Strength-maturity Relationship of BCSA Cement Concrete

Aziz Hasan Mahmood, Ian Hampton
Antoun, Guildford, NSW 2161

Abstract: In this study, the maturity method as specified in ASTM C1074 and TfNSW T382 was followed to develop a correlation between belitic calcium sulfoaluminate (BCSA) cement concrete maturity, and its strength based on laboratory investigations. The ANTOUN 20/80/40 mix, registered as a SP40HES mix on the TfNSW Register of Concrete Mixes, and conforming to TfNSW QA Specification 3201, was considered to develop the strength-maturity correlation. Mortar cubes cured at 15 °C, 23 °C, and 30 °C were tested for compressive strength at 1, 2, 4, 8, 16, 32, and 64 hours, and analysed as per ANNEX A1 of ASTM C1074 to determine the datum temperature, T_0. The datum temperature and cumulative temperature recorded on BCSA Cement Concrete cylindrical specimens were fed into a maturity equation to determine the temperature-time factor, $M(t)$. Meanwhile, the compressive strength of the concrete was determined at 2, 4, 6, 8, and 24 hours and plotted against the relevant $M(t)$ to obtain a strong logarithmic correlation between BCSA Cement Concrete maturity and compressive strength. The maturity calibration will be tested to predict the in-place concrete strength for reliability assessments.

Keywords: BCSA Cement Concrete, maturity method, temperature-time factor, datum temperature.

1. INTRODUCTION

A multi-storey under-construction building in Fairfax County, Virginia, experienced a progressive collapse on 2 March 1973. The tragedy left 34 workers injured and 14 people dead. Following the incident, the premature removal of formwork was identified as the technical cause of the collapse, which induced punching shear stress beyond the four-day-old concrete capacity [1]. Although the relative strength data obtained on samples collected on-site and cured at constant temperature conditions were perceived to be sufficient for formwork removal, the actual concrete strength was impacted by an ambient temperature that was recorded to be at an average of 7 °C [1]. This sparked interest in the “maturity method”, a relatively new technique of the time for forecasting in-place strength development under varying temperature circumstances.

Another major construction failure of a cooling tower on Willow Island, West Virginia, on 27 April 1978 claimed the lives of 51 workers on the scaffolding system that was anchored to the partially finished shell. Once again, the most probable cause of the collapse was identified as insufficient concrete strength to support the ongoing construction loads from being exposed to an estimated average ambient temperature of 10 °C [2]. Following these incidents, there was a strong drive towards standards and specifications to reliably estimate in-place construction concrete strength. The National Bureau of Standards (NBS) led research in developing the first standard, ASTM C1074 on the application of the maturity method. Alongside the original research and development from NBS, the standard reflected the prior research of McIntosh, 1949 [3], Nurse, 1949 [4], Saul [5], Malhotra [6], Freiesleben Hansen and Pedersen [7] on the principles of concrete maturity. Since then, concrete strength estimates from maturity determinations have been incorporated in several standards worldwide and very recently, Transport for New South Wales (TfNSW), the State Road Authority has published its own test method TfNSW T382.

Concrete maturity relates to concrete temperature, time, and strength development. The assumption in the maturity method in its simplest form is if two samples of the same concrete have the same maturity (as calculated based on Arrhenius law), they will have the same strength even if they were cured under different temperatures conditions. Continuous monitoring of the concrete temperature provides a temperature history that is utilised to calculate the maturity index as specified in the standards. Within a controlled laboratory environment, for a specific concrete mix, the correlation between strength (compressive or flexural) and the maturity index is established which in turn, is used to estimate the on-site concrete strength based on temperature monitoring on-site that is used to calculate concrete maturity. Once a strength-maturity correlation is established for a particular concrete mix, it can be used to estimate the on-site strength of concrete to allow the start of critical construction activities such as walking on concrete, formwork removal, the opening of concrete pavements to traffic, post-tensioning of reinforcing tendons, termination of weather protection, etc.

