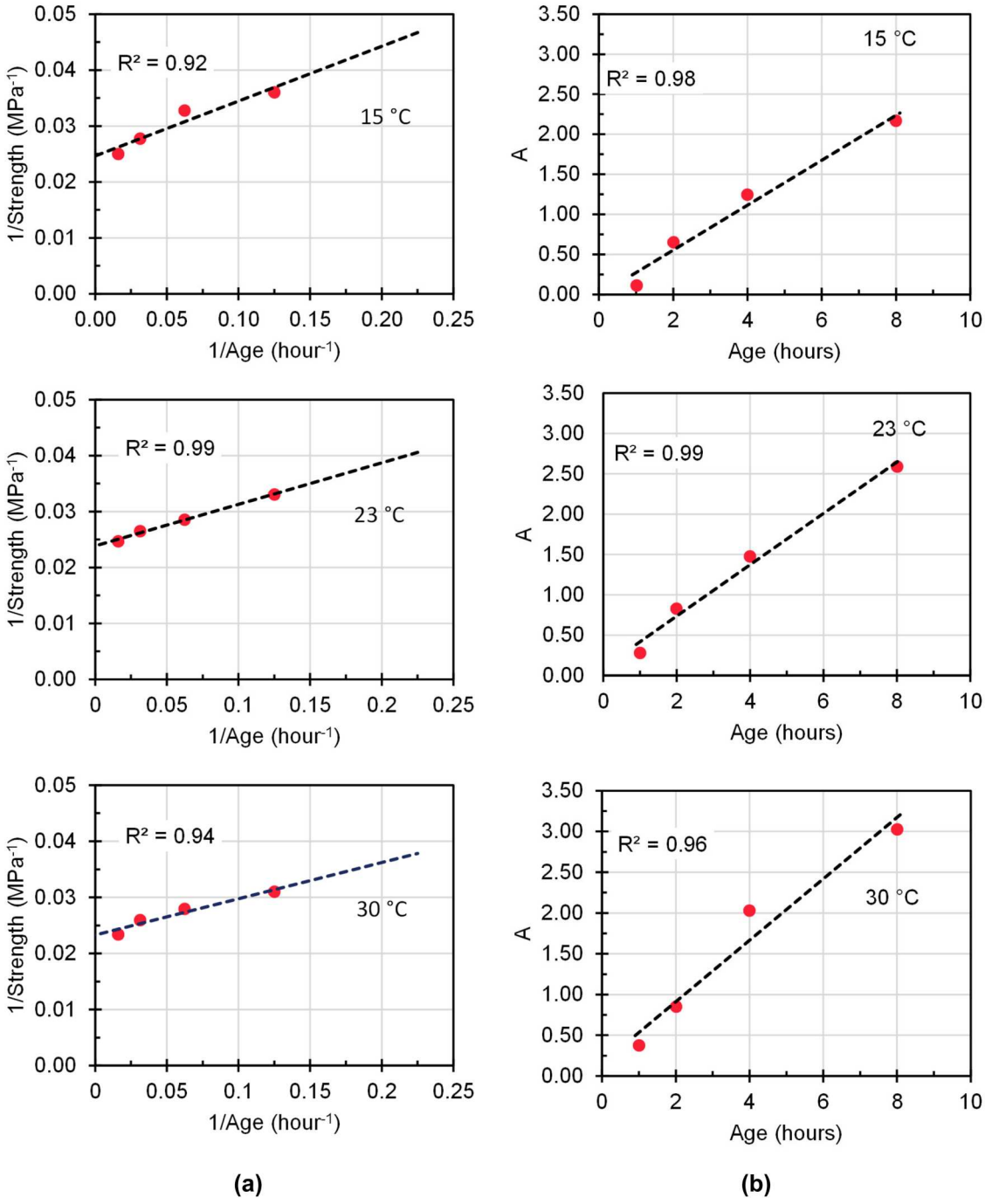

Figure 6. (a) Deducing limiting strength, S_u; (b) Deducing k-value of BCSA cement.

