

Determination of the datum temperature for applying maturity in cold weathers

Determinación de la temperatura datum para la aplicación de la madurez en climas fríos

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Fecha de Recepción: 28/01/2020

Fecha de Aceptación: 03/03/2020

PAG 84-99

Abstract

The recently approved Chilean standard NCh3565 for the use of Concrete Maturity to estimate the Concrete Strength has greatly facilitated the technological transfer of new wireless measurement technologies with online connection (IoT), represented by the maturity sensors. In this sense, preliminary on field tests carried out on pavements incorporating sensors in the city of Punta Arenas made it possible to detect that the assignment of the value of the Datum Temperature to the fixed value of 0 °C does not deliver the real resistance results determined by means of control cylinders and concrete cores. This work deepens on this topic proposing as a conclusion the use of a variable value of Datum Temperature for cold climates.

Keywords: Concrete, Pavements, Cold Climate, Maturity, Datum Temperature

Resumen

La reciente entrada en vigencia de la norma chilena NCh3565 sobre el uso de la Madurez del Hormigón para estimar la Resistencia del hormigón, ha facilitado enormemente la transferencia tecnológica de nuevas tecnologías inalámbricas de medición con conexión en línea, representada por los sensores de madurez. En este sentido, pruebas preliminares de terreno realizadas en pavimentos de prueba con sensores en la ciudad de Punta Arenas permitieron detectar que la asignación del valor de la Temperatura Datum al valor fijo de 0°C no entrega los resultados de resistencia real determinados mediante cilindros de control y testigos. Este trabajo profundiza sobre este tema proponiendo como conclusión el uso de un valor variable de Temperatura Datum en climas fríos.

Palabras clave: Hormigón, Pavimentos, Clima Frío, Madurez, Temperatura Datum

1. Introduction

After holding sessions for a year, the Technical Committee for the Standard NCh3565 finished the wording of the standard regulating the procedure for the use of Concrete Maturity for estimating concrete strength. With the participation of representatives of cement companies, ready-mix concrete companies, laboratories, consultants and technology suppliers, this standard, based on ASTM C1074, represents a novel and interesting progress aimed at the practical use of this methodology on site, rather than the use ascribed to laboratories only. For example, regarding the execution of the calibration curve, called “Strength-Maturity Relationship”, it defines the use of the same type of concrete that will be used in place, provided by a ready-mix plant (manufactured in compliance with NCh1934). Only in the case of the initial stage of the works, this concrete can be produced in the laboratory, according to NCh1018.

Furthermore, five (5) age should be defined for the strength measurement, properly covering the study time period, and maintaining the age of 7 and 28 days as control. For example, for demoulding or tensioning tasks, this time period should take between 1 to 5 days, but process controls at later ages should consider 14 and 28 days of age.

The standard’s definition regarding the value assigned to the “Datum Temperature”, which is defined as the temperature below which concrete ceases to gain strength given that the chemical reaction of cement stops, is quite significant for the present study. This temperature has been defined by the value $T_0=0^{\circ}\text{C}$, thereby highlighting that this value should be adjusted in case of cold weather hardening conditions. This paper aims at giving guidelines for using the maturity method under cold weather placement conditions.

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2. Background

The strength of a concrete mix properly placed, compacted and cured will depend on its age and temperature history development due to the hydration of cement. In relation to the strength gain, the combined effect of time and temperature can be quantified through the maturity function, which assumes that if two mixes of the same concrete have equal maturity values, even under different temperature conditions, their strength should be the same. Already in 1951 (Carino, 2001), Saul summarized the researches of that time, especially concerning steam-cured concrete, suggesting the need of using a “datum temperature” for a correct application of the method see (Figure 1):

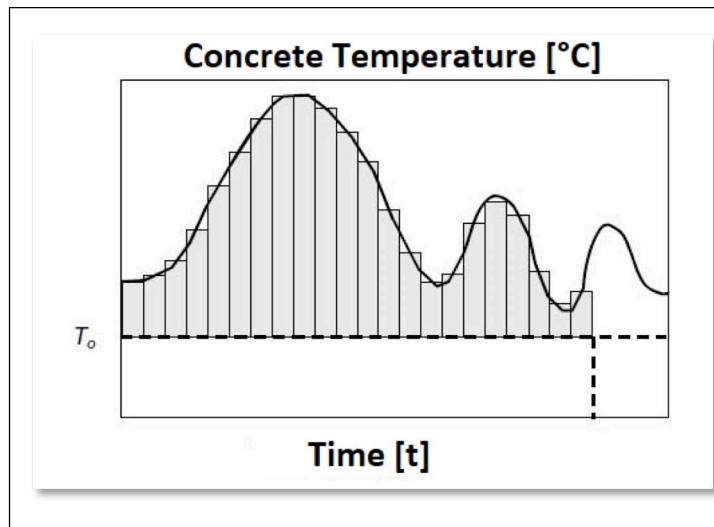


Figure 1. The Nurse-Saul maturity function

The developed function see (Equation 1) is known as the “Nurse-Saul” function. In this linear function, only the time intervals in which the temperature is higher than T_0 contribute to the strength gain. Moreover, it also determined that once the concrete sets, it will continue to gain strength and harden even at temperatures below 0°C . The studies of Saul and other researchers of that period led to define $T_0 = -10^{\circ}\text{C}$.

$$M(t) = \sum [T - T_0] * \Delta t \quad (1)$$

Where:

- $M(t)$ = Maturity function [$^{\circ}\text{C}\cdot\text{h}$]
- T = Average temperature during each time interval [$^{\circ}\text{C}$]
- T_0 = Datum temperature [$^{\circ}\text{C}$]
- Δt = Time interval [hours]

Subsequent researches demonstrated that, when using the “Nurse-Saul” function, a crossover effect was produced in the strength development and early and late maturity, mainly influenced by the concrete temperature at early age and the difference in the type of chemical products generated in each case. Thus, in these cases, certain authors (Carino, 2001) propose the use of the Arrhenius function (Equation 2), so as to compensate the deficiencies evidenced with Equation 1. This equation uses the concept of “equivalent age”, which is the time required to obtain the same maturity, but at a different temperature from the reference temperature.

$$t_{eq} = \sum \exp \left[-\frac{E_{Act}}{K} * \left(\frac{1}{T_a} - \frac{1}{T_s} \right) \right] x \Delta t \quad (2)$$

Where:

- t_{eq} = Equivalent age [days; hours]
- E_{Act} = Activation energy; [J/mol]
- K = Gas constant; 8.314472 [J/mol*K]
- T_a = Average temperature during interval; 273+ T_a [°K]
- T_s = Specified reference temperature: 20°C; 273+20 = 293 [°K]
- Δt = Time interval [hours]

Both ways of calculating the maturity function were incorporated in the first version of the ASTM C1074 (ASTM, 1989), which even indicated laboratory procedures for determining the activation energy of a given cement, thus being able to adequately apply (Equation 2). Several methods can be applied to determine the activation methods, such as measuring the strength of mortar cubes, the heat of hydration or the chemical shrinkage of the cement paste.