Although maturity curves have been established for various types of concrete utilising various types of cement and its various blends, literature does not provide evidence of any available maturity curve for BCSA Cement Concrete, which utilises a unique belitic calcium sulfoaluminate cement (BCSA) conforming to ASTM C1600 as an “ultra-rapid hardening” hydraulic cement. As such, BCSA Cement Concrete (also known as Rapid Set Cement Concrete) is predominantly applied in maintenance projects that require a quick return to services such as airport concrete taxiways and highway concrete pavements. The opening of such assets following concrete placement is usually within a tight 4-6 hours shift and an estimate of the in-place concrete is of the utmost importance. At this stage, the authors pioneered the determination of the datum temperature of BCSA Cement Concrete and developed the maturity curve for their registered mix under SP40HES as per TfNSW QA Specification 3201. This paper provides technical details of the methods and outcomes while preserving any detail considered intellectual property and of commercial advantage over competitors.

2. EXPERIMENTAL METHODS

2.1. The Maturity Concept

The concept of maturity, i.e., the extent of the development of strength of concrete, is to relate concrete temperature, age, and its strength development. The concept assumes that two samples of the same concrete mix will have the same strength at a time when they reach the same maturity, despite being cured under different conditions.

The ASTM C1074 allows computing the maturity index from concrete temperature measurements using two alternative functions – (i) the temperature-time factor, and (ii) the equivalent age function. In this study, the strength-maturity relationship of BCSA Cement Concrete has been established using the temperature-time factor as defined below and further discussions will be limited to this function only.

$$M(t) = \sum (T_a - T_o)\Delta t \tag{1}$$

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, °C. The approximate value of the datum temperature may be assumed as 0 °C as per ASTM C1074 and the studies of Carino and Lew [8], however, for other types of cement and for a blended cement, it is the best practice to experimentally determine the datum temperature. In this study, the datum temperature of Rapid Set Cement is determined as per the Annex A of ASTM C1074.

2.2. MATERIALS AND MIX DESIGN

2.2.1. Aggregates

For this study, natural gravel and manufactured sand were respectively sourced from Peats Ridge and Peppertree quarries in New South Wales, Australia. The material properties of the aggregates are summarised in Tables 1 and 2 while Fig. 1 illustrates the combined particle size distribution (PSD) of the aggregates used for batching concrete. It is to be noted that all aggregate properties and their combined PSD conform to TfNSW QA Specification 3201.

2.2.2. Cement

A belitic calcium sulfoaluminate cement (BCSA) conforming to ASTM C1600, sourced from CTS Cement Manufacturing Corp., was used as the sole binder in concrete manufacture. The chemical composition of the cement as determined using X-ray fluorescence is provided in Table 3 and its engineering properties are summarised in Table 4. The initial setting time of the cement is only 16 min and as such, a proprietary Citric Acid solution is used to regulate the setting as a retarder. Also, the fineness index is 605 m2/kg, about 50% higher than GP Cement. The concrete mix design parameters are compiled in Table 5. The concrete mix design is proprietary in nature and as such, will not be disclosed in the paper. However, it is registered with the TfNSW Register of Concrete Mixes as ANTOUN 20/80/40 as a HES mix conforming to QA Specification 3201.

Property	Requirement	Test Method	Result
Particle density	2.1-3.2 t/m^3	AS 1141.6	2.97 kg/m^3
Bulk density	Min: 1.20 t/m^3	AS 1141.4	1.68 kg/m^3
Water absorption	Max: 2.5%	AS 1141.6	0.5%
Material finer than 0.075 mm	Max: 2.0%	AS 1141.11.1	1%
Material finer than 0.002 mm	Max: 1.0%	AS 1141.13	0%
Particle shape, 3:1 ratio	Max: 10	AS 1141.14	2
Flakiness index	Max: 35%	AS 1141.15	29%
Wet strength	Min: 80 kN	AS 1141.22	435 kN
Wet/Dry variation	Max: 35%	AS 1141.22	2%
Los Angeles value	Max: 30%	AS 1141.23	11%
Sodium sulphate soundness	Max: 6%	AS 1141.24	0.2%
Weak particles	Max: 0.5%	AS 1141.32	0%
Light particles	Max: 1.0%	AS 1141.31	0%
Sugar content	Negative	AS 1141.35	Negative

Table 1. Properties of coarse aggregate.

