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Use of maturity method to estimate early age compressive strength of slab in cold weather

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Abstract

Accurate estimation of the in situ strength of concrete at early age is very important as it provides the necessary information required to start subsequent construction operations. Overestimation of the strength may cause serious safety hazards and underestimation may lead to unnecessary costly delays. This study investigates the performance of the maturity method in estimating the strength of in situ concrete subjected to cold weather at early age. Instrumented concrete slabs were subjected to cold weather conditions at early ages and their strengths were measured using drilled core samples from the slab. Sensors embedded in the slabs measured the temperature in the concrete which was used to estimate the strength using the maturity method. The measured core strengths at 24 and 72 h after casting are then compared with the estimated strengths using the maturity method and its performance is evaluated. The core strengths are also compared with the strength of standard cylinders cured at the same condition as the slabs. More than 250 cylinders from two slab thicknesses and four batches of concrete were used in the experiments to obtain statistically significant experimental data. The results show that the maturity method performed much better than the standard cylinder strength. On average the standard cylinder strength underestimated the core strength by more than 40% while the maturity method overestimated the strength by less than 10% with a lower variation.

KEYWORDS

cold weather concrete, core strength, early-age concrete strength, equivalent age, maturity method

1 | INTRODUCTION

Critical construction activities, such as formwork removal, post-tensioning, lifting precast members, and termination of cold weather protection require the determination of the strength of in situ concrete. Waiting too

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long to perform these activities can be expensive but acting too early can have a detrimental effect on the structure. A classic example of the latter is the progressive collapse of a portion of a multi-story building in Fairfax County, Virginia USA, in 1973, which claimed 14 lives and resulted in 34 injuries and a failure of a cooling tower being constructed in Willow Island, West Virginia, USA, in 1978, which claimed 51 lives.[1] These failures initiated research in the area of estimating the in situ strength of concrete during construction.

The maturity method estimates the concrete strength based on the combined effect of time and temperature. The origin of the method can be traced back to a series of papers dealing with accelerated curing methods.[2–4] McIntosh[2] investigated electrical curing of concrete and found that the amount of hydration is proportional to the area under the temperature–time curve above the datum temperature of 30°F (temperature at which hydration virtually ceases). McIntosh[2] termed this area 'basic age" of the concrete and measured it in °F × hours. Nurse[3] investigated steam curing of concrete and plotted the product of time and temperature against the strength of concrete expressed as a percentage of the strength of the concrete after 3 days storage at normal temperature. Nurse[3] used the curves to estimate the minimum steaming conditions to achieve a target strength and to estimate the concrete strength after a certain steam curing scenario. Saul[4] investigated the principles underlying the steam curing of concrete at atmospheric temperature and defined maturity as the age of concrete multiplied by the average temperature above freezing which the concrete has maintained. For a particular concrete mix, Saul stated that the strength of concrete stay constant whatever combinations of temperature and time go to make up the maturity.

As stated by Tank and Carino[5] the Nurse-Saul method was based on empirical observations, and is adequate only under certain conditions. When different samples of a given concrete experience dissimilar early-age temperature, the method does not correctly represent the effect of curing temperature on strength development.[5] Arrhenius maturity method which accounts for the nonlinear rate of hydration of cement caused by the effect of temperature was later developed by Hansen and Pedersen.[6] Due to its advantages, the maturity method has been the center of research for early age in-situ strength assessment of concrete. Various methods, standards and variation of the method have been proposed and used throughout the world.[1, 7–12]

The current study was conducted in Canberra Australia and was designed to simulate the winter conditions of Canberra. The city is known for its cold winters and warm summers. In winter the temperature at night time can drop below 0°C while the mean maximum day time temperature is about 14°C. A common curing method in this area is keeping the form in place, that is, preservation of moisture. Standard cylinders and maturity method based on cylinders kept in an insulated box are commonly used for estimating the strength.

Some researches on the performance of maturity method in cold weather were reported[13–15]; however, these researches are mainly based on heat curing. The performance of the method for predicting the early age strength of concrete in cold weather without heat curing still needs to be investigated. Furthermore, there is no research available in the open literature which investigated the correlation between in situ strength and strength estimated using maturity method at an early age (1-- 3 days) and in cold weather (less than 10°C), hence the need for this research. Both conventional concrete cylinder method and maturity method are compared with core strength of concrete to have a clear understanding on their performance on estimating the strength of the cold weather concrete.

2 | EXPERIMENTAL PROGRAM

2.1 | Introduction

The experimental program is comprised of testing standard concrete cylinders and slabs. Both the cylinders and the slabs were casted from the same concrete batches and were instrumented with temperature sensors. The standard cylinder specimens were tested at different ages up to 7 days to establish the relationship between concrete age, temperature and strength. The slab specimens were used to investigate the in-situ strength of concrete. The slabs were core drilled at 24 and 72 h after casting. The cores and standard cylinders were then tested for their compressive strength.

Using the age, temperature, and strength of the standard cylinders, a maturity curve is established. The maturity curve is then used to estimate the compressive strength of the slab. This compressive strength and the strength from the standard cylinder were then compared with the core strength of the concrete.

2.2 | Slab specimen

Two slab sizes were selected based on the common thickness ranges used in the industry and the number of cores required. These are 900 mm × 900 mm with 300 mm thickness and 850 mm × 650 mm with 150 mm thickness. The formworks for each slab were fitted with Styrofoam on all four sides to prevent heat loss and simulate the continuity of slabs. The Styrofoam were then covered with plastic for ease of demolding and reuse. Details of the specimens are as shown in Figure 1.

Temperature sensors were placed in the formwork using stretched fishing wires as shown in Figure 1. For the 300 mm thick slabs, sensors were placed at 100 mm and 200 mm along the thickness of the slab in the middle of the length and about 150 mm along the width of the slab as show in Figure 1. For the 150 mm thick slabs, the temperature sensor was placed in the middle of the slab along the thickness and length of the slab and about 150 mm along the width of the slab as shown in Figure 1. In addition, sensors were placed at the top and bottom of the slabs to capture the temperature variation along the thickness.

A ready-mixed concrete, mix proportion as shown in Table 1, with a target 28 days compressive strength of 60 MPa was delivered and casted in the laboratory. A total of four batches of concrete were prepared. For each batch, four slabs, two 150 mm thick and two 300 mm thick, were casted with 100 mm diameter by 200 mm height cylinders which are prepared and cured in the same condition as the slabs. The temperature sensors were programed to record the temperature history of the concrete every 5 min.

