Concrete Calorimetry:

A Valuable Tool for Industrialized Construction

Building under construction using industrialized systems.

Construction, especially affordable housing construction, poses a major challenge for the industry: improving the quality of the final product while reducing construction times and optimizing associated costs. The growing use of industrialized construction systems requires the use of special concretes, with a certain level of performance in terms of rheology and early strength development, and the availability of reliable evaluation systems to establish the potential quality of concrete at an early age. These systems are now common, and today it is not unusual to find, in our setting, major housing projects with buildings that exceed 20 stories.

Eng. Germán E. Arbeláez Rodríguez
General Manager, Tecnología en Obra & Asociados SAS
Photos and diagrams: Courtesy of Germán Arbeláez

Measuring Concrete Calorimetry

The maturity of concrete has been studied for decades, a concept linked to the temperature increase the material experiences as a result of the heat generated during the cement hydration process. This temperature rise is especially noticeable during the first 24 hours after the concrete is produced, a period during which the intensity of the hydration reaction is high.

In a construction sector that is increasingly industrialized, with ever more demanding work schedules, applying the maturity concept and, in general, systematically measuring changes in concrete temperature has become more necessary and popular, since it allows the strength at a given age to be estimated with a good degree of reliability. According to NTC 3756 (Procedure for Estimating Concrete Strength by the Maturity Method), whose antecedent is ASTM C-1074, maturity can be expressed in two ways:

- The first expression of maturity is known as the Temperature-Time Factor. This corresponds to the area under the curve describing the concrete's thermal profile. When this expression is used, strength is considered a linear function of temperature development over time.
- The second and more convenient expression of maturity is known as Equivalent Age. It refers to the curing time equivalent to a standard reference temperature of 20°C. When concrete cures at temperatures higher than the reference temperature, the equivalent age is greater than clock time, and the opposite occurs when curing takes place at temperatures below the reference.

The mathematical function underlying this expression uses not only the standard reference temperature, but also certain thermodynamic constants, notably the activation energy of the cement and the gas constant. For this reason, when Equivalent Age is used to express the maturity of concrete, strength is considered a non-linear function of temperature development over time.

When maturity is measured in terms of Equivalent Age, it is possible to construct a Strength-Maturity Curve. This curve has a shape very similar (not to say identical) to that of the Strength-Time Curve. In other words, just as strength development is directly proportional to the natural logarithm of the concrete's age (expressed in days or hours), it is also proportional to the natural logarithm of maturity (expressed in days or equivalent curing hours).

Although measuring maturity is a reliable mechanism for understanding the mechanical performance of concrete (see Figure 1), it is limited by the need to keep measuring the temperature of the mix until the equivalent curing time (or equivalent age) corresponds to the strength expected for making critical construction decisions: stripping formwork, cutting or tensioning pre-stressing cables, lifting a precast element, validating compliance with f'c, etc. This is why, for normal-strength concretes specified at 28 days, instrumentation would need to be maintained for several weeks, which would mean a costly and sometimes unnecessary waste of resources.

On the other hand, the temperature a concrete element experiences is a consequence not only of the hydration heat generated by the cement contained in the mix, but also of its size, geometry, and the protection to which it is subjected after placement (degree of formwork confinement and/or thermal conductivity of the material it is made of, implementation of autogenous curing chambers, among others).

Walls and slabs built using industrialized systems.

Ambient temperature will have a significant influence on thin and/or small elements, and little influence on massive elements (especially in their interior). Along these lines, it can be stated that maturity at a given age does not depend solely and exclusively on the main intrinsic characteristics of the concrete that influence the development of hydration heat (content, type, chemical composition, and fineness of the cement; type and content of supplementary cementitious materials; water-to-cementitious-materials ratio; content and type of admixtures).