The BCSA cement utilised in the formulation of the concrete is different to typical calcium sulfoaluminate cement as it is composed primarily of ye'elimite ($C_4A_3\bar{S}$) and belite (C_2S) [9] [10] [11]. The hydration of ye'elimite is rapid in nature and forms ettringite as the main reaction product in plastic phase and monosulfate, depending on the composition [12] [13]. The strong crystal structure of ettringite offers high compressive strength at early ages [14] [15]. The belite reacts slower after ye'elimite has been consumed in hydration and contributes to strength development at later ages [10] [16].

Property	Requirement	Test Method	Result
Particle density	2.1-3.2 t/m^3	AS 1141.5	2.72 t/m^3
Bulk density	Min: 1.20 t/m^3	AS 1141.4	1.86 t/m^3
Water absorption	Max: 2.5%	AS 1141.5	0.6%
Material finer than 0.075 mm	Max: 20%	AS 1141.11.1	8%
Material finer than 0.002 mm	Not Applicable	AS 1141.13	1.3%
Methylene blue adsorption value (MBAV)	Not Applicable	AS 1141.66	3 mg/g
Deleterious fines index (DFI)	Max: 150	0.0075*MBAV	24
Weighted average loss	Max: 6.0%	AS 1141.24	0.3%
Degradation factor	Min: 60	AS 1141.25.3	73
Light particle	Max: 1%	AS 1141.31	0
Organic impurities	Not darker than reference solution	AS 1141.34	Not Darker
Sugar content	Negative	AS 1141.35	Negative

Table 2. Properties of fine aggregate.

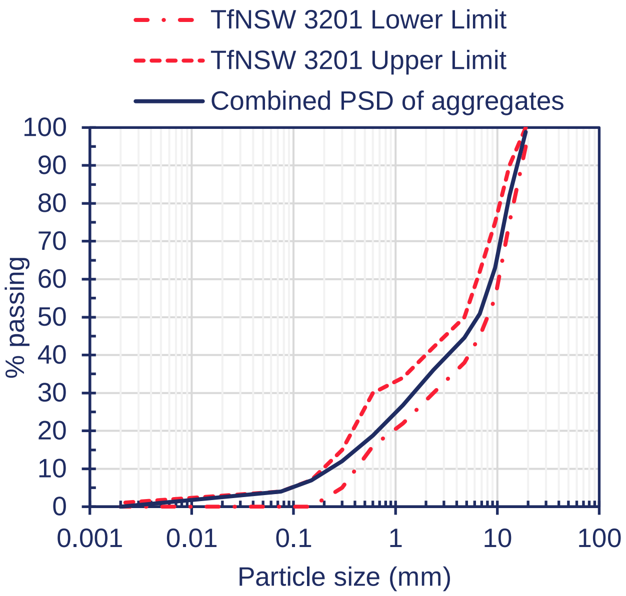


Fig. 1. Particle size distribution (PSD) of combined aggregates.

2.3. Test Details

2.3.1. Determination of Datum Temperature

To determine the datum temperature (T_0) for establishing the temperature-time factor, 50 mm mortar cube specimens were made and cured in water baths maintained at 15 °C, 23 °C, and 30 °C to be tested at specific ages of 1, 2, 4, 8, 16, 32, and 64 hours as allowed in TfNSW T382 test method. The choice of 15 °C and 30 °C represent the minimum and maximum concrete temperatures expected on-site during the period when strengths are estimated using maturity functions. The 23 °C is representative of the general concrete temperature at discharge. Three sets of 50 mm mortar cubes were prepared in accordance with AS 1012.8.3 and cured at the designated temperatures until testing.

Oxide Composition	Mass %
SiO_2	13.74
Al_2O_3	15.51
Fe_2O_3	0.72
CaO	50.8
MgO	0.93
SO_3	15.8
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
Loss on ignition (LOI)	1.3

Table 3. Chemical oxide compositions of BCSA cement.

Property	Test Method	Result
Setting Time	AS 2350.4	Initial 16 min; Final 20 min
Soundness	AS 2350.5	1%
Chloride content	AS 2350.7	0.042%
SO3 Content*	AS 2350.2	15.8%
Compressive Strength at 7 days	AS 2350.11	55.5 MPa
Compressive Strength at 28 days	AS 2350.11	60.1 MPa
Shrinkage at 28 days	AS 2350.13	220 με
Loss on ignition (LOI)	AS 2350.2	1.3%
Fineness Index	AS 2350.9	605 m^2/kg

Table 4. Properties of BCSA cement.