TABLE 1 Concrete mix proportion

Ingredients	Amount (per m^3)
Cement	475 kg
Fly ash	85 kg
10 mm coarse aggregate	265 kg
20 mm coarse aggregate	740 kg
Fine aggregate	630 kg
Water	180 kg[a]
High range water reducer	2.25 litter
Accelerator	2.80 litter
Water reducer and set Accelerator	2.24 litter

[a]Batch 1 has a higher water content.

For Batches 1–3, the concrete was exposed to an alternating +8°C and −8°C temperature (T1). Every 24 h, the concrete was exposed to −8°C for about 10–12 h to simulate the coldest temperature and duration in Canberra. Batch 4 was exposed to a constant 5°C temperature (T2).

Figure 2 shows a 300 mm thick slab ready for drilling. Minimum of six 94 mm diameter cores were drilled for the 150 mm thick slab. For the 300 mm thick slab five 94 mm diameter cores were drilled except for the first

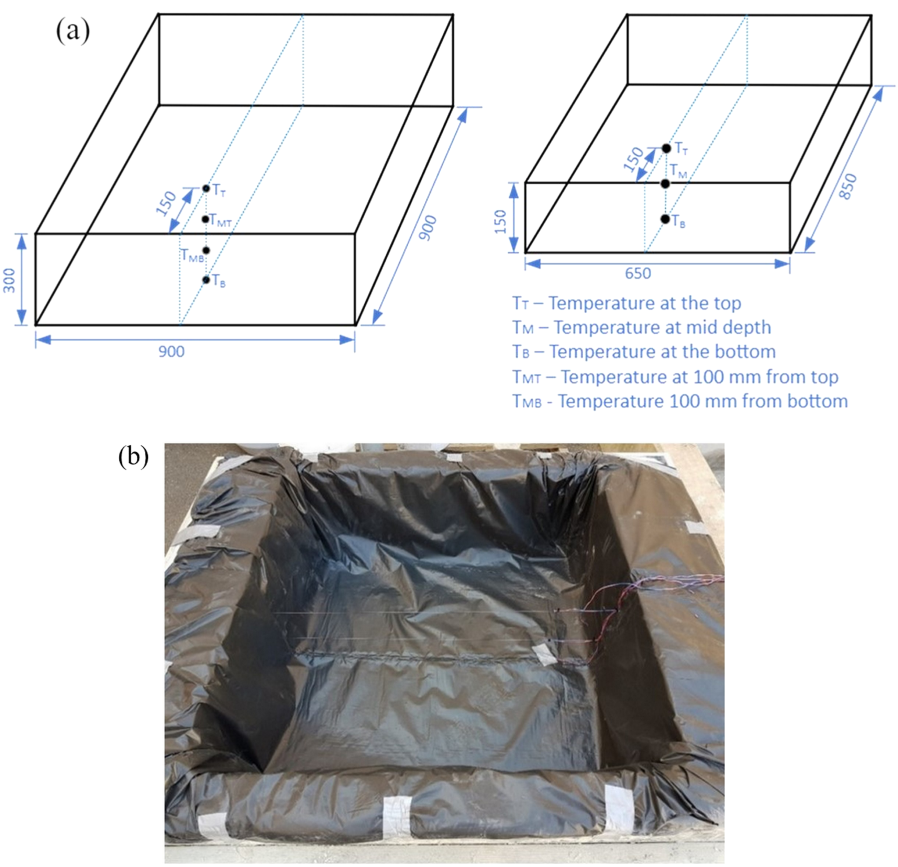

FIGURE 1 (a) Schematic of slabs and sensor locations (dimensions in mm) and (b) 300 mm thick slab formwork ready for casting

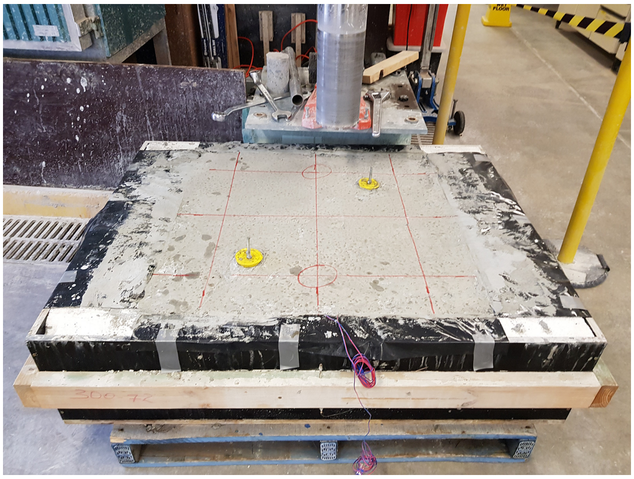

FIGURE 2 300 mm thick slab ready for core drilling

and second batches were four 140 mm diameter cores were drilled on average. The 94 mm diameter cores for the 300 mm thick slab were further saw cut into two equal cylinders at the mid length to test the top and bottom part of the slab individually. The drilling and testing were performed at 24 and 72 h after concrete casting.

The samples were drilled perpendicular to the concrete surface and away from formed joints as per AS 1012.14[16] and ASTM C42[17] recommendations. Both the core samples and cylinders were then prepared for testing by grinding their end faces. Figure 3 shows standard cylinder and core drilled samples ready for testing. The compression tests were then performed as per the recommendation of AS 1012.14.

2.3 | Maturity curve calibration specimens

Maturity curve is a plot the maturity of concrete and its strength. The maturity of the concrete is a single factor that represents the age and temperature history of the concrete and is indicative of the strength of the concrete. Different concretes will have different maturity curves. Hence this curve should be calibrated for each concrete. Three of the batches, that is, 1, 3, and 4 included two sets of at least 16 concrete cylinders each for calibrating the maturity curve. In Batch 1, one set of the cylinders were kept in the environmental control room (23°C) in the laboratory while the second set was kept in an insulated box at the site: a common calibration method used in Canberra. In Batches 3 and 4, one set from each batch was kept in the refrigerated container at the same temperature as the slabs while the other set was kept in an insulated box at the site. The cylinders were tested at different time intervals up to 7 days. For each batch, two of the cylinders were instrumented with temperature sensors in the middle of the cylinder to capture the temperature history of the concrete every 5 min. Table 2 shows the summary of the experimental program.

