ISSUES ON MONITORING AND SIMULATING THE THERMO-MECHANICAL BEHAVIOUR OF CONCRETE SINCE EARLY AGES

Miguel Azenha (1) and Rui Faria (2)

(1) ISISE, University of Minho, Portugal
(2) LABEST, University of Porto, Portugal

Abstract
Even though the numerical simulation of concrete at early ages is an issue that has been studied for decades with thermo-mechanical approaches, several doubts still exist in the scientific community in regard to the modeling strategies and accuracy of predictions. In view of such challenges, the teams of the University of Minho and the University of Porto have been conducting research in the field, following a holistic strategy that encompasses: (i) material characterization in laboratory, (ii) thermo-mechanical simulation and (iii) in-situ monitoring for validation of simulations. The present paper aims to provide information about our current state of knowledge in these three vectors, while discussing limitations and development prospects.

Résumé
Bien que la simulation numérique du comportement au jeune âge des bétons soit un sujet étudié depuis plusieurs années, il existe encore des questions dans la communauté scientifique relatives aux stratégies de modélisation et à la précision des prédictions. En vue de répondre à ces questions, l’Université du Minho et l’Université de Porto conduisent des recherches suivant une approche holistique qui comprend : (i) une caractérisation du matériau en laboratoire, (ii) des simulations thermo-mécanique, et (iii) des mesures in-situ afin de valider ces simulations. Cet article vise à fournir des éléments d’information sur ces trois domaines, en discutant les limitations et les perspectives.

1. INTRODUCTION
Structures encompassing mass concrete usually endure significant temperature variations at early ages, in correspondence to the exothermal character of cement hydration reactions. Restraint to the deformations associated to these temperature changes can induce initial stress levels that may reach the tensile strength of concrete and cause cracking. In view of such problem, numerical simulation tools are deemed necessary to allow prediction of such stresses, and take precautionary measures to avoid concrete thermal cracking (e.g. precooling aggregates, internal cooling of concrete, changing mix proportions, adjusting the construction
sequence, etc.). The staffs of the University of Minho and the University of Porto have been dedicating research efforts during the last decade to the study of concrete structural performance since its early ages, with integrated approaches to the numerical prediction of early-age stresses with strong support on both laboratory material characterization and in-situ monitoring. The research approach is significantly centred in a sound choice of simulation models, modelling options and material parameters, in view of actual application for real-scale structures. The present paper aims to provide brief information about our accumulated experience in the field, encompassing issues and experiences related to monitoring both in laboratory and in-situ conditions (Section 2), material characterization (Section 3) and applications with corresponding numerical simulation (Section 4).

2. MONITORING

A fundamental point for validation of numerical prediction models is the availability of in-situ collected information for comparison. Such data collection is not always straightforward, and several doubts and problems arise in such attempts. This section is separated in three sub-sections – thermal monitoring, mechanical monitoring and data logging –, aiming to provide information about our currently adopted strategies.

2.1 Thermal monitoring

The recourse to measurements with embedded temperature sensors in concrete is relatively widespread. We often use thermocouples of type K, which are very cheap (reel supply), resistant and provide reasonable measurement accuracies within ±1°C. When more accurate measurements are required, PT100 RTD thermometers are used, with accuracies that rely within ±0.1°C. Even though they are not expensive, the PT100 sensors are much more costly than thermocouples, and they demand more labour for preparation, as a casing is required to protect the sensor from being damaged by concrete (wetness). Another topic of importance is the support of sensors within mass concrete, as it is often desired to know the temperature in the core where no reinforcement exists. For such purpose, PVC tubes are recommended as their thermal conductivity is low, and cross-sections can be selected according to physical needs. These PVC tubes may be partially placed into position in previous casting stages.

Complementary to embedded sensing, surface temperature measurements can be taken with infrared thermometers, which are relatively cheap and have levels of accuracy that are usually compatible with those of thermocouples. Nonetheless, it should be stated that this kind of device demands a direct line of sight into the object of measure. Therefore, in the presence of obstacles such as formworks it is impossible to directly measure the concrete temperatures, which is a serious drawback. In line with the same technology, the thermography cameras allow simultaneous measurement of thousands of pixels (usually 640×480). This can be quite convenient for temperature assessment after formwork removal, and it has been tested for such purpose in a laboratory application that will be presented in this paper.

