Breaking Cylinders: Is It the Only Option?

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Introduction

In construction projects – whether infrastructure or building projects – quality of execution is the most important aspect for ensuring the good performance of the resulting product in terms of structural stability and finish, and ultimately, for guaranteeing that the intended service life is met.

For this reason, and in the case of buildings, the Colombian Standards for Earthquake-Resistant Design and Construction (NSR-10) clearly state the mandatory nature of technical supervision in order to ensure "verification that the construction of the building's structure adheres to the plans, designs, and specifications prepared by the structural designer." The technical supervisor must not only have the knowledge and experience indispensable to performing this role, but also the judgment needed to detect anomalies and recommend both corrective measures and actions aimed at eliminating the causes of real or potential problems that could harm the quality of the project's execution.

In the case of concrete, it is not only the quality of the material itself that matters – which in turn depends on the use of competent raw materials and the suitability of the mix design, dosing, mixing, and transport processes – but also the effectiveness of the user (contractor, builder) during receiving, placing, compacting, finishing, protection, and curing activities.

Correctly performing concrete performance tests — especially strength testing — is fundamental to ensuring its quality.

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At this point it is worth noting that correctly performing the material's performance tests, especially strength testing, is also a fundamental aspect of ensuring product quality.

Nothing is gained by properly carrying out the processes mentioned above (both those related to material quality and those related to its handling) if quality tests cannot be performed with equal correctness – using probably erroneous information for decision-making, and creating confusion as a result. Management – that is, the senior leadership of the construction company and the project management – usually has as its primary objective meeting construction schedules and budgets, which is perfectly understandable in a world as competitive as today's. However, it is common for such schedules and budgets to be developed under criteria that do not necessarily consider, or do not give due priority to, quality of execution. For this reason, construction deficiencies sometimes arise, or decisions are made that work against achieving the desired results in terms of structural stability and service-life assurance.

Speaking of the use of test specimens to verify the strength of concrete, it is not only important to correctly apply the regulatory guidelines for their preparation, protection, curing, and testing. What is truly fundamental is to subject the results to an appropriate evaluation process, based on statistical techniques such as those described in NTC 2275 – Recommended Procedure for the Evaluation of Concrete Strength Test Results, whose reference document is ACI 214 – Guide to Evaluation of Strength Test Results of Concrete, published by the American Concrete Institute. Unfortunately, in our setting it is common for the evaluation of results to be limited to checking whether each individual sample meets the specified strength, and it is normal for specimens to be prepared and tested at ages earlier than the specification requires, but without timely verification of whether the concrete's strength is evolving correctly and in line with the percentages specified by the concrete supplier for each age. Are there solutions to these shortcomings? Of course there are – the management of every construction company is obligated to provide site directors and resident engineers with the training, tools, and guidance needed to put into practice a statistical evaluation of results based on probabilistic criteria.

Evaluating Strength by Means of Cylinders

NSR-10 specifies in its Section C.5.6, as the sole criterion for evaluating and accepting concrete, the preparation and testing of cylinders. This is the law, and therefore, on any construction project carried out in our setting under the NSR-10 guidelines (directly or indirectly), cylinders must be taken to be tested at the specified strength age of the concrete (usually 28 days) and, preferably, at earlier ages as well (for example 1 day, 3 days, 7 days, 14 days) to verify whether strength development is adequate.

The preparation of cylinders, as well as their storage and protection during the first hours, transport between the job site and the laboratory (including the handling, loading, and unloading activities associated with transport), curing, and testing, are all activities that are easily affected by multiple external factors. Can this be controlled? Of course it can. Is it easy to control? Not always – especially because, from a certain point onward, the test specimens (cylinders, beams, among others) are no longer under the project's custody. For this reason – even if it costs a bit more – laboratories should always be chosen that have distinguished themselves in the market for their independence and good performance in terms of the quality of their operating and information-management processes. However, playing devil's advocate, in a city like Bogotá, with the poor condition of the roads that its residents suffer through so much, who can guarantee that it is easy to adequately protect concrete cylinders that were prepared on site with such care and, in most cases, following normative guidelines to the letter? A difficult question to answer, isn't it?