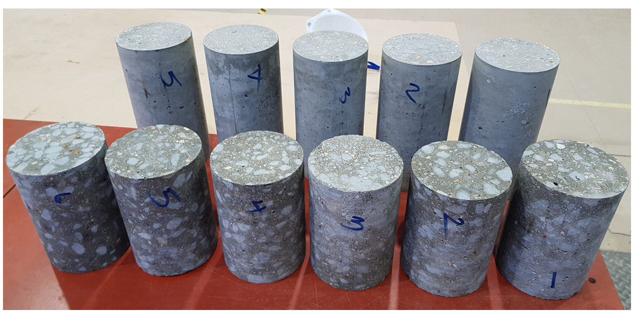

FIGURE 3 Core sample from 150 mm thick slab (six samples) and standard cylinder (five samples)

3 | RESULTS AND DATA ANALYSIS

Temperature of the slabs and the cylinders and the ambient temperature of the refrigerated container were recorded every 5 min until the end of the test, which is 3 days for the slabs and up to 7 days for the maturity cylinders. Compressive strength of the standard cylinders and the cores from the slabs were measured for each of the batch.

3.1 | Temperature–time history

Temperature sensors were placed in both the slabs and cylinders. The temperature sensor locations in the slabs were selected to be representative of the temperature at the locations of coring. The early age temperature varied along the thickness of the slabs. Figure 4 (a) and (b) shows the temperature variation for 300 and 150 mm thick slabs, respectively. As can be seen in this figure, the extent of variation along the thickness is affected by the slab thickness. The 300 mm thick slab displayed a higher temperature variation which reaches up to 25°C (difference between top and bottom) around 10 h after casting while the 150 mm thick slab displayed a much less value. The temperature at the top of the slab was generally influenced by the ambient temperature of the container. The highest temperature for the 300 mm thick slab was observed at 100 mm from the bottom of the

TABLE 2 Summary of experimental program

Batch	Note	Temperature	Specimens	Number of samples
1	Cylinder prepared for both laboratory and site calibration Has a higher water to cement ratio due to additional water at the mixing plant	T1	24 h 150 mm slab	8
			24 h 300 mm slab	4
			72 h 150 mm slab	6
			72 h 300 mm slab	6
			Standard cylinders	46
2	No maturity calibration	T1	24 h 150 mm slab	6
			24 h 300 mm slab	4
			72 h 150 mm slab	6
			72 h 300 mm slab	3
			Standard cylinders	17
3	Cylinder prepared for both laboratory and site calibration	T1	24 h 150 mm slab	6
			24 h 300 mm slab	3
			72 h 150 mm slab	6
			72 h 300 mm slab	5
			Standard cylinders	51
4	Cylinder prepared for both laboratory and site calibration	T2	24 h 150 mm slab	6
			24 h 300 mm slab	7
			72 h 150 mm slab	6
			72 h 300 mm slab	12
			Standard cylinders	48

slab while the 150 mm thick slab showed a similar temperature in the middle and at the bottom of the slab.

As can be observed from Figure 4(a), the temperature variation along the thickness of the slab decreases as the age of the concrete increases. This is because of the decrease in the rate of heat of hydration with the age of the concrete. Figure 4(c) and (d) shows temperatures of the container, the middle of the 150 and 300 mm thick slabs and the cylinders for Batch 3 (at T1) and Batch 4 (at T2), respectively. As can be observed in this figure, due to the heat generated from the concrete, the target temperatures were not met accurately especially at early age. The cylinder specimens displayed the closest temperature to the container temperature than both 150 and 300 mm thick slabs. Both slabs, especially the 300 mm thick slab, showed a considerable difference from the container temperature due to their high heat of hydration, lower total surface area to volume ratio and lower exposed surface area to volume ratio compared to the cylinders. From Figure 4, it can also be observed that Batch 1 has the highest temperature. As explained in Table 2, this batch has a higher water to cement ratio due to higher water added at the mixing plant. This resulted in more microstructural space for hydration, resulting in increased rate of heat development,[18–22] hence the higher temperature.

3.2 | Determination of the in-situ strength of concrete: Core strength

The core strength is an effective way of determining the strength of in-situ concrete.[23,24] Thus, it is often used for calibration of other methods.[25] However, the compressive strength of the core samples is generally lower than that of the conventional cylinders due to the drilling process.[20] Factors, such as length to diameter ratio, diameter, and treatment of the core affect the strength of the core samples. In this study the core strength is compared with the strength from the maturity method which is based on standard cylinders. The comparison of the core strength with the maturity strength should be performed after modifying the core strength to account for factors, such as diameter, length to diameter ratio, and drilling operation effects. Standards, such as AS 1012.14[16] and ACI 214.4R[26], give such procedures for modifying the core strength. In this report, the ACI 214.4R method is