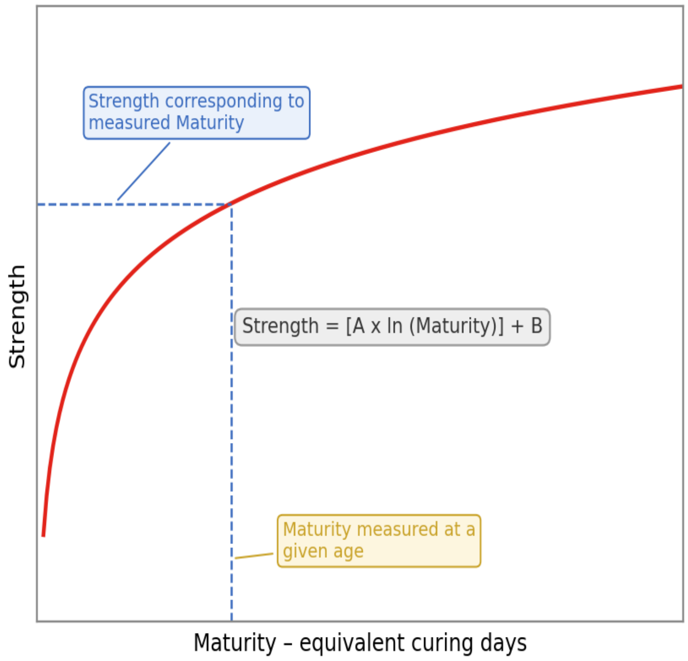

Figure 1. Strength as a function of concrete maturity.

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For the reasons explained above, applying the maturity method makes sense in precast operations, where strength requirements must be met at a very early age, the size and geometry of the elements tend to be standard, and temperature and humidity conditions are controlled during casting and the setting process (or at least tend to be stable).

The limitations of the maturity method can be overcome by building a thermal profile of the concrete under adiabatic conditions, that is, without heat loss or gain. Or, in more practical terms: if a concrete sample is isolated from the influence of ambient temperature, a thermal profile like the one shown in Figure 2 will be generated. From the thermal profile, it is easy to identify a series of variables that define the concrete's true potential without the influence of external factors.

The Thermal Profile

When a concrete sample is thermally isolated, a thermal profile is generated that depends solely and exclusively on the temperature changes the material experiences. In other words, the temperature increase is caused by the generation of hydration heat from the cementitious material, and the subsequent decrease occurs because the hydration reaction loses the intensity of the first hours of curing, allowing the generated heat to dissipate.

The temperature profile describing a concrete sample instrumented under thermally isolated conditions is proportional to the adiabatic heat signature which — since it can be considered similar to the "fingerprint" of a concrete produced with certain materials dosed according to a specific mix design — determines the reproducibility of the type of concrete being instrumented. The thermal-profile variable that makes it possible to establish such reproducibility is the Maximum Temperature Differential (ΔTmax), which corresponds to the difference between the Initial Temperature (To) and the Maximum Temperature (Tmax). (See Figure 2.)

In the thermal profile, obtained under adiabatic conditions, several zones can easily be identified:

- Thermal stability zone, in which the concrete's temperature is stable. This zone corresponds to the concrete's workability time. When the thermal profile does not show this zone, it means the workability time is very short, or that a lot of time has passed between the concrete's production and the start of temperature readings (attributable to a delay in the concrete delivery to the site or a delay in taking the calorimetry sample).
- Setting zone, in which the concrete's temperature increases significantly until it reaches a maximum value. Initial set occurs at an intermediate point within this zone. Final set occurs at a time very close to the moment the maximum temperature is reached (time at Tmax). Identifying and understanding this zone reduces uncertainty when structural elements show setting delays attributable to low curing temperatures (especially at night) or dosing errors.
- Temperature dissipation zone, in which the temperatures the concrete develops progressively decrease because the hydration reaction of the cementitious material loses intensity relative to what it showed during the first hours.

The Maximum Temperature Differential (ΔTmax) is directly proportional to the mechanical strength of a specific type of concrete produced with certain given materials. In other words, the higher the ΔTmax, the higher the strength, and vice versa. This correlation has been verified through quality control on tens of thousands of cubic meters of concrete over more than a decade. The great advantage of using ΔTmax is that, in most cases, it can be obtained within the first 24 hours after the concrete is produced, making it possible to establish its potential performance. This makes calorimetric measurement a timely system for the construction of buildings using industrialized systems, where a high degree of certainty is required to keep up with expected paces, since just a few days after the walls and slabs of an apartment are poured, the structure has already advanced several floors.