The methodology of ASTM C1074 for calculating T_o and E_a by measuring the strength is plotted in Figure 2. With strength data at three curing temperatures and different ages, an equation has to be fitted to a series of data (ultimate strength S_w , age at the beginning of the strength development t_o , and rate constant of strength development k) using a linear regression, which allows plotting the inverse of the k value based on the curing temperatures. The crossover point with the value 0 of axis Y corresponds to T_o . In a second graph, including the natural logarithm of the value k and the inverse of the absolute temperature, the curve slope for calculating E_a is determined.

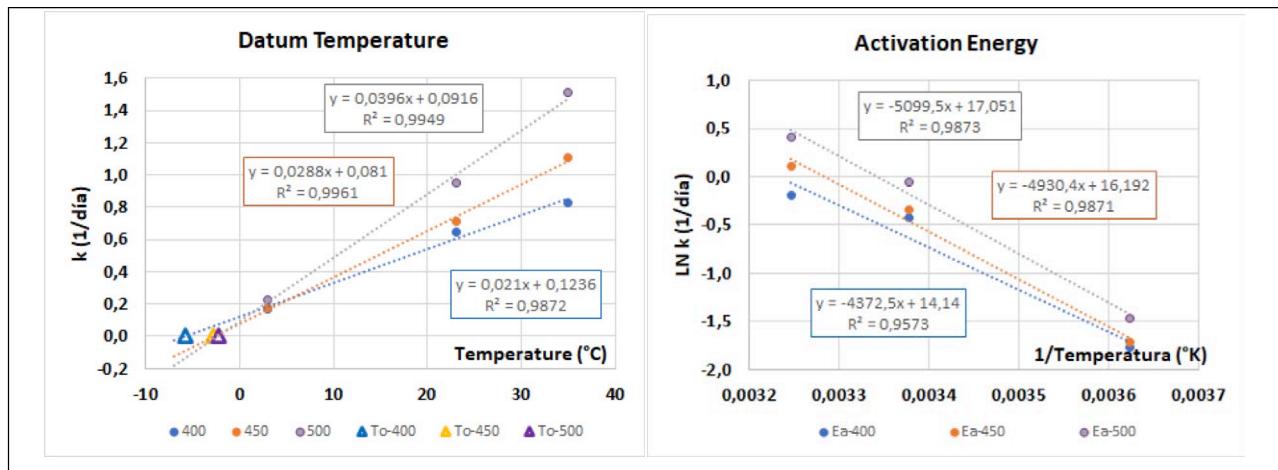


Figure 2. Determination of datum temperature and activation energy according to ASTM C1074

The data plotted in Figure 2 (Ebensperger, 2019) allowed determining the following values of T_o and E_a for a national high-strength cement with different contents of cement see (Table 1).



Table 1. Values of *To* and *Ea* calculated in a high-strength pozzolanic cement

Cement Content [kg/m ³]	Datum Temperature [°C]	Activation Energy [J/mol]
400	-5.9°	36,400
450	-2.8°	41,000
500	-2.3°	42,400

Another way of determining the value of the activation energy **Ea** consists in measuring the heat of hydration of the cement paste with an adiabatic or semi-adiabatic Langavant calorimeter, at three temperatures, generally 10, 20 and 30°C. These measurement results provide different parameters (Xu et al., 2010) represented by Equation 3. The instrument automatically fits the values according to each heating curve, in order to finally deliver the value of **Ea**, plotting the value of **ln (τ)** with the inverse of the absolute temperature.

$$\alpha(t_{eq}) = \alpha_u * \exp \left[- \left(\frac{\tau}{t_{eq}} \right)^\beta \right] \quad (3)$$

Where:

- α** = Hydration degree at certain equivalent age [-]
- t_{eq}** = Equivalent age [hours]
- α_u** = Ultimate degree of hydration [-]
- τ** = Time parameter of hydration [hours]
- β** = Shape parameter of hydration [-]

The results of tests performed with this technique in high-strength pozzolanic cement used in this research, are shown as an example in (Figure 3).

Considering that both **To** and **Ea** refer to the same concrete mix, both values should be related and compatible with each other. The authors (Lee and Hover, 2015) and (Lee and Hover, 2016) present a detailed work on this subject, in two recent papers, whose final analysis results are shown in (Figure 4).