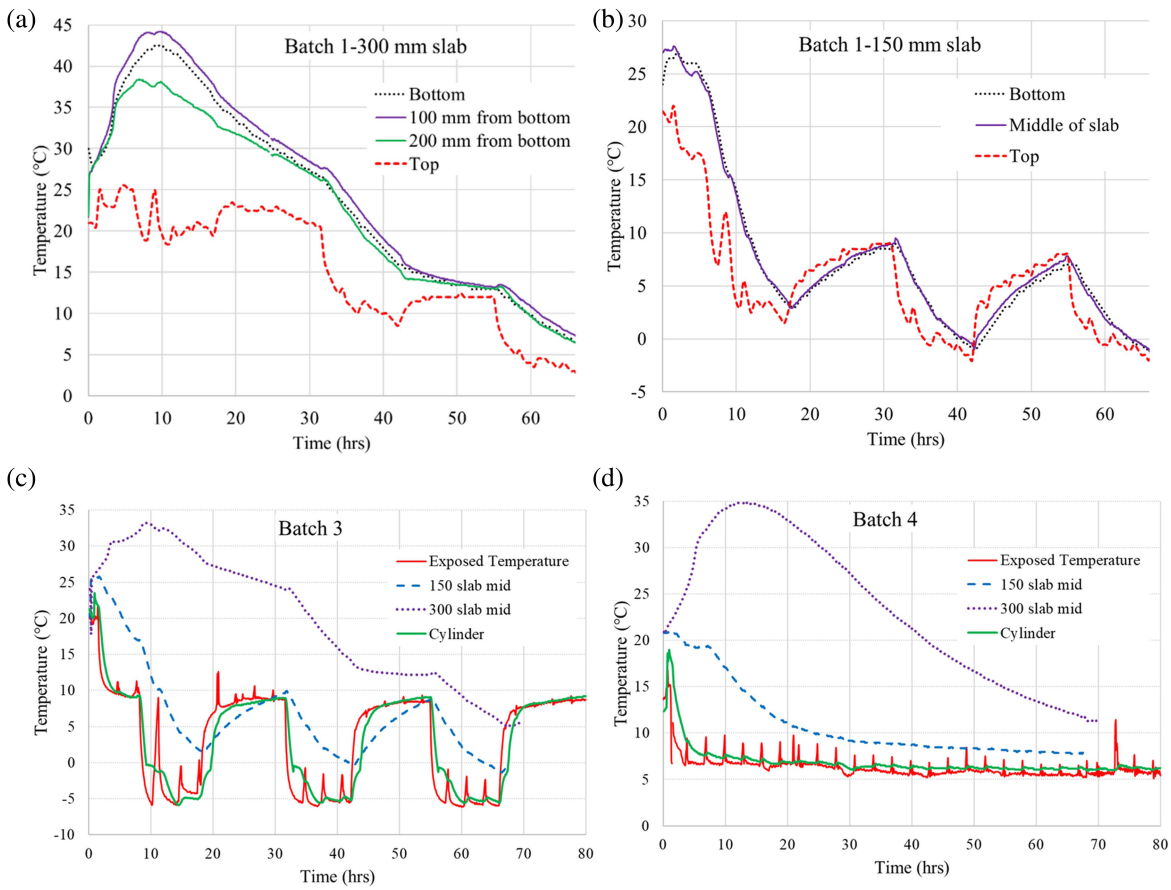

FIGURE 4 Temperature–time history (a) along the thickness of Batch 1–300 mm thick slab (b) along the thickness of Batch 1–150 mm thick slab (c) Batch 3 (d) Batch 4

followed as it accounts for the strength reduction coming from core drilling process. As per ACI 214.4R the strength correlation is given by Equation (1):

$$f_c = F_{l/d} F_{\text{dia}} F_{mc} F_d f_{\text{core}} \tag{1}$$

$F_{l/d}$ is the factor for length to diameter ratio, as per ACI 214.4R and assuming standard treatment it is given by:

$$1 - \{0.13 - \alpha f_{\text{core}}\}\left(2 - \frac{l}{d}\right)^2, \text{where } \alpha \text{ is } 0.00043 \tag{2}$$

F_{dia} is the strength correction for core diameter and is taken as 1 for the 94 mm diameter cores and 0.98 for the 140 mm diameter cores. F_{mc} is the strength correction factor for core moisture content and is taken as 1 assuming a standard treatment. F_d is the correction factor for damage due to core drilling operation and is taken as 1.06. f_{core} is the original strength of core specimen.

3.3 | Calibration of maturity curves

In the process of estimating concrete strength using maturity method, two main steps are involved. In the first step, the age and temperature history of the concrete is converted to a single factor called maturity or equivalent age (EA). In the second step, the EA of the concrete is correlated with the strength of the concrete. In this study, the Arrhenius method (Equation (3)) which accounts for the nonlinear rate of hydration of cement, is adopted for calculating the EA of the concrete.

$$\text{EA} = \sum_0^t e^{\frac{-E}{R}\left[\frac{1}{273+T} - \frac{1}{273+T_r}\right]} . \Delta t \tag{3}$$

TABLE 3 Strength-maturity curve-fitting parameters

Batch		Function: Logarithmic a	b	Bernhardt M_o	A	S_∞	Hansen and Pedersen S_∞	τ	α
1	Lab	10.5	22.3	4.7	0.75	43.2	66.1	83.4	0.47
	Site	10.7	23.3	9.3	0.95	39.9	37.9	32.2	1.02
3	Lab	15.1	30.3	6.1	0.96	105.6	72.7	41.8	0.84
	Site	21.0	49.3	8.5	1.26	93.6	57.8	29.0	1.24
4	Lab	15.0	28.9	5.1	0.99	92.9	87.9	54.0	0.66
	Site	17.2	38.3	8.0	1.28	64.2	54.6	29.6	1.08

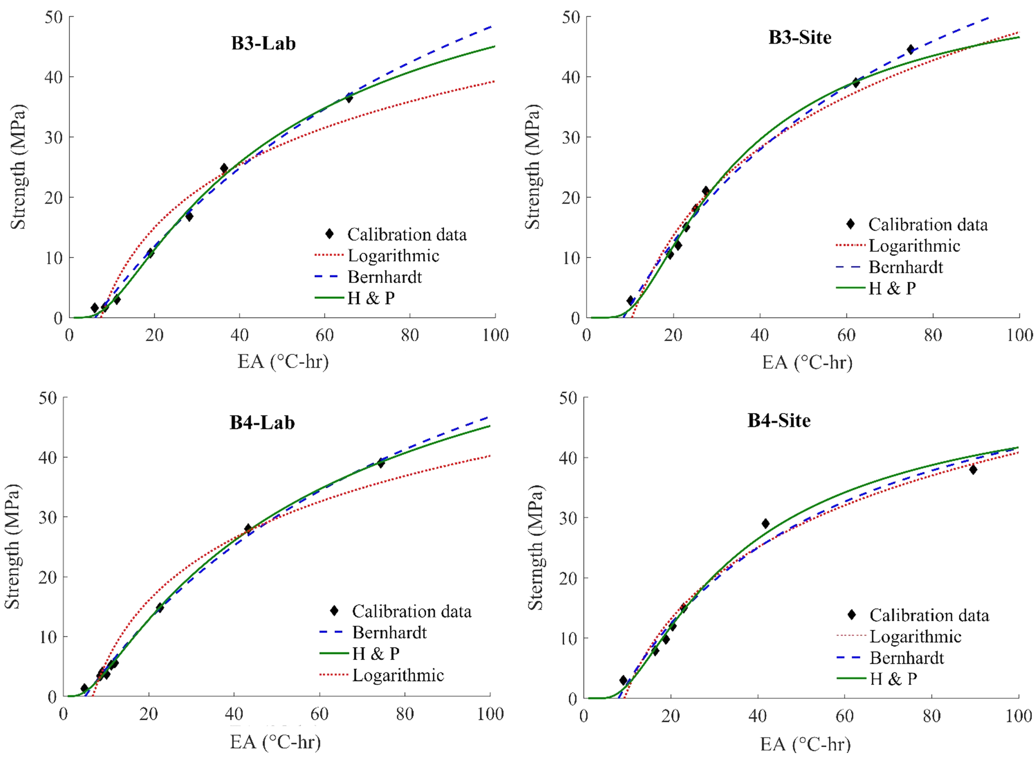

FIGURE 5 Batches 3 and 4 equivalent age vs strength data and curves

where R is universal gas constant (8.3144 J/(mol K), T_r is reference temperature (taken as 20°C) and T is average concrete temperature (°C) during Δt. E is activation energy (J/mol).

The activation energy used should not be confused with the Arrhenius's activation energy. The value used in Equation (3) can be obtained for each individual concrete mixture as per ASTM C1074.[7] Recommended values from literature can also be used for normal strength concrete[27,28] or it can also be calculated based on the average temperature of concrete during curing as per Hansen and Pedersen.[6] A value of 42 kJ/mol, as per Malhotra and Carino[28] is adopted in this study.