Mix designation	SP40HES as per TfNSW QA Specification 3201
Nominal aggregate size	20 mm
Total aggregate to cement mass ratio	4.60
W/C ratio	0.43
Sand to total aggregate volume ratio	0.44

Table 5. Concrete mix design parameters.

The mortar specimens were proportioned to have a sand-to-cement ratio (by mass) that is the same as the sand-to-gravel ratio of the SP40HES mix under investigation. The mix proportion of the concrete mix is proprietary and as such, is not shared in this manuscript. However, critical concrete properties are included in this paper for an understanding of the mix.

At specified ages, two cubes under each curing regime were tested with provisions for an additional test in case test results deviated by more than 5.0 MPa. The strength versus age data was later analysed to determine the relationship between the rate constant, k for strength development and the curing temperature. Details are presented in Results and Discussions.

2.3.2. Determination of Maturity Function

Once the datum temperature was determined, it was used to compute the temperature-time factor maturity function of equation (1). To that extent, fresh concrete was batched at 23 °C ambient conditions in a laboratory planetary mixer. The aggregates in their natural moisture state were blended in the mixer before introducing the cement. This was quickly followed by the addition of Citric Acid as a retarder before adding the solution of mix water and superplasticiser to the mix. The water content was adjusted for the excess moisture in the aggregates beyond their absorption capacity. Mixing was continued for about 5 min to ensure a homogeneous mix. The slump of concrete was determined following AS 1012.3.1 before 15 cylindrical specimens were prepared in accordance with AS 1012.8.1. Two temperature probes were embedded in two cylinders within ±15 mm of the centres and immediately connected to data loggers to continually monitor the fresh concrete's temperature immediately after casting. All specimens were then stored in a 23 °C curing chamber and demoulded after 1 hour of batching and moist cured in a water bath, except for the two cylinders with the embedded temperature probes. The specimens were sulphur-capped before testing for uniaxial compressive strength at the ages of 2, 4, 6, 8, and 24 hours as allowed in TfNSW T382. For each test, two specimens were used unless the deviation in strength was beyond 10%.

The cumulative temperature-time factor was calculated for the instrumented specimens at each test age. The time interval (Δt) was 1 min for temperature measurements. The average compressive strength was then plotted against the cumulative average value of the maturity index and a best-fit curve was drawn through the data to determine the strength-maturity relationship for BCSA Cement Concrete.

3. RESULTS AND DISCUSSIONS

3.1. SP40HES Concrete Properties

The properties of the proprietary SP40HES mix are summarised in Table 6. Several unique characteristics of BCSA Cement Concrete can be identified from the summarised data. For instance, from the strength development data, the rapid nature of the strength gain is obvious; the mix reaches over 30.0 MPa compressive strength and about 4.0 MPa flexural strength in the first two hours of batching. Moreover, for such high-strength concrete, the shrinkage is substantially low despite using no supplementary cementitious material or shrinkage-reducing admixture in the mix. The inherent low shrinkage property of BCSA Cement Concrete can be related to its reaction products. In the plastic phase, the major reaction product identified in the mix is ettringite as opposed to Portlandite and CSH for GP Cement. Although there is consensus in the research community about the potential degradation risks of delayed ettringite formation in concrete, the ettringite phase in BCSA Cement Concrete initiates in the plastic phase and does not pose any durability threat. Further research is underway to evaluate various reaction products of Rapid Set Cement and will be published in due course.

Another superiority of BCSA Cement Concrete over conventional concrete can be appreciated through its “zero” water permeability. The permeability data indicates that the concrete simply does not allow any deterrent ingress or at the very least, limits ingress. As such, the durability of BCSA Cement Concrete is expected to be excellent and little research has been undertaken in the past to confirm its excellent sulphate resistivity [9], strength development over a period of 17 years [17], etc.