Further than merely monitoring internal or surface temperatures in concrete, it is important to characterize the environmental conditions for use in numerical models. Environmental temperature is amongst the most important information to be gathered. However, care should be taken to protect the corresponding sensor and measure the actual dry-bulb temperature, i.e., the air temperature measured by a sensor which is shielded from the effects of solar/night
radiation and moisture. Solar radiation can be monitored with recourse to a low cost pyranometer, based on a photodiode detector having enough accuracy for validation purposes of solar radiation prediction models.

In regard to wind speed measurements, both hot-wire anemometers and revolving blade anemometers have been used. Even though the hot-wire solution provides more accurate measurements, it is probably unnecessary. In fact, wind speed suffers dramatic changes both in time and space (microclimatic effects), and thus measurements taken in-situ just serve as a reference for assessing boundary coefficients. Whenever possible, the environmental information collected in-situ should be compared and complemented with information gathered from nearby weather stations, which often result in an interesting data bank to establishing environmental scenarios for simulation regarding distinct times of the year.

2.2 Mechanical monitoring

The best assessment of a mechanical simulation software for self-induced thermal effects would certainly come from a sensor with the capability of measuring stresses. Nonetheless, due to several difficulties specifically related to concrete, namely its viscoelastic behaviour, the establishment of a stress measurement system is quite difficult. Even though there is a commercial system for stress measurement in mass concrete (named the stress meter) [1], we have not yet tested it.

In view of what has been stated, our actions for validation of numerical mechanical models have been centred in the use of embedded strain gages. A pilot experiment in a 60×30×60cm³ unreinforced concrete specimen has been conducted in laboratory conditions, with comparison of the performance of several types of sensors: embeddable electric strain gages, vibrating wire strain gages with plastic casing, and vibrating wire strain gages with metallic casing [2, 3]. Such experiment led to the observation that: (i) vibrating wire strain gages are much more reliable than electric gages, being almost independent of electromagnetic disturbances, and having stable output signals after power failures or connection/disconnection of wiring (i.e., the signal is absolute); (ii) temperature compensation of the sensor output is much more straightforward and reliable in the case of vibrating wire strain gages; (iii) the combined use of vibrating wire strain gages with plastic and metallic casings (the first ones particularly devised for concrete at early ages) allows the determination of the instant at which the metallic sensors become solidarized to concrete (occurring as soon as both sensors yield equal response trends). In view of the enumerated conclusions, our strain measurements in real field applications are now conducted exclusively with recourse to embeddable vibrating wire strain gages.

2.3 Data logging

In regard to data logging, in-situ measurements usually demand for solutions that allow autonomous measurement of several types of sensors simultaneously, and that can be powered by a battery for a relatively long period. In our research these requisites are satisfied using DataTaker®-based solutions, particularly the DT-80G, together with the expansion modules CEM20. These solutions allow the simultaneous monitoring of more than 25 temperature and/or strain sensors, with a resolution of 18 bits. The small size of the data logger, its autonomous operation and memory capacity (assured by ordinary flash drives), and its low power consumption assure the possibility of being placed in-situ, inside a protective housing that also contains a battery, in continuous operation for weeks.
3. CHARACTERIZATION OF CONCRETE PROPERTIES

In view of the final purpose of supporting models and material properties for use in numerical simulations, some remarks are made next in regard to our usual strategies and approaches (both conceptual and experimental).