Among the wide range of infrastructure and building projects, many require critical construction decisions to be made just a few hours after the concrete for certain elements has been poured. This is the case with industrialized housing construction, the construction of bridges with pre-stressed elements, the pouring of pylons on cable-stayed bridges, projects with a significant component of precast elements, and fast-track pavement repair work; the list is long and could go on.

One alternative for obtaining the evidence needed to make these critical construction decisions (stripping formwork, tensioning, raising or "climbing" slip forms, stripping and installing precast elements, driving piles, putting elements into service, etc.) is breaking cylinders at a very early age (for example 8, 12, 18, or 24 hours). Many builders do this, some without any consideration of thermal protection. The drawback in this case is that, in so few hours, the concrete is still very young, poorly matured, and highly vulnerable. For this reason, the multiple external factors already mentioned can dramatically affect the result and, consequently, lead to errors and/or mistakes in decision-making. And who suffers the consequences? The structural stability of the project and, of course, its service life. Figure 1 shows the high variability of cylinders cured conventionally and tested at 24 hours for two different types of concrete.

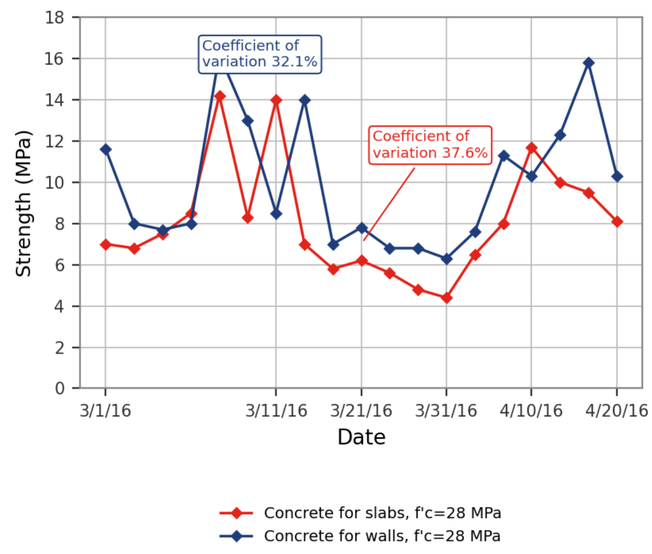

Figure 1. High variability of cylinders cured conventionally and tested at 24 hours, for two different types of concrete.

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To minimize the vulnerability of cylinders prepared for very-early-age testing, it is possible to apply accelerated curing mechanisms such as those mentioned in Section C.5.11.3 of NSR-10, among others. In this case, the specimens must be subjected to a combination of high temperature and humidity, notably high-pressure steam, atmospheric-pressure steam, boiling water, among others. To learn or project the potential strength of concrete based on accelerated curing methods, it is necessary to construct a statistically robust graph and/or equation correlating the strength of accelerated-cured cylinders with the strength of conventionally cured cylinders tested at the specified age.

Alternative Methodologies

But is preparing and testing specimens/cylinders the only option for controlling concrete quality? The answer is no.

For years it has been common practice to apply quality-control methodologies based on measuring the amount of hydration heat generated by the cementitious material present in the mix, during the first 12 to 24 hours counted from the moment the ingredients are dosed and mixed, since it is during this interval that the reaction reaches its maximum intensity.

Maturity Method

In a construction sector that is increasingly dynamic and industrialized, with ever more demanding work schedules, the systematic measurement of the combined effects of concrete temperature and time has become popular and necessary, since, as noted, it allows the strength at a given age to be estimated with a good level of confidence.

A major advantage of applying these methods is that they establish the intrinsic quality of the concrete. This means that, once the hydration process has begun, measurement takes place while the material's properties evolve without alteration and with minimal or no influence from external factors. In other words, it determines what is happening in the concrete's "inner workings."

Among the methods based on measuring the generation of hydration heat from the cementitious material present in the mix, the Maturity Method and the Adiabatic Heat Signature Generation Method stand out.

Maturity can be defined as the degree of hydration of the cement present in a concrete mix, which is, in turn, one of the factors with the greatest influence on the development of mechanical strength. 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:

1. Temperature-time factor. This is the name given to the first expression of maturity, which corresponds to the area under the curve describing the thermal profile of the concrete placed in the structure. When this expression is used, strength is considered a linear function of temperature development over time.