profile over time with an additional curve showing the air temperature profile to assist in interpreting the results. It is to be noted that the overall expansion and contraction of the slab were not averaged, but the two gauges were utilised to provide indicative values to assess strain profiles at the top 75 mm of the slab and mid-depth (290 mm from the top)

In the analysis, the dimensional changes from daily temperature fluctuations (concrete thermal effect) were not removed to visualise the actual dimensional change (strain) of the slab under ambient conditions. As such, interesting features were identified in the slab strain measurements, such as, the expansions and contractions closely following the temperature fluctuation patterns. Until March 1, the night and day temperature did not deviate much and consequently, the slab strain was steadily positive (contraction). However, following 1 March, day and night temperature fluctuations became more obvious and this was also reflected in the dimensional changes recorded in the VW strain gauges, although

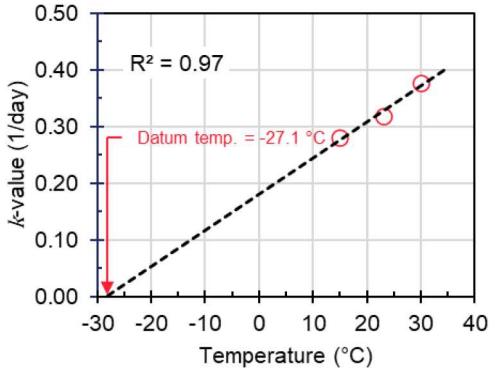

Figure 7. Determination of datum temperature from *k* value.

Table 7. The recorded slump of concrete against a nominated slump of 100 ± 20 mm.

Slab ID	Slump 1	Slump 2	Slump 3	Slump 4	Slump 5	Avg. Slump*
Whiskey 4 Trial Slab	100	90	90	110	90	100
Sierra Slab 1	100	90	110	100	80	100
Sierra Slab 2	90	100	110	110	–	100
Sierra Slab 3	85	85	80	120	100	90
Sierra Slab 4	90	110	100	110	100	100

*Rounded to the nearest 5 mm for slumps of 100 mm and less and to the nearest 10 mm for slumps greater than 100 mm as per AS 1012.3.1.

within a magnitude of just 50 με. The dimensional change from daily temperature fluctuations will be removed in later analyses at a later stage to evaluate the moisture strain behaviour of BCSA cement concrete.

Overall, the BCSA cement concrete slab showed little dimensional change in the first week of placement and was at the onset of a plateau (if thermal expansion/contraction is neglected) after the first 72 h. The sensor readings of the top 75 mm sensor fluctuated in the range of 50–110 με while the mid-depth sensor recorded a relatively higher strain in the range of 150–190 με. This dimensional change, from the combination of autogenous and drying shrinkage, is significantly low compared to Australian GP cement concrete. For comparison, TfNSW allows up to 450 με of drying shrinkage for concrete pavement bases at 21 days (28 days, if the first 7 days of water curing is considered). Also, it is noteworthy to consider that AS 1012.13 for drying shrinkage determination specifies specimens to be cured in lime-saturated water baths for the first 7 days of casting to eliminate any shrinkage from autogenous cement hydration.

From Figure 9, greater shrinkage data was captured at the mid-depth section of the slab than at the top 75 mm, which is also identified in the differential strain reading (not shown in the figure). This trend in the data indicates that the mid-section of the slab contracts more than the top, at least at the edge location where the gauges were installed (Figure 3), allowing the slab to swell in a convex geometry with no warping phenomenon occurring on its surface. This phenomenon has also been observed in another independent previous study (McNerney *et al.* 2021). Because of the lifetime pressure of aeroplanes pressing down on their elevated edges, typical GP cement concrete slabs would curl up in a concave geometry at the edges or joints, which is a high-rate failure point for the slab. The lifetime of the slab at the edges is expected to be significantly increased as the BCSA cement concrete slab swells rather than curls.