Batches 1, 3, and 4 included two sets of at least 16 concrete cylinders for calibrating the maturity curve. For each set two of the cylinders were instrumented with temperature sensors in the middle of the cylinder to capture the temperature history of the concrete every 5 min. The maturity of the concrete is calculated using these temperatures and Equation (3). Once the maturity of the concrete is calculated, three strength-maturity functions, that is, a Logarithmic function as per Plowman[29] (Equation 4), a hyperbolic function suggested by Bernhardt[30]

TABLE 4 Compressive strength comparison

Specimen	Equivalent age (°C-hr)	Average Core strength	Cylinder to core strength ratio	Maturity strength to core strength ratio			
				Logarithmic		H. & P.	
				Lab	Site	Lab	Site
B1-24T1-150	25.4	11	0.41	1.08	1.03	1.05	0.96
B1-24T1-300	56.7	18.4	0.24	1.10	1.08	1.08	1.18
B1-72T1-150	36.4	13.3	0.89	1.18	1.14	1.14	1.18
B1-72T1-300	92.5	23.3	0.51	1.09	1.08	1.09	1.16
B2-24T1-150	28.7	18.5	0.38	1.13	1.10	1.00	1.09
B2-24T1-300	77.5	31.2	0.23	1.15	1.26	1.28	1.30
B2-72T1-150	38.5	22.7	0.89	1.12	1.14	1.09	1.19
B2-72T1-300	112.8	35.5	0.57	1.17	1.31	1.34	1.28
B3-24T1-150	19.9	10.4	0.53	1.43	1.30	1.08	1.13
B3-24T1-300	32.0	21.7	0.25	1.02	1.08	0.96	1.10
B3-72T1-150	34.1	24.7	0.82	0.93	1.00	0.90	1.03
B3-72T1-300T	61.0	29.1	0.69	1.09	1.27	1.21	1.33
B3-72T1-300B	80.7	43.6	0.46	0.83	0.98	0.94	1.00
B3-72T1-300	74.0	34.7	0.58	1.00	1.18	1.13	1.22
B4-24T2-150	21.9	12.4	0.56	1.41	1.20	1.16	1.11
B4-24T2-300T	33.2	21.9	0.32	1.08	1.00	1.01	1.03
B4-24T2-300B	40.6	29.6	0.23	0.90	0.86	0.89	0.91
B4-72T2-150	41.1	24.7	0.99	1.09	1.04	1.08	1.10
B4-72T2-300T	72.4	33.4	0.73	1.06	1.06	1.16	1.12
B4-72T2-300B	91.7	39.4	0.62	0.99	1.00	1.10	1.03

TABLE 5 Average strength to core strength ratio

Specimen type		T1 standard cylinder to core strength	T2 standard cylinder to core strength	Logarithmic to core strength		H & P to core strength	
				Lab	Site	Lab	Site
24 h-150 mm		0.44	0.56	1.30	1.17	1.10	1.07
24 h-300 mm		0.24	0.27	1.02	1.01	0.99	1.05
24 h overall	Average	0.34	0.37	1.14	1.08	1.03	1.06
	STDV	0.12	0.17	0.20	0.14	0.09	0.10
72 h-150 mm		0.87	0.99	1.06	1.06	1.04	1.10
72 h-300 mm		0.56	0.68	1.01	1.10	1.11	1.14
72 h overall	Average	0.66	0.78	1.03	1.08	1.08	1.13
	STDV	0.17	0.19	0.10	0.10	0.10	0.11
Average		0.53	0.58	1.08	1.08	1.06	1.10
SD		0.23	0.28	0.16	0.11	0.10	0.11

Note: Average ratios for maturity are calculated from Batches 1, 3, and 4 as these are the only batches with calibration. Naming example: 24 h-150 mm—average of all the 150 mm slabs tested at 24 h.

and modified by Malhotra and Carino[28] (Equation 5) and an equation suggested by Hansen and Pedersen[6] (Equation 6) were curve fitted with the maturity strength data.

$$S = a + b\log(M) \tag{4}$$

$$S = \frac{M - M_o}{\frac{1}{A} + \frac{M - M_o}{S_\infty}} \tag{5}$$

$$S = S_\infty e^{-\left(\frac{\tau}{M}\right)^\alpha} \tag{6}$$

where S is the strength, a and b are curve fitting parameters related to water to cement ratio and cement type, M is the maturity of concrete expressed as EA, S_∞ is the limiting strength, τ is characteristic time constant, M_o an offset maturity where strength development starts and α is shape factor.

The resulting curve-fitting parameters for both the laboratory and site calibrated specimens are as shown in Table 3. Figure 5 shows the calibration data with each of the function for Batches 3 and 4. As can be observed in this figure, in both Batches 3 and 4, Bernhardt, and Hansen and Pedersen (H & P) equations gave a better fit for both laboratory and site calibrated specimens. For the laboratory calibrated specimens up to about 40°C-h EA, the Logarithmic function overestimated the compressive strength and at higher EA it underestimated the strength. Both Bernhardt and Hansen and Pedersen functions intercept the Logarithmic function at about 40°C-hr and fitted well with the data before as well as after 40°C-h. The laboratory cylinders (in Batches 3 and 4) were exposed to a much lower temperature compared to the site cylinders as the site cylinders were kept in an insulated box, which resulted in a higher temperature due to exothermic reaction. As can be seen in Figure 5, the site calibrated curves showed a much less difference between the Logarithmic and the other functions. Hence, the difference between the Logarithmic and the other functions is due to the lower temperature of the laboratory calibrated specimens, showing the sensitivity of the Logarithmic function to temperature. From the Bernhardt, and Hansen and Pedersen functions, the Hansen and Pedersen function performs slightly better and is conservative at higher maturities making it the preferred function. The Logarithmic function is not the most accurate one, however, due to its simplicity it is a commonly used method. Hence, for comparative purpose both the Hansen and Pedersen and Logarithmic functions are used throughout the analysis in this study.

As can be observed in Figure 5, the Logarithmic curves clearly defined an intercept for the EA axis while the Hansen and Pedersen curves showed a tangent to the axis. The EA at which the Logarithmic curves cross the axis and the EA at which the Hansen and Pedersen curves start increasing in strength are close to each other. This EA is about 5–7°C-h which is about 8–14 h in case of the laboratory calibrated cylinders. This means that for a concrete structure which displays a similar temperature as these cylinders, no activity should be conducted on the structure during this period as the concrete has a very low compressive strength.