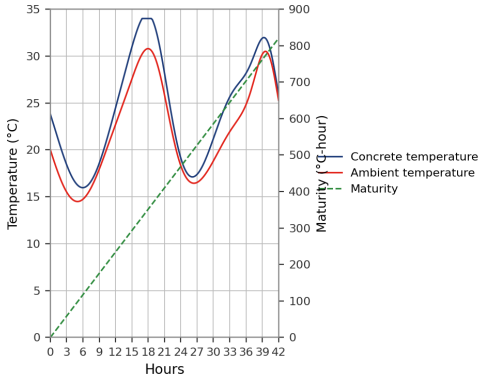

Figure 2. Temperature of the placed concrete & maturity calculated as a temperature-time factor.

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2. Equivalent age, as the second expression of maturity is known. This is defined as the curing time equivalent to a standard reference temperature of 20°C. When the placed concrete cures at

temperatures higher than the reference temperature, the equivalent age is greater than clock time; 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.

Instrumentation of a concrete slab for industrialized systems in order to determine maturity. The photo shows the thermocouples and the digital temperature recorder.

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There is a directly proportional relationship between the maturity of concrete and its strength at a given age. For this reason, it is possible to build a correlation model between the two properties, which will make it possible to estimate the concrete's mechanical competence at a given moment. This model must exist for each type of concrete from each supplier. It would be irresponsible to implement the method without the specific model for the type of concrete being monitored.

Every test method has advantages and limitations. The most relevant ones for quality control of concrete via maturity are listed below:

Advantages

- It is possible to reliably evaluate the properties of the placed concrete.
- The impact of external factors such as low nighttime temperatures or the influence of protection and curing processes (or their absence) can be established.
- Based on the strength–maturity correlation model, strength can be estimated and critical construction decisions can be made.
- It is useful for concretes whose strength is specified at a very early age (precast industry).

Limitations

- Temperature of the mix must be measured until the moment when the maturity corresponding to the strength expected for the critical construction decision is reached. For this reason, if it is applied to estimate strengths specified at ages greater than 24 or 48 hours, instrumentation must be maintained for a prolonged period, which entails a waste of resources that can be costly and sometimes unnecessary.
- Measurement equipment (digital temperature recorders) runs a high risk of loss or damage.
- Thermocouples (cables connecting the measurement equipment to the instrumented points of the structure) can easily be disconnected or torn out by continuous traffic or carelessness by site personnel; in this case the entire test is at risk of being lost, and if temperature readings are not available for the full testing period, it is impossible to calculate maturity.

Adiabatic Heat Signature Generation Method

When a fresh concrete sample of constant mass is thermally isolated, and its temperature evolution is measured from the moment of mixing until an instant after the maximum temperature is reached, a thermal profile is generated (in much less than 24 hours, typically) whose properties are directly proportional to the concrete's quality in terms of mechanical strength. This thermal profile is known as the Adiabatic Heat Signature.

This method is based on the directly proportional relationship that exists between the amount of hydration heat generated by a concrete and its strength at a given age. For this reason, just as with the maturity method described above, it is possible to build a correlation model between the thermal properties and the mechanical properties of the material, which will make it possible to reliably and precisely estimate, in less than 24 hours, the potential performance of the concrete, especially its strength at the specified age.

The physical principles behind the correlation referenced in the preceding paragraph are very simple: on one hand, strength development is a function of cement hydration (which is evidenced through the increase in heat of hydration); and on the other, the temperature increase is a function of the increase in heat for a constant-mass sample prepared with a material of a given specific heat. Combining these two principles, briefly described above (one taken from cement and concrete technology, the other from thermodynamics), it can be said that the development of concrete strength is a function of the temperature increase in an adiabatic medium without heat loss or gain. This correlation has been extensively proven in our setting – over approximately 20 years – through quality control on multiple construction projects whose combined concrete volume totals several million cubic meters.

Each type of concrete has its own Adiabatic Heat Signature. This is like its DNA, because the thermal profile is generated during a gestation period corresponding to the transition between the fresh and hardened states, and a large part of its mechanical properties during its service life depend on it.