5.4. Temperature profile

Several important insights into the expedient concrete from the temperature monitoring can be determined

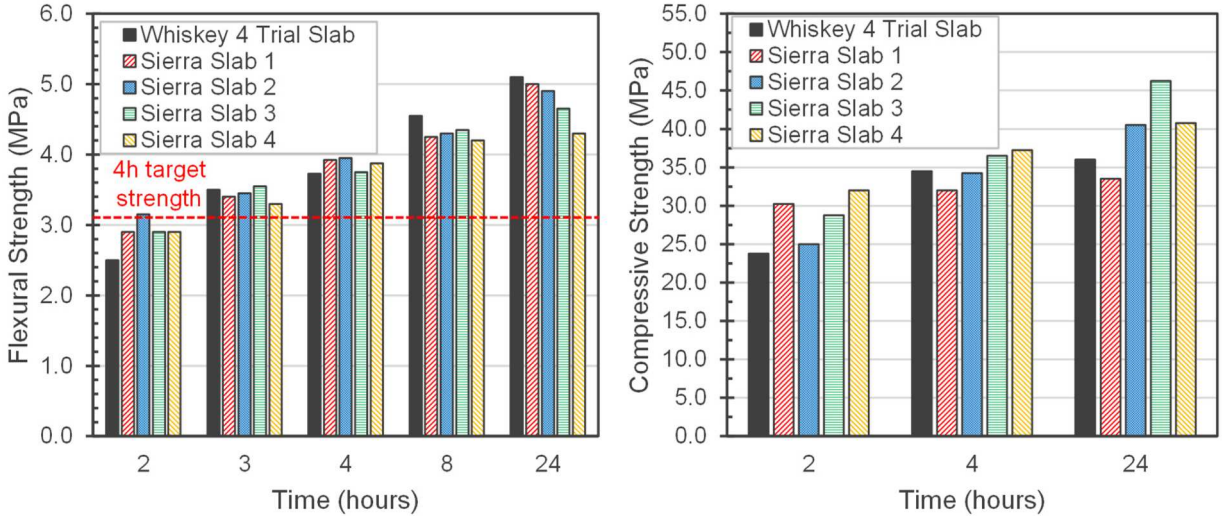

Figure 8. Flexural strength and compressive strength development of MBU-supplied BCSA cement concrete.

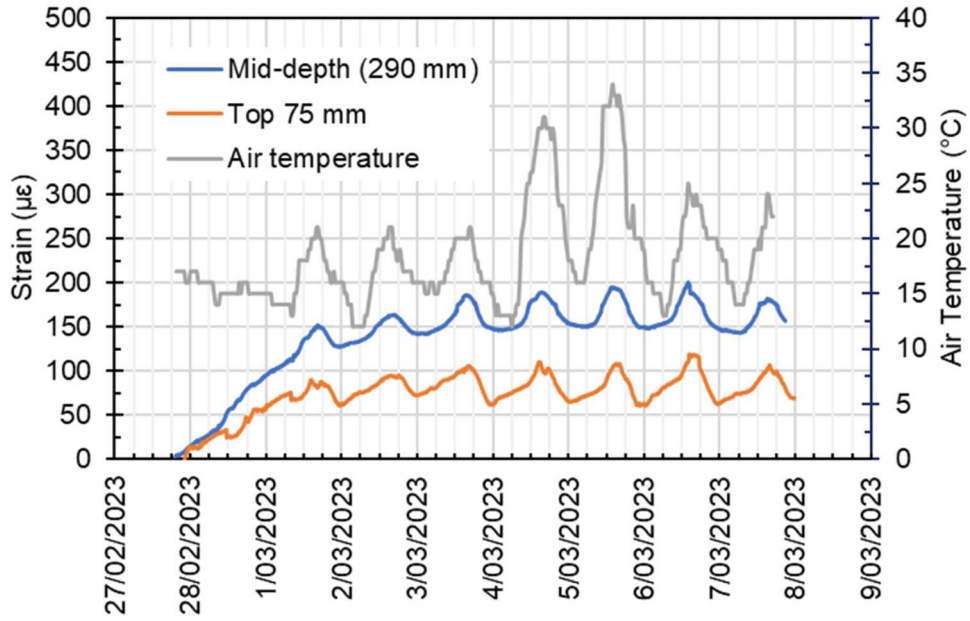

Figure 9. Strain at the top 75 mm of the slab and mid-depth (290 mm) as recorded by VW strain gauges (each major tick mark on the horizontal axis indicates midnight on the date, and the minor tick marks progressively indicate 6 am, 12, 6 pm).