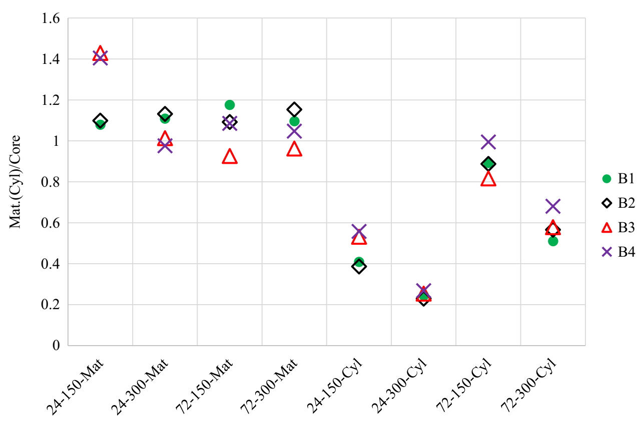

FIGURE 6 Cylinder and maturity strength to core strength ratio (logarithmic lab calibration)

3.4 | Prediction of the in-situ strength of concrete: Maturity method

In the maturity method, the in-situ strength of the concrete was estimated using the temperature sensors installed at specific locations of the slabs, which was also the location of the coring. In case of the 150 mm slab as there was only one sensor in the mid depth of the slab, the temperature from this sensor was used to calculate the equivalent age. In case of the 300 mm thick slab, different approaches were taken based on the type of core tested. When a 140 mm diameter core was taken, the temperature sensor at 100 mm from the top of the slab was used to calculate the strength. For the 300 mm thick slab in case of Batches 3 and 4 two strengths were estimated separately for the top and bottom part of the slab. For the top part of the slab the strength was calculated averaging the temperature at 100 mm from the top of the slab and the temperature at the top of the slab (about 10 mm deep into the concrete). For the bottom part of the slab the temperature at 100 mm from the bottom of the slab was used. The in-situ strength of the concrete was then calculated using the EA and the established strength-maturity relationships as shown in Figure 5.

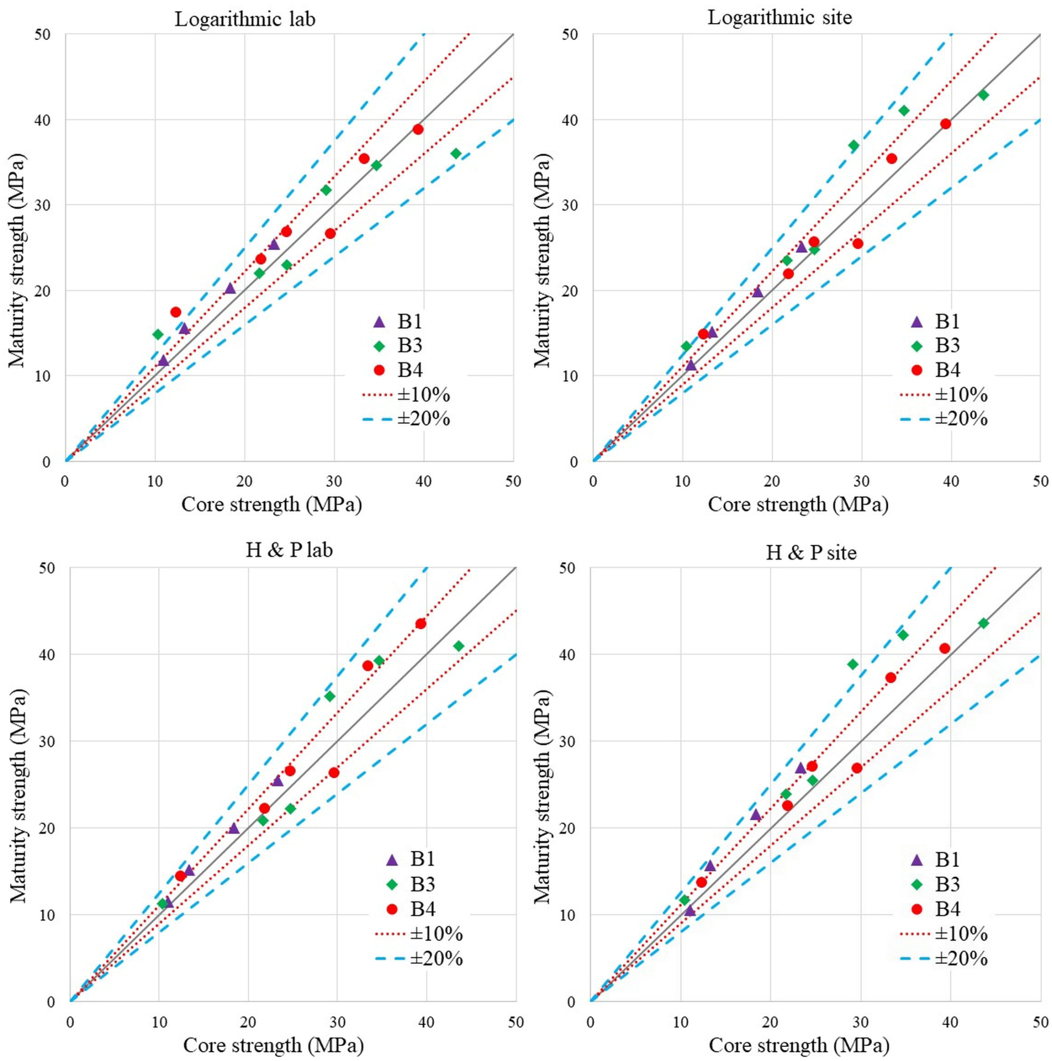

FIGURE 7 Maturity versus core strength

Since Batch 2 was not calibrated for maturity, its strength was estimated by using the average of Batches 3 and 4 maturity curves. Batch 1's maturity was not included in the average because the concrete has a higher water to cement ratio as noted in Tables 1 and 2.

The EA, average core strength, standard cylinder to core strength ratio, and maturity strength to core strength ratio are summarized in Table 4. The specimens are identified by the batch number, age of the specimen during test, temperature exposure type and thickness of the slab. In case of the 300 mm thick slab starting from Batch 3, T and B are used to identify the top and bottom section of the slab, respectively.

4 | DISCUSSION

The results showed a significant difference between the standard cylinder and maturity methods of strength assessments. The cylinder method highly underestimated the compressive strength of the slab while the maturity method gave a good estimate. The following section gives details regarding these findings.