Test	Test Method	Results
Slump	AS 1012.3.1	75 mm
Compressive strength (2 hours)	AS 1012.9	32.8 ± 0.8 MPa
Compressive strength (3 hours)	AS 1012.9	37.5 ± 2.6 MPa
Compressive strength (7 days)	AS 1012.9	57.9 ± 1.9 MPa
Compressive strength (28 days)	AS 1012.9	64.4 ± 4.8 MPa
Flexural strength (2 hours)	AS 1012.11	3.9 ± 0.2 MPa
Flexural strength (28 days)	AS 1012.11	5.3 ± 0.0 MPa
Drying shrinkage (21 days)	AS 1012.13	80 με
Chloride ion content	AS 1012.20.1	0.43 kg/m^3
Chloride migration coefficient from non-steady-state migration experiments	NT Build 492	1.78 x 10-12 m^2/sec
Water permeability	DIN 1045 Part 5	0.0 mm
Mass per unit volume	AS 1012.12.1	2500 ± 20 kg/m^3

Table 6. Properties of SP40HES BCSA Cement Concrete.

3.2. Datum Temperature

The datum temperature for the concrete mix was determined as per Annex A1 of ASTM C1074, based on the compressive strength of the mortar specimens. Fig. 2 provides the strength development of the mortars under different curing conditions. As expected, the compressive strength improved with increasing curing temperature. The mortar compressive strength was determined at 1, 2, 4, 8, 16, 32, and 64 hours and the reciprocal of compressive strength (y-axis) versus the reciprocal of age (x-axis) for the last four test ages of 8, 16, 32, and 64 hours was plotted as shown in Fig. 3. The y-axis intercepts of the linear trendlines were measured for each curing temperatures of 15 °C, 23 °C, and 30 °C, and the inverse of the intercepts provided the limiting strength, S_u for each curing regime.

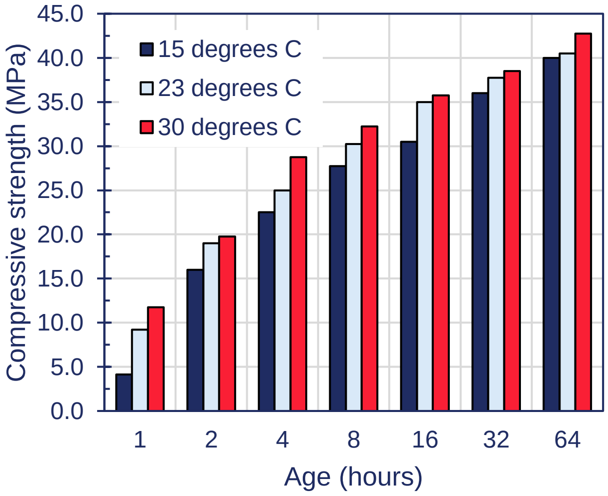
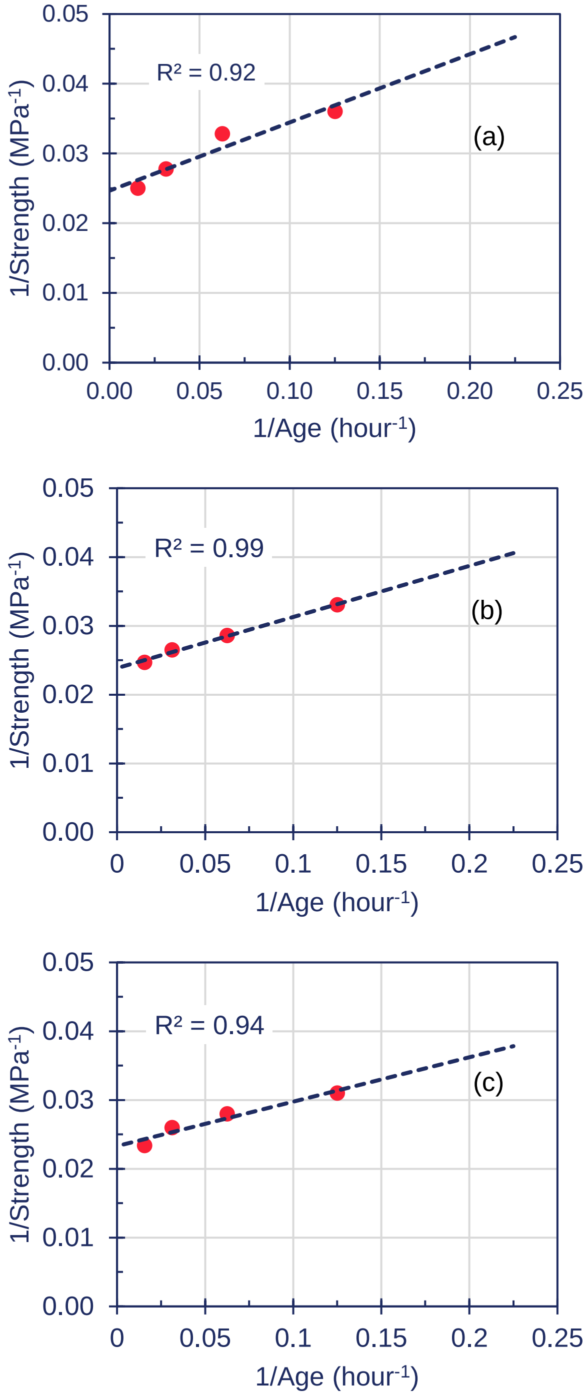