from Figure 10 which illustrates the temperature profile of the off-site trial slab at various locations and depths over time. Critical findings on the magnitude and time of occurrence of the peak temperature can be identified from the figure. For instance, the peak temperature of 73°C was recorded at the centre of the slab at midspan (please refer to Figures 1 and 2, Sensor 1), which is greatly influenced by the heat of hydration of the surrounding BCA cement in the mass concrete. The rest of the sensors recorded a maximum of about 60°C temperature at the top 100 mm or near the corner of the slab. This indicates a thermal gradient along the slab depth, subject to further data recording in separate projects and applications. All peak temperatures were recorded at around 3–4 h of discharge, marking it as the critical time to monitor the concrete for possible thermal cracks. It is to be noted that the concrete temperature at discharge from the trucks ranged between

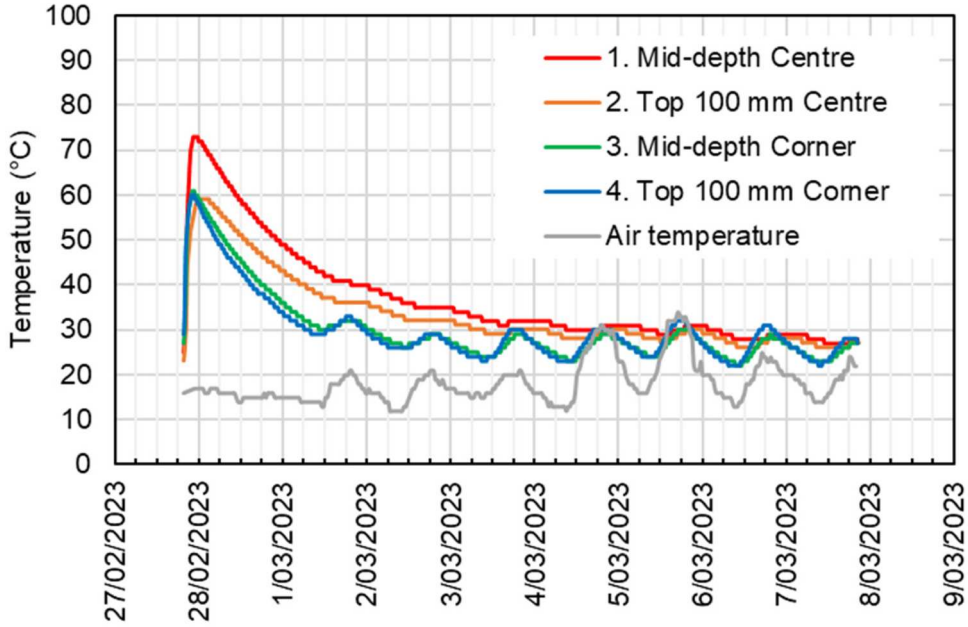

Figure 10. Real-time temperature profile of BCSA cement concrete installed at Whiskey 4 Trial slab.

22.8–23.2°C, and at the 3–4 h mark of the pour, the surface temperature ranged between 40–45°C (measured with a thermal laser gun). The temperature rise in the first 3–4 h is reflective of the product's rapid strength gain in the first 4 h of placement. This data also assists in identifying the critical timeframe when measures need to be undertaken to limit the temperature gradient of the slab surface and ambient conditions to avoid the occurrence of thermal hairline cracks.