4.1 | Comparison of conventional cylinder strength and core strength

In most of the batches, the cylinder method of estimating compressive strength of slab, as can be seen in Table 4, highly underestimated the compressive strength of the slab. This is due to the difference in the size of the standard cylinder and the slabs. The slabs, due to their bigger size, preserve most of the heat generated during hydration and thus are less affected by the low temperature they are exposed to. The cylinders on the other hand have more surface area to volume ratio exposing them to the external low temperature resulting in a much lower

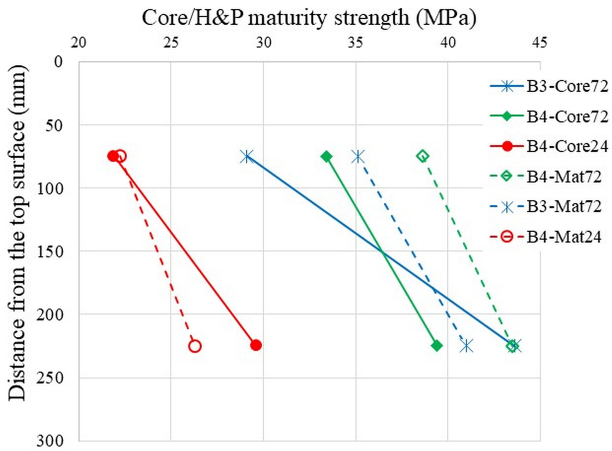

FIGURE 8 Core and maturity strength along the depth of the slab (300 mm slab)

concrete temperature which in turn lowers their strength due to lack of favorable temperature for hydration. Table 5 shows the average ratio of the standard cylinder to core strength as well as maturity strength to core strength. Figure 6 shows the average ratio of cylinder to core strength and maturity strength to core strength.

As can be seen in Table 5 and Figure 6, the performance of the standard cylinder in estimating the concrete strength varies with temperature, age and slab thickness. The worst estimate was observed in case of 24 h-300 mm specimens while the best estimate was observed in case of 72 h-150 mm specimens. The standard cylinders underestimated the concrete strength by 76% at T1 exposure for 24 h-300 mm specimens while it gives almost the same strength as the core for 72 h-150 mm specimens at T2 exposure. The standard cylinders were unable to properly estimate the strength of 24 h-300 mm specimens due to the relative early age of the concrete and the higher thickness of the slab. For Portland cement the maximum rate of heat evolution occurs within the first 24 h. Thus, more heat is generated in the concrete in this period. This higher heat generation creates a relatively higher difference between the cylinders and the slabs when compared to the concrete tested at 72 h. For instance, for B3-72T1-300 slab, a maximum temperature of 35°C was observed around 9.5 h mark. At the 24th h, the slab has a temperature of 26°C while the cylinders have a temperature of only 8°C. At the 70th h, the slab has a temperature of 5.5°C while the cylinders have a temperature of 7°C showing a much lower difference between the slab and the cylinder. The concrete in the slab takes the advantage of the higher temperature at the early age resulting in a higher strength while the rate of hydration in the cylinders is adversely affected by the lower ambient temperature.

The 300 mm thick slabs generated more heat than the 150 mm thick slab especially at early age because of its bigger volume. This higher heat results in a higher early age strength as can be observed in Table 4. It can also be observed that the lower the temperature of exposure, the lower the accuracy of the cylinders. For example, for 72 h-300 mm at T1 exposure, the cylinders underestimated the strength by 44% while at T2 exposure they underestimated by 32%. The cylinder method of strength estimation got better with the increase of exposure temperature. However, even at T2 exposure, there is a considerable amount of underestimation of the slab strength depending on the specimen type. It may be safe to use cylinder methods for concrete activities due to their underprediction of the strength of the slab; however, this amount of underprediction can be expensive as it affects various activities such as formwork removal, application of prestressing and lifting of precast members. This clearly shows the limitation of

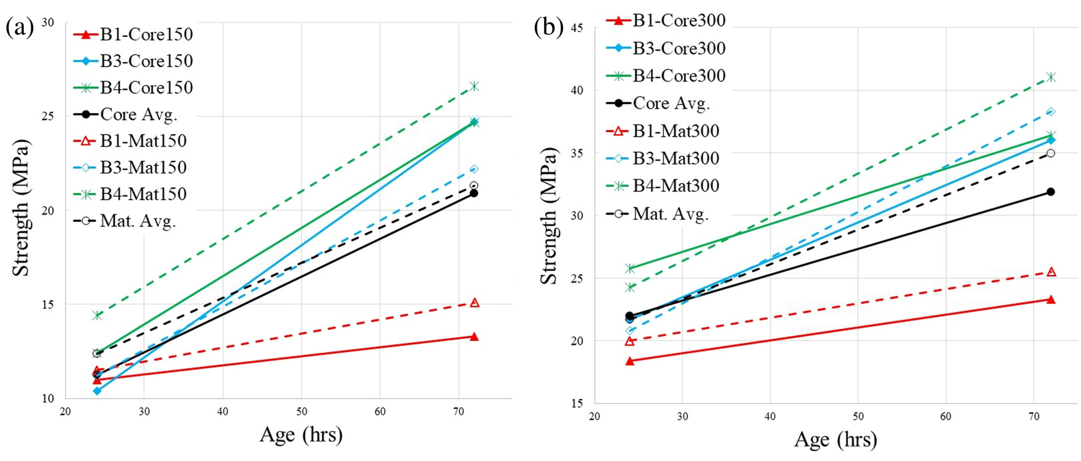

FIGURE 9 Core and H&P maturity strength vs time (a) 150 mm slab (b) 300 mm slab

cylinders cured at the same condition as the slabs in estimating the compressive strength of the slab in cold weather. Such cylinders are no longer allowed by standards such as ACI 306–16[31] in cold weather concreting practices because of their inability in simulating the curing history of the real structure.

4.2 | Maturity strength prediction versus core strength

As can be seen in Table 5 and Figure 7, the maturity methods showed a good performance in estimating the strength of the slab. On average, as can be seen in Table 5, using the laboratory calibrated specimens, the Hansen and Pedersen equation overestimated the slab strength by about 6% while the Logarithmic equation overestimates by about 8%. Both site and laboratory calibrated maturity methods estimated the core strength within 10% on average. This shows that in cold weather, the maturity method is a much better alternative for estimating the early age strength of concrete.

From the maturity methods Hansen and Pedersen equation showed a better result compared to the Logarithmic equation. The Logarithmic function, as can be seen from Table 4, highly overestimate the strength of the concrete for B3-24-150 and B4-24-150 specimens. For the same specimens, Hansen and Pedersen maturity equation showed an average overestimation of about 12%. This is due to the Logarithmic curve's failure to fit most of the data especially in case of laboratory cured specimens as shown in Figure 5. Studying the average values for each age group as shown in Table 5, it can be observed that at the early age (24 h) the Logarithmic function shows a higher ratio for the laboratory calibration specimens than at later age (72 h).