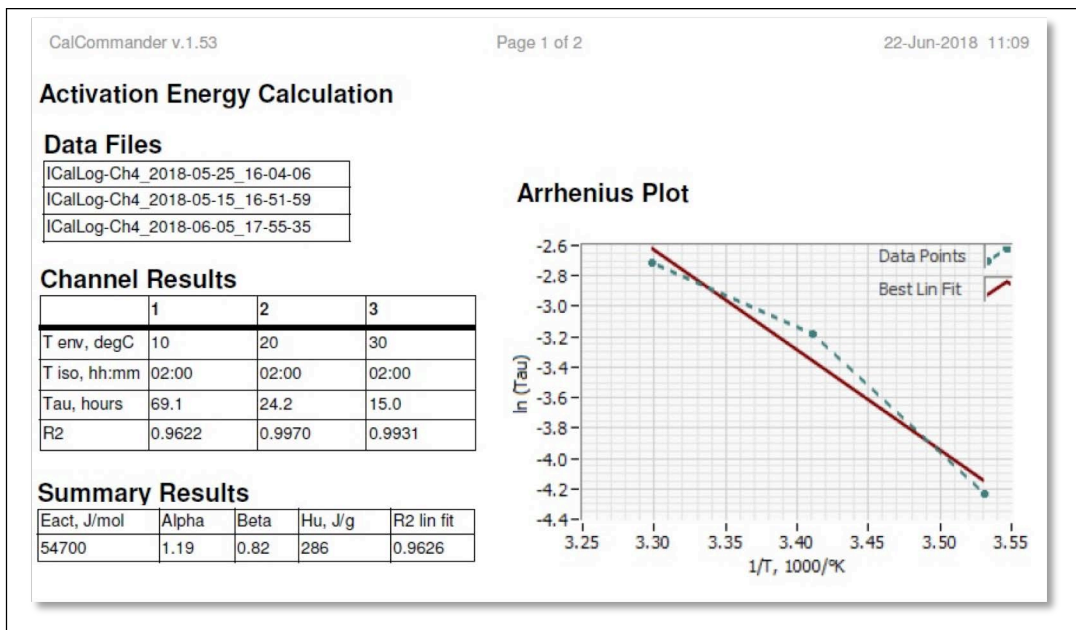


Figure 3. Determination of the activation energy by calorimetry

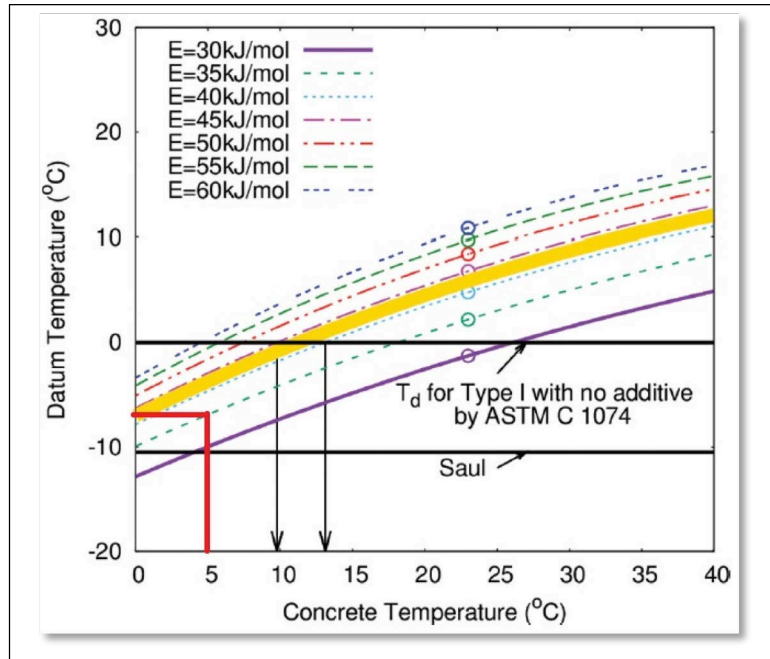


Figure 4. Datum temperature based on activation energy and concrete curing temperature

The yellow zone represents the conditions defined by ASTM C1074 for the applicability of the Maturity Method, which should correspond to concrete temperatures between 10 and 13°C, and E_a between 40,000 and 45,000 J/mol. Above these temperatures, T_o should be even higher than 0°C, and with temperatures closer to 0°C T_o approaches the value of -10°C. The main conclusion of this figure lies in the fact that datum temperature depends on the curing temperature of concrete, and it is not a single value depending just on the type and content of the cement. This is consistent with (Neville, 2012), who mentions that $T_o = -10^\circ\text{C}$ is generally used for ages up to 28 days with concrete temperatures between 0 and 20°C.

The value of $T_o = -10^\circ\text{C}$ was used for a long time, and as a way to facilitate the application of both versions of the Method, it was standardized through ASTM C1074-87, which recommended, in 1989, the value of $T_o = 0^\circ\text{C}$ when using Type I cement without additives (pure Portland cement), and a curing temperature ranging from 0 to 40°C. For other conditions requiring a greater accuracy in the strength estimation, T_o should be determined according to the methodology proposed in Annex 1 there of. There is no clarity as to why the ASTM established the value of $T_o = 0^\circ\text{C}$ instead of $T_o = -10^\circ\text{C}$, but it is most likely because, for many years, the United States used solely the Type I cement. On the other hand, according to the already mentioned author (Lee, 2018), there is really no theoretical basis justifying the use of $T_o = 0^\circ\text{C}$. The value of $T_o = -10^\circ\text{C}$ was proposed by observations showing that the strength development is insignificant below that temperature; however, this value does not guarantee the accuracy of the strength estimation by the maturity method. The choice of the value of T_o depends on the mix (that is, type of cement, w/c ratio, cementitious materials) and the in-place concrete temperature. Even if there is no clear trend, the analysis of multiple data reveals that using a higher T_o in warm weather and a lower T_o in cold weather provides a higher precision of the Method.

Studies addressing the maturity method in Chile have been scarce. At the end of the eighties (Covarrubias, 1988) pointed out the use of $T_o = -10^\circ\text{C}$, as well as (Videla and Parada, 1988), who indicated a value between -10°C and -12°C for pozzolanic cements. Subsequently, the work of (Videla et al., 1995) applied the value of $T_o = -10^\circ\text{C}$ in concrete manufactured with different national cements. A more recent work (Carrillo, 2011), considering three national cements, two cement contents and values of T_o and E_a calculated according to ASTM C1074, showed the obvious effect of the type of cement used and the cement content, which indicates that the value of T_o for a concrete mix most probably depends on the mix dosage.

The current standard NCh3565 only included the use of the "Nurse-Saul" Method, because it is simpler to use than the Arrhenius Method, which requires complex laboratory measurements. Its use has been limited to the case of concrete with long-term temperatures above 40°C (massive and steam-cured concrete), due to probable effects of strength reduction at later ages. The recommended datum temperature T_o was 0°C for all cases, explicitly

indicating that only under cold weather conditions a different value could be used which is appropriate for these conditions. This indication was incorporated once the first developments of this study were presented to the Standard Committee (Ebensperger, 2018).

Moreover, the same standard indicates how the Strength-Maturity Relationship (Calibration Curve) should be calculated, using the following equation (Equation 4).

$$R(t) = A + B * \ln [M(t)] \quad (4)$$

Where:

- R(t)** = Strength estimation function [MPa]
- M(t)** = Maturity function [°C-h];
- A, B** = Parameters of the semi-logarithmic equation

The standard stipulates additional requirements, such as the accuracy of the correlation curve ($r^2 > 0.95$), applicable age range and verification procedure of the calibration curve over time, according to the strength deviation in relation to the initial calibration values.

It is important to highlight that the use of a constant value of **To** could seriously affect the strength estimation, as demonstrated by a study (Carrillo, 2011), which detected significant differences depending on whether it was early or later strength. This leads to consider the impossibility of estimating the strength, both at an early and later age, with a single strength-maturity relationship. Regarding this aspect, (Abdel-Jawad, 2006) determined that the use of the “Nurse-Saul” equation under the conditions established in ASTM C1074 will underestimate the strength for low-temperature curing, and will overestimate it for higher curing temperatures.

In his practical work under cold weather (Torres, 2019) compared the effect of considering the execution of the calibration curve under standardized laboratory conditions (cylinders in curing chamber) “as in ground conditions (test specimens outdoors).” The comparison between the strengths estimated with both calibration curves and the actual strengths obtained in core samples from pavements, showed that using strength data of cylinders kept in place to generate the calibration curve delivered less satisfactory results than when using the calibration curve under standardized conditions. In this research, the datum temperature remained fixed at **To**= 0°C, which of course influenced the end results.

3. Development

3.1 Weather Conditions

A testing field was prepared in the production facilities of Concremag S.A. in the city of Punta Arenas. Figure 5 shows the weather conditions during the months in which the experience was carried out. The lowest ambient temperature recorded was -4°C.