It is worth mentioning that — unlike specimens that are taken and tested to determine mechanical strength — when concrete is controlled through thermal-profile parameters, its "intrinsic quality" is being established. This means there is minimal influence from external factors which, if not properly controlled, can lead to results that are not representative of the material's actual quality. To ensure the measurement of concrete's "intrinsic quality," it is enough to use properly calibrated measuring equipment and to keep constant values for the sample's degree of insulation, its size, and the location of the temperature-reading point.

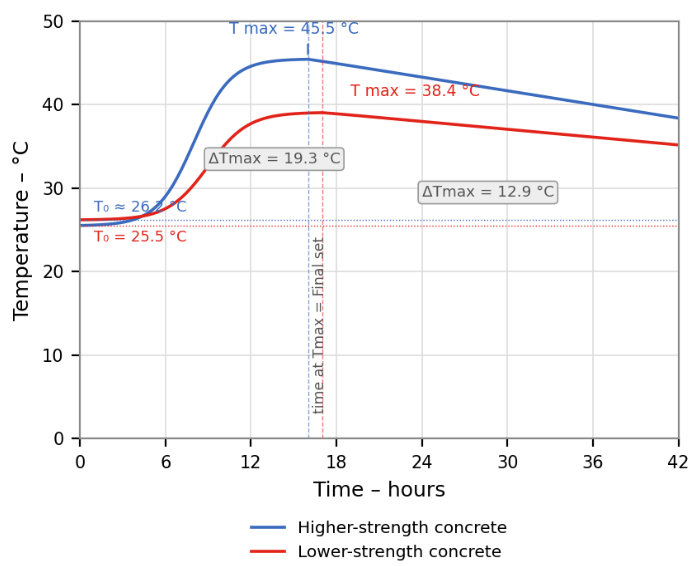

Figure 2. Thermal profile of two different concretes.

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Additionally, it is necessary to have the skills required to process large volumes of information using appropriate statistical techniques, making it possible to generate correlation models with an adequate level of confidence.

- Knowledge of concrete technology as a material, especially its thermal behavior. It is often assumed that having the equipment is enough for adequate quality control of concrete via calorimetry. Unfortunately, there are companies in our setting that own the equipment but lack the knowledge and experience needed to properly provide the service.

Figure 3 shows the typical instrumentation scheme for establishing the potential quality of concrete through its thermal profile.

Characteristic Quality of Concrete

In order for concrete calorimetry to be used as a mechanism for estimating the potential performance of concrete, it is necessary to have a statistically adequate number of samples, and to carry out the following tests on them in parallel:

- Tests to establish the thermal profile under adiabatic conditions, and from it obtain the Maximum Temperature Differential (ΔTmax).
- Representative strength tests, based on NTC 550 (Preparation and Curing of Specimens on Site) and NTC 673 (Compressive Strength Test of Standard Concrete Cylinders).

By applying a series of appropriate statistical techniques to the calorimetry and strength data, a Characteristic Quality model is obtained, which is nothing more than a correlation between the Maximum Temperature Differential (ΔTmax) and Strength at different ages.