Another trend of interest in the temperature profile is the rise and fall of concrete temperature within the top 100 mm, which closely follows the daily ambient temperature profile. Information on concrete temperature collected in this study can be utilised to optimise mix design, placement, and critical on-site methodologies, including curing methodology to limit thermal and plastic shrinkage cracks to a practical minimum.

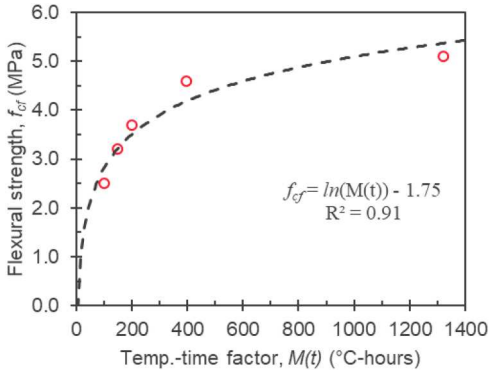

Figure 11. Flexural strength-maturity relationship of BCSA cement concrete.

5.5. Strength-maturity correlation determination

The maturity of BCSA cement concrete was determined at 2, 3, 4, 8, and 24 h from the temperature records utilising equation (1). The flexural strengths are plotted against the corresponding maturity, as illustrated in Figure 10, to correlate these parameters. A reasonably strong logarithmic correlation ($R^2 = 0.91$) has been established. The correlation has further been utilised to predict the on-site concrete strength of BCSA cement concrete slabs as part of the on-site trials.

5.6. Assessment of the accuracy of the model predictions

The concrete maturity correlation developed in Section 5.5 was applied to the four on-site trial slabs replaced with BCSA cement concrete on a live taxiway at Melbourne Airport and the off-site trial slab. Each slab

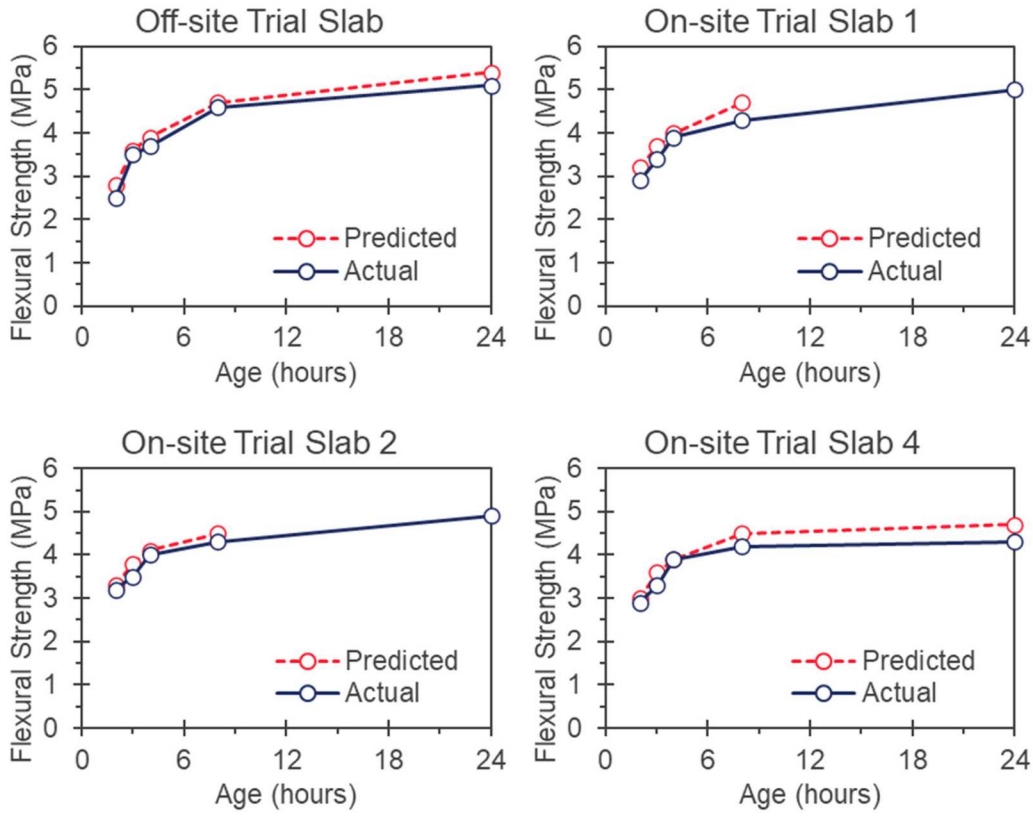

Figure 12. Assessment of the accuracy of the proposed strength-maturity correlation of BCSA cement concrete.