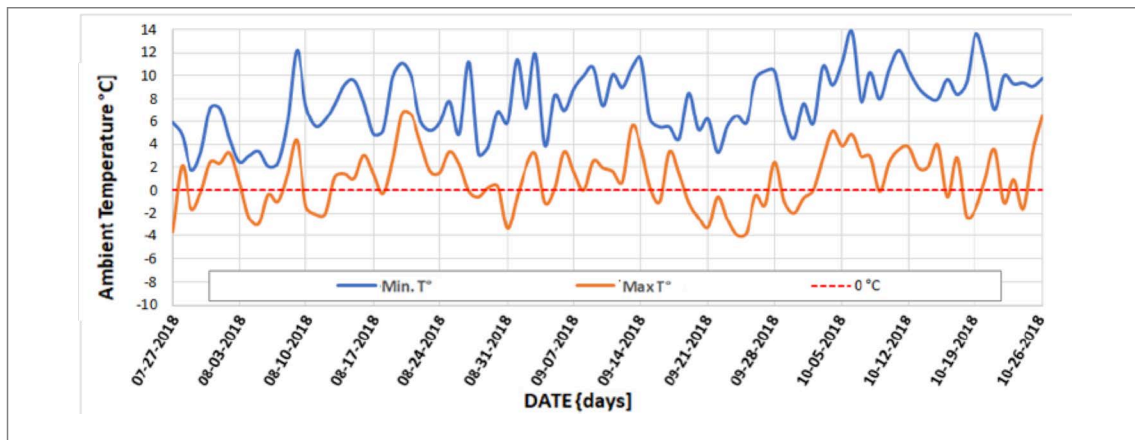


Figure 5. Weather conditions during the initial hardening process of concrete



Based on the standard NCh170:2016, cold weather is when, during the three days before concreting, the average daily temperature is below 5°C and the ambient temperature is lower than or equal to 10°C for more than 12 h, consecutive or accumulated, in a time lapse of 24 h. Figure 6 clearly shows that these conditions were fully met, even two weeks before placing the concrete. This meant that warm water had to be added to the concrete, in order to rely on a fresh concrete temperature, over 5°C, when placing the concrete.

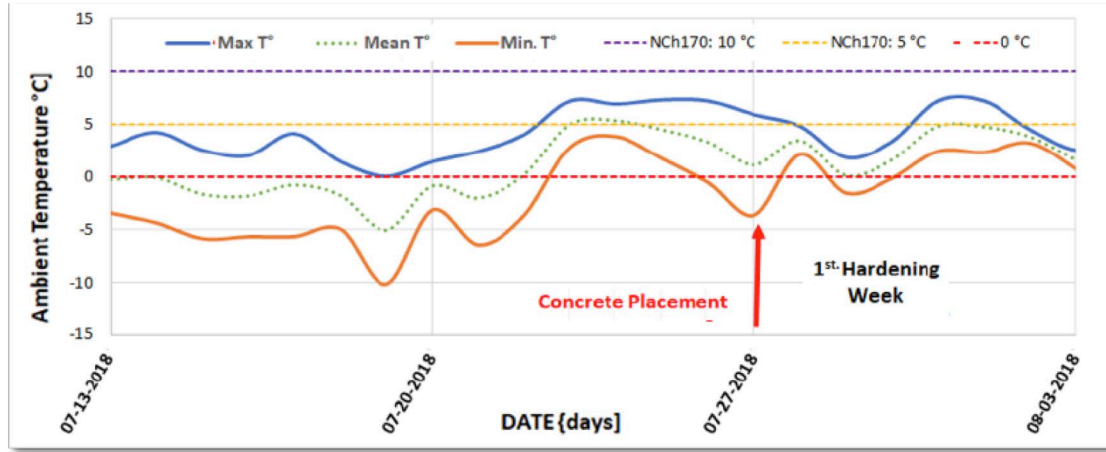


Figura 6. Análisis de Condiciones de Clima Frío según NCh170:2016

3.2 Equipment

The equipment considered for concrete manufacturing and associated tests is the following:

- Mixing plant, with a vertical mixer with a capacity of 4 m³/hour.
- Mixer trucks, which immediately transport the already mixed concrete from the plant to the testing point.
- Steel cylindrical molds of 100x300mm and prismatic molds of 150x150x500mm for controlling the compressive and flexural strength.
- SmartRock 2° sensors used for the execution of the calibration curve and then for the temperature measurement in the testing fields.

3.3 Materials

The materials used and their dosage are indicated in (Table 2):

Table 2: Dosage of the concrete mix type HF 4.6 (80) 25/6

Material	Content [kg/m ³]
PCR Portland Pozzolan Cement – High Strength	320
Net Water	144
Regular Sand 5mm	796
Pea Gravel 25mm	493
Crushed Gravel 25mm	606
Plasticizer Admixture, MasterPolyheed 710 at 0.55% of the weight of cement	1.76
Air-entraining Admixture, MasterAir® 100 at 0.035% of the weight of cement	0.112
Water/Cement Ratio	0.45



3.4 Field Activities

The activities were performed according to the following timeline:

Preparation of the testing field

The 12-cm thick pavement slab measured 3.5 m wide and 5.0 m long. Retaining metallic were used for the borders.

Concrete Manufacturing

The plant manufactured 1.8 m³ of concrete.

Tests on Fresh Concrete

Routine fresh concrete tests were performed, such as:

- Concrete and ambient temperature
- Workability through the Abrams slump cone, according to NCh1019
- Concrete density and Air content

Preparation of Test Specimens

Two series of cylinders were made, based on the indications in the standard NCh1017:

Series A) Cylinder specimens for the calibration curve, according to NCh3565:2018, under curing conditions according to NCh1017, at the age of 1, 3, 5, 7 and 28 days.

Series B) Control cylinder specimens under open-air curing conditions.

Additionally, prismatic specimens were prepared according to the indications in NCh1017 for flexural strength tests, with the aim of verifying the design strength at 28 and 90 days.

Construction of the Testing Field

Once all test specimens were manufactured, the concrete was poured in the field, compacted with a mechanical vibrator and smoothed with a screed. One area of the field was protected from the cold weather with a blanket made of geotextile and mineral wool, and the other area was left unprotected. All in-place cylinders were protected in the same way.

Installation of Maturity Sensors

SmartRock 2 sensors were placed in two cylinders of each series. Four sensors were embedded in the pavement, two in the protected area and two in the unprotected one. This type of state-of-the-art sensors allow the input of the datum temperature value, recorded every 15 minutes.

Tests on Hardened Concrete

At the age of 2 days, the cylinders of series A) were transported to the laboratory for curing under standardized conditions under water. The cylinders of series B) were kept on site until the day before the age of each test. The compressive tests were executed in the laboratory of the Department of Construction Engineering at the University of Magallanes, in Chile.

Core Extraction

Cores of 4" were extracted at different ages according to NCh1171/1, evaluated according to NCh1171/2, and tested at the age of 1, 3, 5, 7, 14, 28 and 90 days in the same laboratory.

Figure 7 includes a series of photos showing the complete field process.