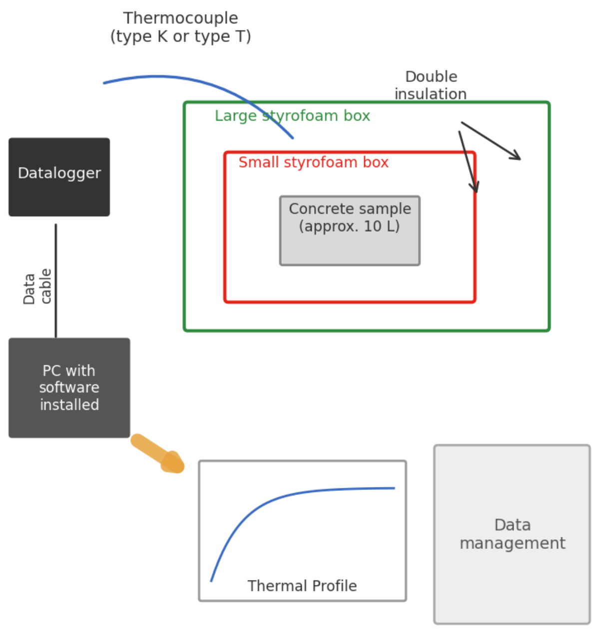

Figure 3. Typical instrumentation scheme for establishing the concrete's thermal profile.

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Instrumentation of concrete samples at a job-site camp.

In Figure 4 it can be seen that at the point where the blue line — corresponding to the minimum expected strength (at 28 days in the graph's example) — intersects the black line representing the specified strength (f'c), the critical ΔT is found, which constitutes the acceptance or rejection criterion for the calorimetry test. It is worth noting that the minimum expected strength is the strength value corresponding to the lowest tenth percentile of the data set used to generate the model.

It is important to make clear that each type of concrete — whose mix design was carried out with specific materials — must have its own characteristic quality model in order to be controlled through calorimetry.

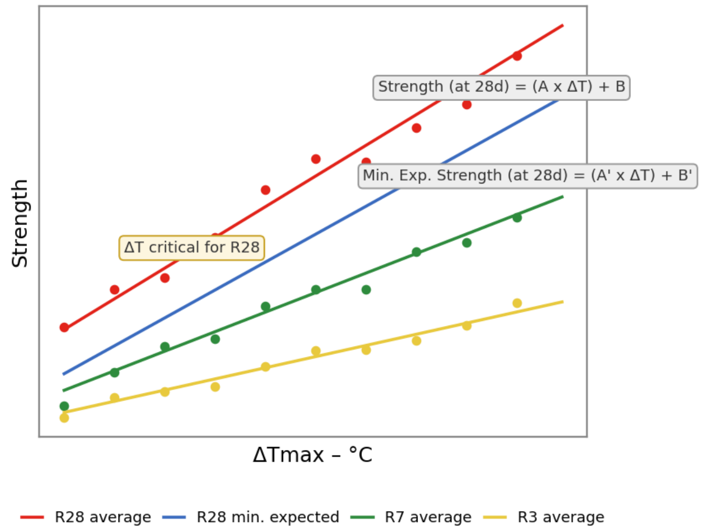

Figure 4. Typical characteristic-quality model (Strength vs. T).
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Applications of Calorimetry

Thanks to the attributes mentioned, concrete calorimetry is highly useful in numerous applications, including those listed below:

- Strength control and formwork-stripping time control in buildings constructed using industrialized systems.
- Monitoring of strength and joint-cutting times in the construction of conventional concrete pavements and pavements requiring fast-track opening to traffic.
- Supervision of critical activities in precasting operations such as formwork stripping, cutting of pre-tensioning cables, moving and/or lifting elements, transporting elements, and pile driving (in the case of precast piles), among others.
- Validation of tensioning times for cast-in-place beams in the construction of bridges and viaducts.
- Instrumentation of massive concrete elements (foundation slabs, dams) to minimize cracking risks caused by high thermal gradients.
- Estimation of the potential quality of cement used by companies that use it as a raw material in producing concrete for their own use (precasters, megaprojects) or for commercial sale and distribution (ready-mix concrete producers).
- Determination of the best time to remove molds from exposed concrete elements (architectural concrete) in order to prevent cracking. In this case, the optimal point corresponds to the moment when the minimum gradient between the placed concrete's temperature and the ambient temperature is reached.
- Resolution of setting-delay problems in structural elements, caused by low curing temperatures (especially at night) or dosing errors.

The author acknowledges the merit of engineers Juan Pablo Ortega and Charles De Wilde, two incomparable friends and professionals who unfortunately are no longer with us. Thanks to their creativity, knowledge, and dedication, monitoring concrete by calorimetry is today a common and highly valued practice in certain sectors of the construction industry in our country.