As can be seen in Figure 7, for the Hansen and Pedersen equation in case of the laboratory calibrated maturity curves, all the maturity predictions are within ±20% of the core strength. In this case, about 70% of the predicted strengths overestimated the core strength while about 25% underestimated it. Similar pattern with about 90% of the prediction laying within ±20% of the core strength is observed for the Logarithmic maturity functions at both site and laboratory calibrations.

4.3 | Depth effect on core strength and maturity strength (300 mm slab)

As can be observed in Figure 8, the compressive strength of the core samples at the bottom of the slab are higher than that at the top of the slab. This is believed to be caused by the temperature variation along the depth and segregation due to the use of concrete vibration during casting. A similar trend was observed by Yikici and Chen[32] in their study of maturity method for mass concrete structures.

Comparison of core strengths at 24 and 72 h indicate that a more pronounced strength variation (top to bottom) was observed in case of the former. Despite their higher strength, cores tested at 72 h showed a lower strength difference between top and bottom. For instance, for Batch 4 the cores tested at 72 h showed a difference of 6 MPa between the top and bottom while those at 24 h showed 7.7 MPa. This is due to the higher hydration rate at the early age of the concrete.

The core strength showed a clear variation along the depth of the slab. The maturity prediction also showed similar trend of increase in strength with the depth of the slab. However, as can be observed from Figure 8, the difference between the top and bottom strength is less pronounced in case of the maturity. Assuming linear variation along the depth, on average the maturity

TABLE 6 Maturity to core strength ratio statistical analysis

	Maturity strength to core strength ratio			
	Logarithmic		H. & P.	
	Lab	Site	Lab	Site
Average (all batches)	1.09	1.11	1.08	1.12
SD	0.14	0.12	0.12	0.11
95% confidence interval	1.03–1.15	1.06–1.16	1.03–1.13	1.07–1.17
t-statistic value	0.34		1.06	
t-Critical value	2.02		2.02	
Mean difference	No statistical significance		No statistical significance	

method showed strength increase of about 1.7 MPa per 50 mm increase in depth while the core strength showed 3.1 MPa. This high strength development along the depth in the case of the core strength is attributed to the segregation of the concrete due to the vibration process. The maturity method is not capable of predicting such effects hence the smaller difference between top and bottom. Since the maturity method generally overestimated the core strength and since the bottom cores showed a higher strength than the top cores, the maturity method showed a better estimation of the bottom core strength than the top cores.

4.4 | Strength development for core and maturity

Figure 9 shows the compressive strength versus age for the core and maturity methods in case of 150 and 300 mm slabs. The figure also shows the average strength versus age for both the core and maturity methods.

Both core and maturity methods showed a considerable increase in strength with age of the concrete. The maturity method predicted a similar strength increase as that of the core strength. For instance, for the 150 mm thick slab an average slope of 4.5 MPa/day is observed for the maturity method while the core strength showed an average slope of about 4.8 MPa/day. A slight increase in slope was observed from 150 mm slab to 300 mm slab in case of the core specimens, that is, from 4.8 to 5.0 MPa/day on average. The maturity method also showed an increase in slope from 150 mm slab to 300 mm slab. On average, the core method showed an average slope of 4.9 MPa/day while the maturity method showed a value of 5.6 MPa/day. This illustrates the maturity method's capability in predicting the strength development of the concrete.

4.5 | Effect of curing temperature

As discussed in Section 2.3, the maturity calibration cylinders were cured in two conditions: one at the laboratory and another at the site. The laboratory cured cylinders, especially for Batches 3 and 4, were exposed to a much lower temperature than the site cured cylinders as they were kept at the same condition as the slabs. It has been reported that concretes with the same maturity can have different strength when the concretes are exposed to significantly different early age curing temperatures.[1,27,32,33] Malhotra and Carino[28] reported that higher early-age temperature results in a higher early age strength. However, at later ages, it was reported to result in a lower limiting strength (maximum strength) than those cured at lower curing temperature. This section investigates the effect of the two temperature settings, that is, laboratory and site, on the accuracy of the maturity method within the studied age range. Table 6 summarizes the average maturity to core strength ratios for the laboratory and site cured cylinders for both the Logarithmic and Hansen and Pedersen methods.

The maximum age of the in-situ concrete in this study is 72 h. At this age the concrete is still at its early age. A higher curing temperature as explained can cause a higher strength at early age. As can be observed from Table 6, the average ratio of strength from the site calibrated cylinders is higher than that from the laboratory calibrated cylinders. This difference can be due to the higher temperature of the concrete in case of the site calibrated cylinders. However, as statistical analysis shows, at 95% confidence level this difference is not statistically significant. Thus, the maturity curves can be obtained from either of the temperature setting without significantly affecting the strength prediction of the concrete in the age range studied.

5 | CONCLUSION

Four batches of 60 MPa concrete were investigated using two slab sizes and cured at two cold weather temperature settings. Concrete temperatures inside the slabs were monitored and converted to equivalent age using the Arrhenius equation. Strength-maturity calibration curves were established for three of the batches. The core strength of the slabs were measured at 24 and 72 h and compared with the maturity predicted and conventional cylinder values. Based on the test results the following conclusions can be made:

1. The temperature of the in situ concrete varied along the depth of the slab. The thickness of the slab affects the variation of temperature along the depth. The 300 mm thick slab showed a much higher variation than the 150 mm thick slab.
2. The Logarithmic function overestimated the cylinder's strength at lower maturities and underestimated them at higher maturities. The Hansen and Pedersen function showed a better fit to the calibration cylinder's strength at the exposed temperature ranges.
3. The maturity method showed a similar rate of strength development as the core cylinders and was not significantly affected by the curing temperature conditions in the investigated age ranges.
4. Compared to standard cylinders cured at the same condition as the slabs the maturity method resulted in a better estimation of the core strength, in terms of average as well as SD. With a proper calibration, the

method can be a more accurate option than the standard cylinder strength method for early age strength assessment of concrete in cold weather.

5. The compressive strength of the core samples increased with the depth of the slab. Core strengths obtained from the bottom part of the slab were significantly higher than those from the top position. The maturity method also showed a similar trend. However, the difference was less pronounced than the core strengths.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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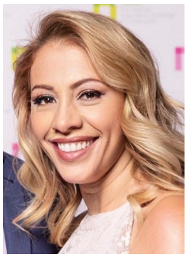

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