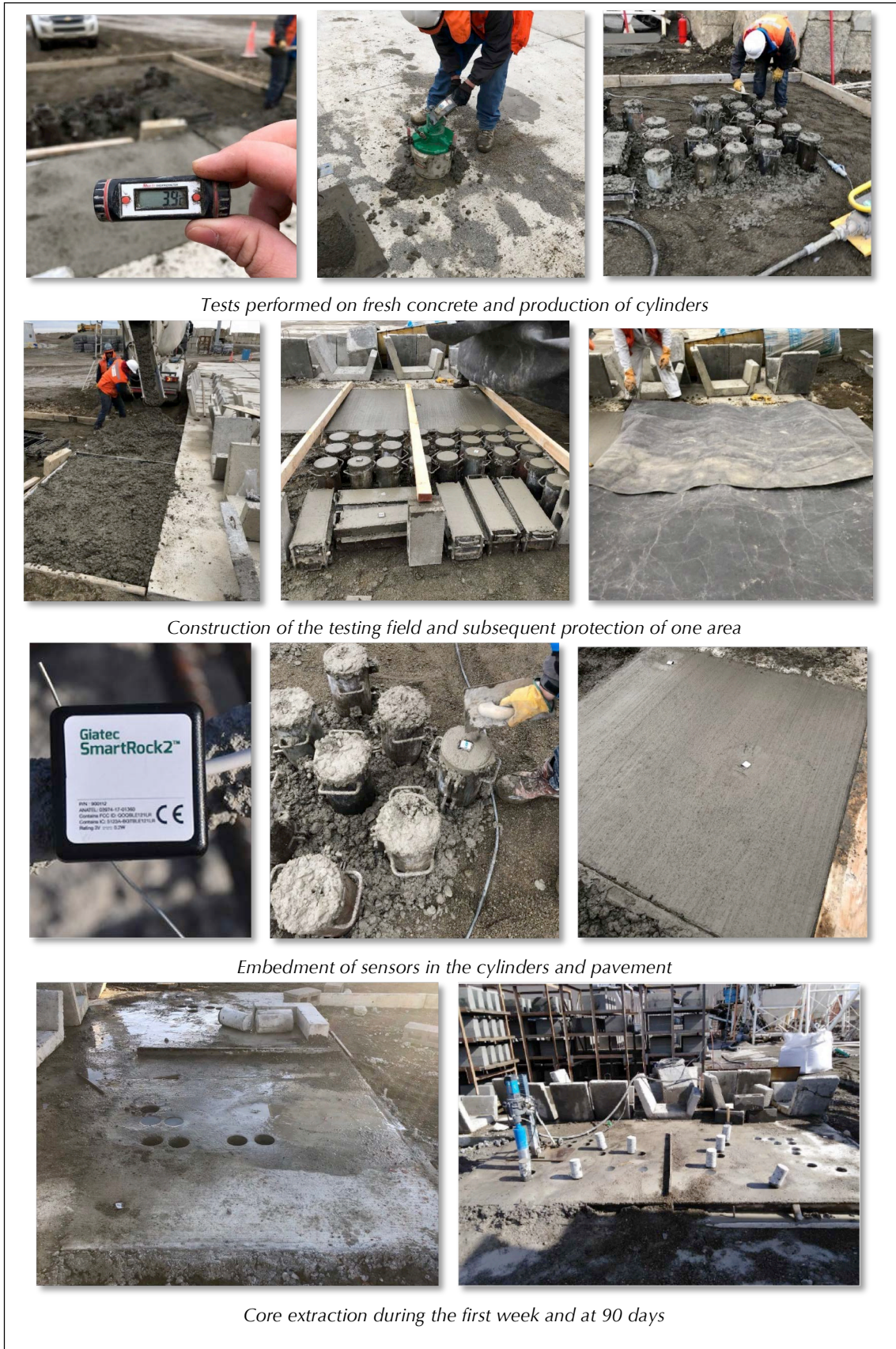


Figure 7. Complete process of the activity of maturity measurement and strength estimation



4. Analysis de results

4.1 Properties of Fresh Concrete

(Table 3) shows the values obtained from the truck sampling:

Table 3. Results for fresh concrete properties

Concrete	Execution Date	Ambient Temperature	Concrete Temperature	Air Content	Density
HF4.6 (80)25/6	Jul.27.2018	3.9 °C	12.1 °C	3.8 %	2,385 kg/m ³ *

* Corresponds to density at 1 day

4.2 Temperature Measurements

(Figure 8) shown the curve measured under standardized curing conditions in the water. On the first day, the cylinder reduced its temperature from 12 °C and remained below 5 °C, despite the fact that it was protected, and then it was kept at 20.8°C on average.

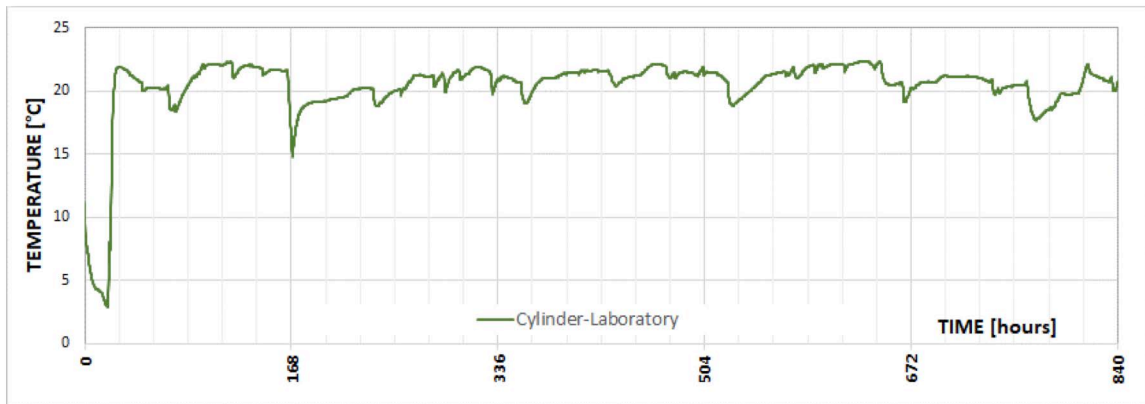


Figure 8. Temperature development in the curing cylinder, under standardized conditions

(Figure 9) compares the temperature development between the cylinder that was kept in the open air throughout the entire study, and the cylinders in both fields, protected and unprotected. During the first week, a slight effect from the protection is observed, but afterwards all three temperatures tend to be equal.

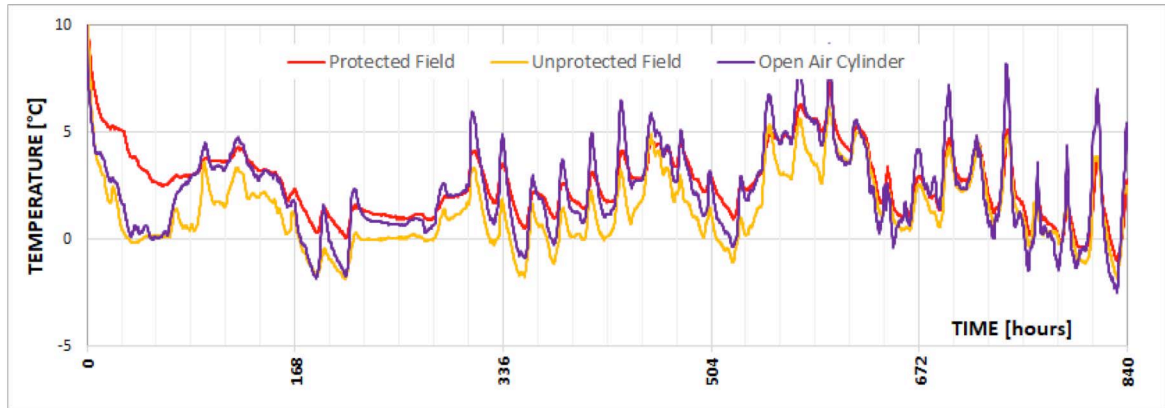


Figure 9. Temperature development in open-air cylinder and field cylinders with and without protection

4.3 Strength Measurement

Table 4 shows the results of the series of standardized cylinders, together with the results of the non-standardized series, in the field with and without protection, and in the control joists.