Fig. 2. Compressive strength development of RSC mortars cured at different temperatures.

In the next phase, the limiting strength, S_u value was used to calculate the A as defined by Eq. (2) below for each age of testing for each curing regime.

$$A = S/(S - S_u) \tag{2}$$



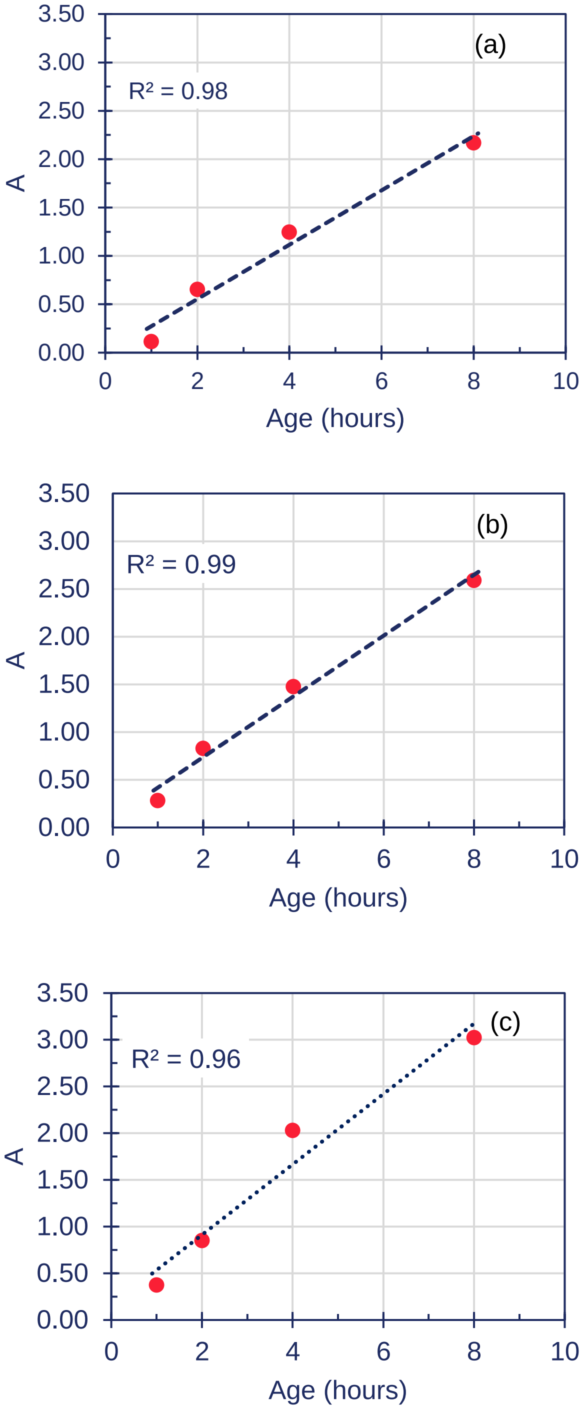


Fig. 3. Determination of limiting strength, S_u of BCSA Cement Concrete at (a) 15 °C, (b) 23 °C, and (c) 30 °C.

Fig. 4. Determination of k-value of BCSA Cement Concrete at (a) 15 °C, (b) 23 °C, and (c) 30 °C.