As with the Maturity Method, the main advantages and limitations of concrete quality control by means of adiabatic heat signature generation are listed below:

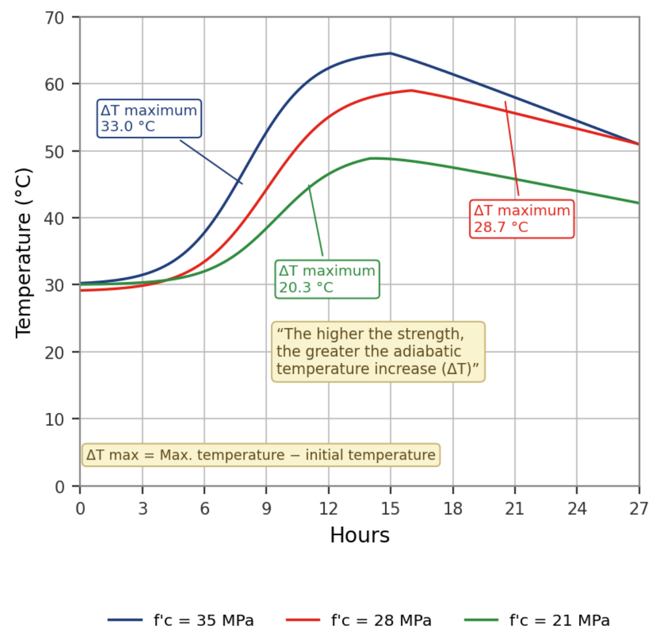

Figure 3. Thermal profiles of concretes of different strength levels, obtained on standard samples under thermal-isolation conditions.

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Advantages

- Based on the Strength–ΔT maximum correlation model, strength can be estimated (at any age previously considered in the model) and critical construction decisions can be made. Knowing the concrete's long-term potential performance in less than 24 hours (generally between 10 and 16 hours) adds a great deal of value.
- The resources required are easy to obtain.
- The test's operating procedure is simple and easy to apply.
- Equipment and samples can be kept in a secure location (the site camp or the job-site laboratory, for example).
- In the event of an unforeseen incident during measurements (a power outage, for example), it is easy to recover the test's critical variables if a contingency plan has been implemented beforehand.
- An accurate interpretation of the thermal profiles makes it possible to track workability time and setting time. In the event of problems with delayed or excessively rapid setting, the causes are easy to identify (usually associated with weather, dosing errors, or the acceptance of relocated concrete deliveries) and appropriate actions can be determined.
- When new concrete products are developed and evaluated at the laboratory level, applying this method is a great help for validating results in a very short time, especially when testing new admixtures, different cement types, and supplementary cementitious materials.

- It is the ideal method for daily, systematic quality control on multiple simultaneous projects, giving site personnel a degree of autonomy even if they do not have a high level of qualification. In such cases it is very important for an expert to supervise and provide ongoing monitoring.
- It is useful both for concretes whose strength is specified at a very early age (precast industry) and for concretes with strength specified at 28 days or more (56, 90 days).

Limitations

- It determines the potential of the concrete used in the structure. If external factors are present that dramatically affect the properties of the placed concrete, parallel mechanisms must be applied, including visual inspection and physical scratch testing. To minimize the impact of external factors, it is always advisable to apply adequate protection to the concrete in the structure.
- When the simple steps of the sampling and testing procedure are not rigorously followed, the results obtained can create confusion. Fortunately, an expert can easily identify this situation.

Final Considerations

It is worth mentioning that the techniques described should be considered alternative and discretionary:

- They are alternative because, given the mandatory nature of NSR-10 with respect to the preparation and testing of cylinders, the information they provide is considered complementary. Ultimately, they help make critical construction decisions in a timely and reliable manner; however, from a legal standpoint, concrete must be accepted solely and exclusively based on the strength results of standardized cylinders.
- They are discretionary because they are not mandatory. They are methods whose implementation is voluntary or, at times, recommended by the structural designer. The management of the construction company agrees to invest additional resources to put these techniques into practice for the value they can add to its projects in terms of timeliness and reliability in decision-making.

A final reflection: in construction projects we are always concerned about the strength of concrete. What about durability? The management of the construction company and site leadership are obligated to consider this property as well, since the structural stability and service life of the structure also depend on it – especially under exposure conditions such as those described in NSR-10 (Chapter C.4) and in NTC 5551 – Durability of Concrete Structures, both of which can compromise the concrete and reinforcing steel placed in the structure.