Table 4. Strength results of specimens and cores [MPa]

Age [d]	Compressive				Flexural
	Standardized Cylinder	Open-air Cylinder	Protected Core	Unprotected Core	Standardized Beam
1	0.25	0.30			
3	4.7	4.6			
7	26.6	18.3	18.6	17.2	3.3
14	36.7	26.8	25.4	25.5	
28	43.2	28.8	28.9*	21.3*	4.8
31	-	-	30.3	22.5	
90	48.4	35.4	43.9	39.1	5.0

*Test was repeated due to defective core

4.4 Calculation of Maturity

The collected data were analyzed until the age of 35 days with 3,360 recordings. (Table 5) indicates the maturity calculated in each case for this age, considering a datum temperature value of $T_0=0^{\circ}\text{C}$:

Table 5. Maturity values for $T_0=0^{\circ}\text{C}$

Age [d]	Compressive			
	Standardized Cylinder	Open-air Cylinder	Protected Field	Unprotected Field
35	19,943	2,405	2,517	1,491



The effect of considering this datum temperature is reflected in Figure 10. In the “Unprotected Field”, four periods with zero maturity gains are observed, given by the fact that the temperature recorded in that pavement for those periods was lower than the used datum temperature ($T_0=0^{\circ}\text{C}$). This basic condition of the maturity method is automatically considered by the sensors, since this value is an input provided by the user.

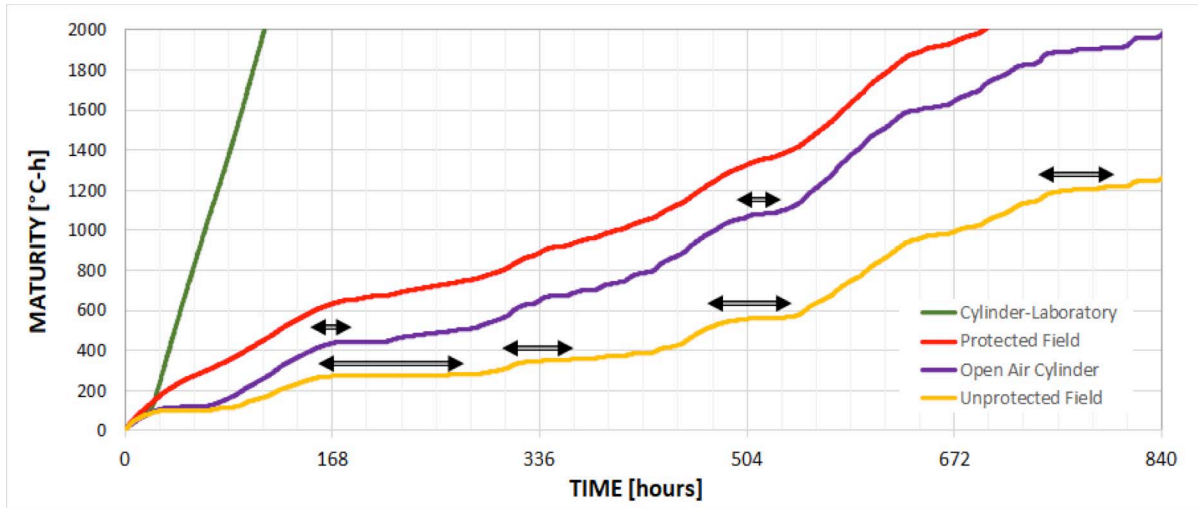


Figure 10. Maturity development in the specimens and testing field for $T_0=0^{\circ}\text{C}$

4.5 Developing of the Strength-Maturity Relationship

In accordance with the standard NCh3565:2018, it is necessary to verify the variability of the strength data obtained (<10% between pairs). Therefore, compressive strength data of standardized cylinders were used. This analysis is shown in Table 6 with the respective graph, and the A and B values of the semi-logarithmic relationship according to Equation 2, in Figure 11. Herein, the values up to the age of 28 days were considered. The value of the correlation coefficient $r^2=0.9655$ of the equation is compliant, since it is higher than 0.95.

Table 6. Values considered for the Strength-Maturity Relationship for $T_0=0^{\circ}\text{C}$

Days	Hours	Testing Date and Hour	Maturity [°C*h]	S1 [MPa]	S2 [Mpa]	Average S [Mpa]	Verification
1*	21.0	07/28/2018 13:37	104	0.3	0.2	0.25	Does not comply
3	71.4	07/30/2018 16:05	1,129	4.8	4.6	4.7	Complies
7	167.3	08/03/2018 16:00	3,178	27.1	26.0	26.6	Complies
14	336.9	08/10/2018 17:35	6,590	36.4	37.0	36.7	Complies
28	672.6	08/24/2018 17:15	13,699	42.1	44.2	43.2	Complies

*Given the temperature conditions below 0°C during the first day, there was almost no strength development until 21 h. This datum was eliminated from the relationship



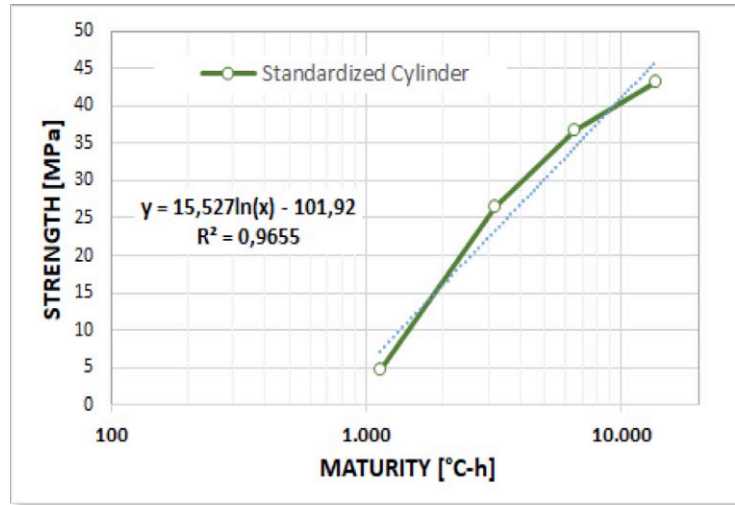


Figure 11. Strength-Maturity Relationship for $T_o=0^\circ\text{C}$

4.6 Verification of Strength Estimations

(Table 12) shows the comparison between the strength values estimated with the maturity method for $T_o=0^\circ\text{C}$ and the strength values obtained in open-air cylinders and cores with and without protection. The fact that, for long periods of time, the concrete's temperature was below 0°C , meant that the strength gain was not estimated.