was instrumented with four temperature sensors (with built-in loggers) at four corners, about 500 mm from the two adjacent faces and mid-depth through the 580 mm deep slabs. The loggers were tied to the corner dowels of the on-site trial slabs; the instrumentation of the off-site trial slab is illustrated in Figures 2 and 3. The rationale for instrumenting the slab with four loggers at the corners is multi-fold. First, the slabs are designed to have no longitudinal and transverse reinforcements except for dowels to provide a mechanical connection between adjacent slabs that provide horizontal movements between contraction joints. Second, the corners of the slab are the most critical areas, as the pouring of BCSA cement concrete starts and ends at these corners within about 30 min of concrete supply. It is reasonably expected that the core of the slab has reached relatively greater strength compared to the corners as it is surrounded by mass concrete at elevated temperatures. As such, temperature profiles in the corners of the slabs provided useful information on the concrete strength at critical areas of the newly installed slabs.

In-place logger data were used to estimate the temperature and strength of concrete over time. An assessment of the strength development curve for a concrete structure was made using the average maturity data from in-place loggers within that structure. Since this exercise was undertaken to assess the reliability of the maturity correlation of BCSA cement concrete, companion flexural beams were cast on-site and tested following standard laboratory curing methods at specific ages. Figure 12 illustrates the 'predicted' and 'actual' strength development of the concrete as determined by the proposed correlation of Figure 11 and laboratory testing, respectively.

It is to be noted that the temperature of Slab 3, installed on the last shift, could not be retrieved following contraction joint cuts and aeronautical ground lighting (AGL) installation. Also, temperature data for the other slabs could not be retrieved beyond 8 h as they were open to live traffic, and all cables attached to the loggers were removed for safe taxiway operations. Despite that, critical early-age strength data could still be predicted with reasonable accuracy for BCSA cement concrete that closely followed the 'actual' strength based on laboratory testing. The predicted strengths were marginally higher than the actual, although within a ± 10% precision, possibly because of the high temperature of the surrounding mass concrete. The predicted strength was utilised to determine the safe time for contraction joint cuts that led to no surface concrete chipping and spalling, confirming the in-situ strength of concrete.

6. Conclusions

Expedient BCSA cement concrete was supplied and installed to manufacture five concrete pavement slabs at Melbourne Airport taxiways. The flexural strength-maturity calibration curve was established at the off-site trial slab at a taxiway apron and tested to predict the on-site slab strength development of the expedient concrete in a live taxiway. Meanwhile, the temperature and strain profiles of the off-site trial slab were monitored for the first week of installation. The following conclusions can be drawn from the data analysis:

- A logarithmic correlation exists between the flexural strength and temperature-time factor of BCSA cement concrete as per ASTM C1074 that successfully predicts the on-site strength development of the concrete within a precision of ±10%.
- The temperature and strain profiles in the top section of airport slabs are influenced by ambient temperature.
- The strain at the mid-depth section of BCSA cement concrete is higher than the top section and, as such, slabs swell in a convex geometry with no warping phenomenon occurring on its surface.
- The maturity method can be applied to BCSA cement concrete.

Acknowledgements

The authors acknowledge the support and assistance provided by Australia Pacific Airports (Melbourne) Pty Ltd (APAM), AECOM Australia, Donald Cant Watts Corke (DCWC), Volumetric Concrete Australia (Antoun), BMD Group, Coffey Testing, and Mahaffey Associates in undertaking the project.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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