The A values for the first 4 ages of testing (1, 2, 4, and 8 hours) were plotted against their respective ages as illustrated in Fig. 4 and the slope of the A versus age curves for each curing temperature are the k values of each curing temperature. The plot of k value against the curing temperatures is shown in Fig. 5 and the X-axis intercept of the linear trendline is the datum temperature (-27.1 °C) for BCSA Cement Concrete. It is to be noted that, the R^2 values associated with Figs. 3-5 designate excellent correlations between the respective parameters.

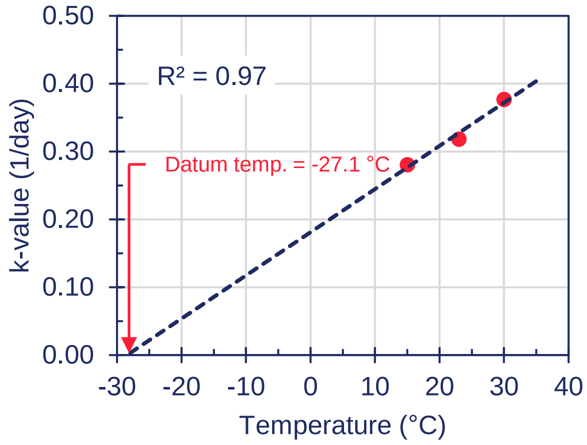


Fig. 5. Determination of BCSA Cement Concrete datum temperature.

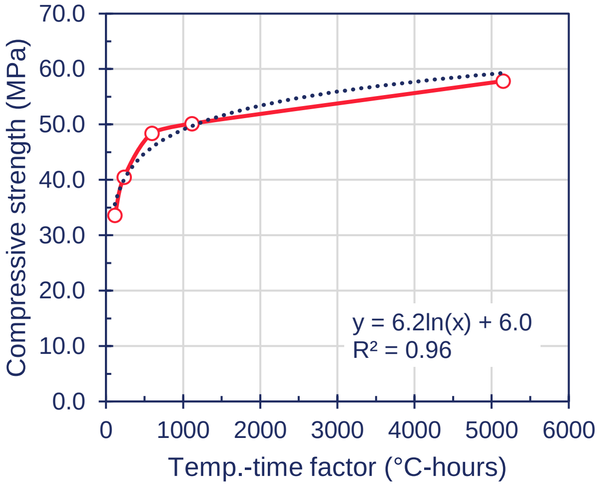


Fig. 6. Strength-maturity correlation of BCSA Cement Concrete SP40HES.

3.3. Strength-maturity Relationship

The correlation between the compressive strength of BCSA Cement Concrete and its temperature-time factor (maturity) is determined following eq. (1) and the calibration curve is illustrated in Fig. 6. A strong logarithmic correlation ($R^2 = 0.96$) is found between strength and maturity. The temperature-time factors and the corresponding compressive strengths at 2, 4, 6, 8, and 24 hours are summarised in Table 7. The calibration curve predicts the compressive strength of concrete for a specified maturity.

Time elapsed	Cumulative temperature-time factor (°C-hours)	Compressive strength (MPa)
2 hours	115.1	33.6
4 hours	234.1	40.5
6 hours	596.2	48.4
8 hours	1113.3	50.2
24 hours	5146.2	57.8

Table 7. Strength and maturity development of BCSA Cement Concrete in the first 24 hours of curing.

4. CONCLUSIONS

- This paper provides technical details of developing a strength-maturity correlation of a BCSA Cement Concrete mix for estimating its in-place strength and monitoring its strength development. In the coming days, this correlation will be tested against field-cast cylinder strength to assess the reliability of the maturity method for BCSA Cement Concrete, and successful application of this relatively simple practice will provide scope for savings in testing and deliver critical information to reopen concrete pavements to traffic. To ensure safety, the user needs to comprehend the inherent limitations of the method before regarding this as absolute. The following are the author’s final comments:

- The temperature-time maturity function and the subsequent correlation is applicable to ANTOUN 20/80/40 mix as registered in the Roads and Maritime Register of Concrete Mixes as updated on 5 December 2022. It may not be compatible with other BCSA Cement Concrete mixes.
- The proposed function of Fig. 6 is to be used to estimate the relative strength gain and should not be considered as the absolute strength. Even cylinder specimens collected from the same mix show deviations from the mean and similar deviations are to be regarded in predicting concrete strength using the BCSA Cement Concrete maturity function.

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