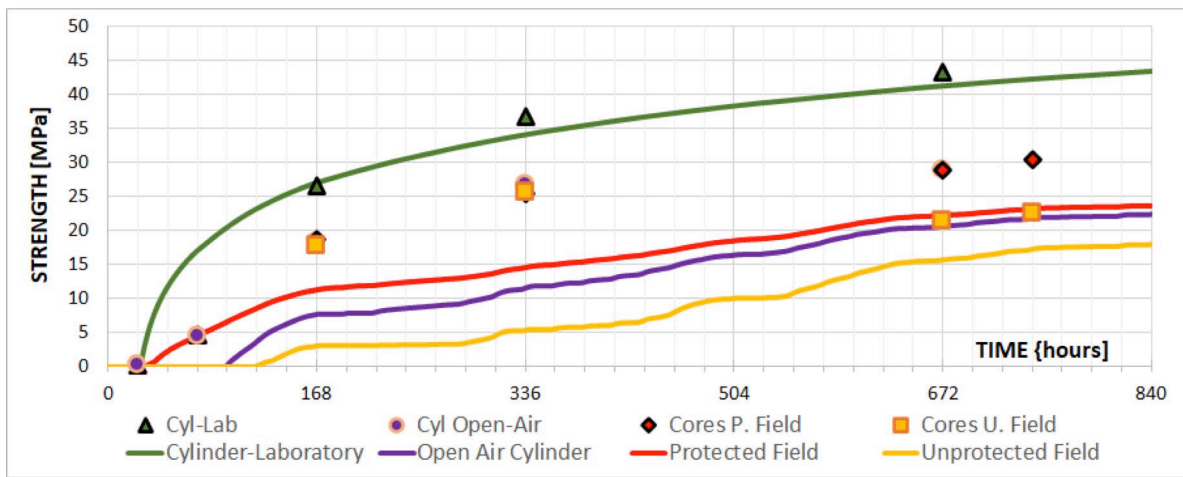


Figure 12. Estimated strength development compared with actual core strength for $T_o=0^\circ\text{C}$

It is obvious that the strength estimation using $T_o=0^\circ\text{C}$ is not valid for cold weather, since all cores did evidence a strength gain, which reached values close to 30 MPa at 28 days (672 hours) in the case of the cylinder and protected field, a gain that the estimation did not consider. In other words, concrete has the capacity to continue the cement hydration and generate strength despite the fact that its internal temperature is below 0°C . The cement reaction is an exothermic reaction that produces constant heat.



4.7 Effect of Varying the Datum Temperature

In order to further develop this process, the value of T_o was varied between 0°C and -10°C . This effect is shown in Figure 13, where the strength estimation curves of the cylinder and the field with and without protection, for $T_o = -10^{\circ}\text{C}$, show an upward trend and their strength value is quite similar. The concrete mix is the same, and when the effect of negative temperature disappears, the three curves show similar estimated strength values, given that their temperature histories are pretty much the same.

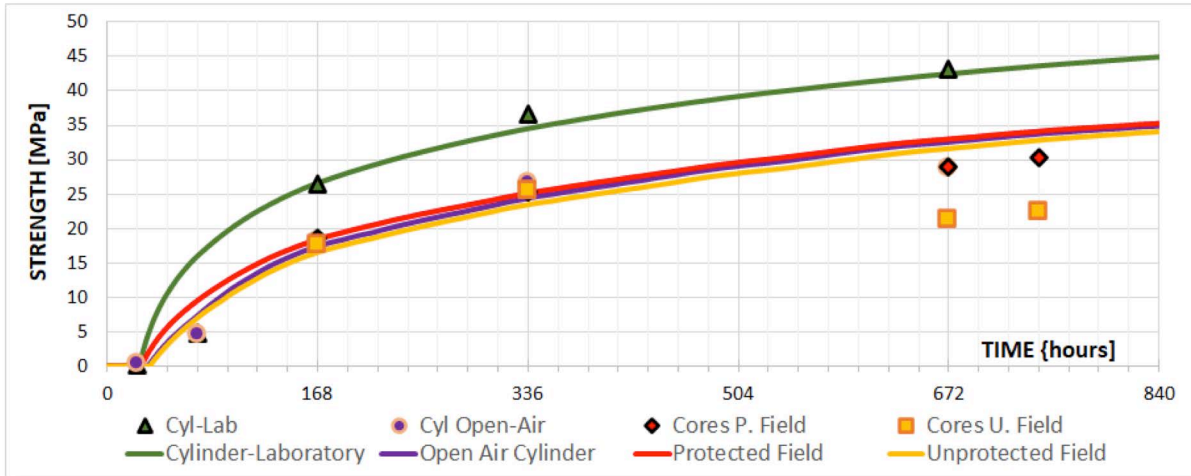


Figure 13. Estimated strength development compared with actual core strength for $T_o = -10^{\circ}\text{C}$

The fact of including eleven values of T_o , from 0°C to -10°C , allowed simulating their effect on the strength estimation, by developing a “Datum Temperature Model”. Since the maturity depends on T_o , any choice of a T_o value will modify the maturity function, the **A** and **B** factors of the Strength-Maturity Relationship, and the maturity curve on site as well. This is represented in Figure 14 and Figure 15, considering the calibration curve data of the standardized cylinder, based on each T_o , and the temperature and actual strength under the “Protected Field” and “Unprotected Field” conditions.

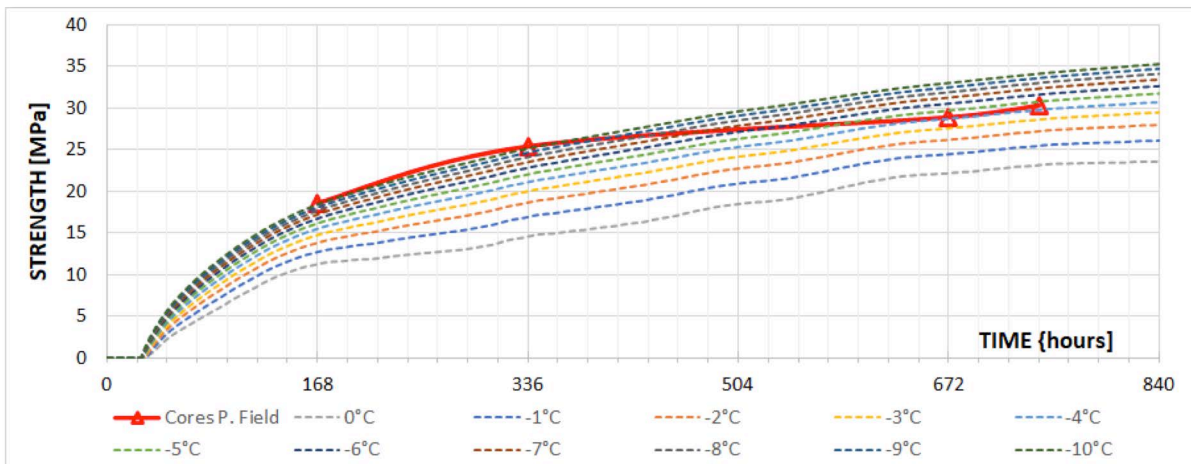


Figure 14. Estimated strength development for different T_o compared with actual core strength under protected field conditions



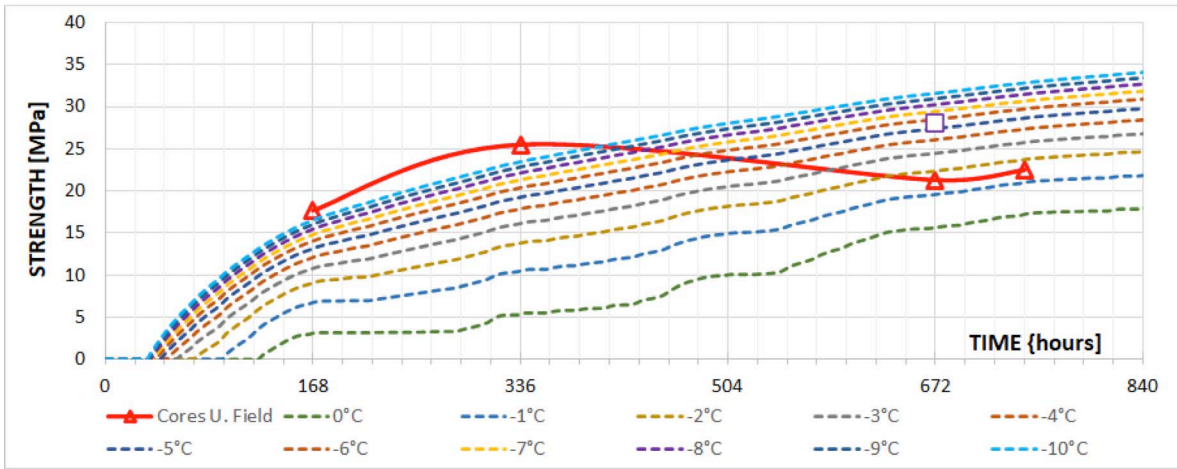


Figure 15. Estimated strength development for different T_o compared with actual core strength under Unprotected Field conditions

As T_o increases, the effect of the temperatures below each T_o decreases. The lowest recorded temperature, both in the cylinder and the fields, corresponded to -2.5°C , which means that with $T_o = -3^\circ\text{C}$, the constant strength gain with the maturity method would be adequately contemplated in the methodology. Both figures allow deducing that, if the objective is to ensure that the estimated strength will get closer to the actual strength, a variable T_o value depending on the age of interest should be used.

The above is better understood when illustrating the relationship between the estimated and actual strength, for different ages, defined as the Strength Index $I_s = S_{Est}/S_{Actual}$. Figure 16 shows the protected field scenario based on datum temperature. Given that the objective is to get the value of I_s closer to 1.0, we observe that at the age of 7 or 14 days, the value should be $T_o = -10^\circ\text{C}$. Whereas, at the age of 28 or 31 days, the value of T_o is close to -5°C .

The conclusion of this analysis is that applying a value of $T_o = 0^\circ\text{C}$ in cold weather will with no doubt underestimate the value of the Strength Index I_s .

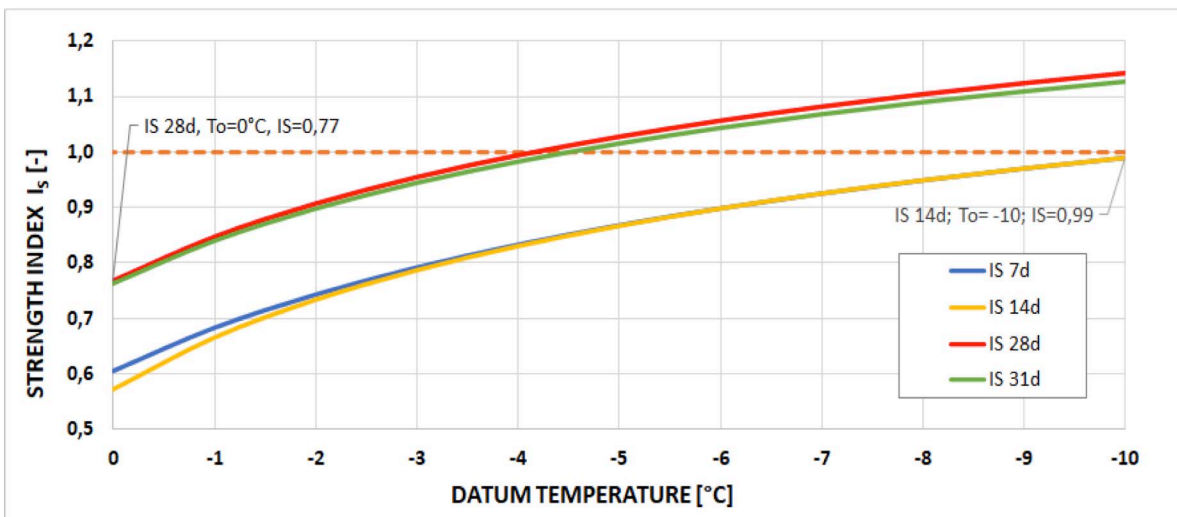


Figure 16. Strength Index based on datum temperature



5. Conclusions

The on-site research allowed collecting enough field data recorded in a low-temperature period in Punta Arenas, Chile. The analysis according to the standard NCh3565:2018, which considered a datum temperature value of $T_0 = 0^\circ\text{C}$ for applying the maturity method, demonstrated its inapplicability in cold weather environments.

The study allows concluding that the use of $T_0 = 0^\circ\text{C}$ in cold weathers generates a significant underestimation of the concrete strength, close to 40% for strengths up to 7 days and 20% for strengths close to 28 days. This means that it is necessary to differentiate between the strength estimation at early age and later age. Regarding the components and the composition used in this experience, the following values are recommended:

- $T_0 = -5^\circ\text{C}$ if the focus is put on later strengths at 28 days.
- $T_0 = -10^\circ\text{C}$ if the focus is put on early strengths up to 7 days.

We suggest the execution of new concrete studies cured under cold weather conditions, with the aim of confirming the recommendations indicated above. Likewise, it would be interesting to study if there is a differentiating effect between strengths at early and later ages under temperate climate conditions. In both cases, the developed model would allow making the corresponding analyses.

6. Acknowledgements

The authors wish to thank the company Concremag for making their facilities available for the execution of the practical experience, the company BDL Soluciones Estructurales for their technical support and disposition concerning the use of SmartRock2 maturity sensors.

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