3.1 Thermal properties

Thermal conductivity $k$ and volumetric specific heat $\rho c$ of concrete are properties of utmost importance for thermal simulations. Several experimental techniques exist for assessing these properties [4], and many expressions have been forwarded for their estimation based on the concrete mix proportions and on the thermal properties of the cement, water and aggregates [4]. We have not conducted experimental work in this field, having always used the secondly mentioned approach to estimate thermal properties. In view of the overall good coherence of the thermal field simulations (when compared to monitoring results), and the relatively low variability of $k$ and $\rho c$, no further research has been conducted in this regard. Another important topic in this concern is the evolution of these properties along hydration: even though several authors report such behaviour, few experimental results exist to back them. By performing parametric simulations to check influence of variations on $k$ and $\rho c$ along hydration [4], it was found that changes on temperature predictions were marginally affected by $k$, and relatively small for the case of varying $\rho c$. We are currently conducting our simulations under the assumption that these properties can be considered as constant.

In what concerns to heat of hydration of cement or concrete, we have conducted an extensive experimental programme to characterize the thermal output of 10 cements produced in Portugal, with recourse to an isothermal calorimeter JAF60 with testing temperatures ranging within the 20-60ºC interval [4]. The gathered experimental data, performed on cement pastes with a water/cement ratio equal to 0.5, allowed the assessment of the parameters for characterization of cement heat generation according to an Arrhenius-type law. Such information in summarized in [4], and it has been used for several simulation cases in Portugal by merely multiplying the generated heat of the database (expressed in W/kg of cement) by the volumetric content of cement in a given mix. Even though this approach is simplified and disregards the buffering effect of aggregates and secondary reactions with fly ash or alike, the obtained results have been rather encouraging, circumventing the necessity of performing actual calorimetric characterization of concrete.

Finally, issues related to the convection boundary coefficients are discussed. Based on wind tunnel experiments and computational fluid dynamics simulations [5], we have concluded that in-situ measurements of wind speed can be quite misleading in regards to the average boundary transfer coefficient to adopt. In fact, even if a regular monitoring of wind speed is performed at a given point near the construction, there is no guarantee that the wind speed around the entire structure is the same. Such detailed characterization (or simulation) would exponentially increase the complexity of the problem without significant improvements in results, which are usually already quite acceptable. The reason for this is that concrete thermal diffusivity is relatively low, and thus thermal losses occur in a relatively slow fashion, with an averaging effect on boundary losses. Therefore, based on our field experience we are currently adopting values around 10W/m²K for low wind situations, having increased values as wind speed becomes non-negligible [4].
3.2 Mechanical properties

One of the most important mechanical properties to assess in view of cracking risk is the tensile strength of concrete. Therefore, in parallel to monitoring programmes we usually conduct tensile strength tests of concrete at several ages (usually 1, 3, 7, 14 and 28 days) through splitting tests. Determination of the compressive strength of concrete (usually performed on cylinders) is also advisable at the same ages, in view of its usefulness for establishing load levels for creep and E-modulus testing. Undertaking of parallel tests for compressive strength of specimens cured at dissimilar temperatures (e.g. 40 °C and the traditional curing at 20 °C) can provide useful information regarding the mechanical activation energy.

E-modulus testing at the several ages mentioned before is also usually performed in view of its importance on stress development. However, a recently proposed methodology for continuous measurement of concrete E-modulus since casting (termed EMM-ARM) [6] is now being used as a replacement to classic cyclic testing of concrete cylinders. With this new methodology, based on the evolution of the resonant frequency of a composite beam that contains the material under test, it is possible to continuously assess the E-modulus of concrete since casting, with explicit detection of the mechanical threshold of concrete.

Creep of concrete needs to be assessed, as it plays an important role in the relaxation of stresses at early ages. Even though the most relevant deformations in concrete occur under tensile stresses, creep testing is much easier to conduct in compression. Therefore, and bearing in mind the reported resemblance between compressive and tensile creep [7], our strategy of testing usually involves compressive basic creep testing at the above mentioned discrete ages. Even though it would be desirable to have creep test results for ages lower than one day, this is not done as it is difficult or even unfeasible to remove the mould off and test specimens at such ages.

Shrinkage of concrete, particularly the one of autogenous nature, should be assessed experimentally in view of its relevance for concrete stress development at early ages.

4. NUMERICAL SIMULATION AND APPLICATIONS

4.1 Computation of temperatures

Computation of the thermal field \( T \) on a concrete structure is accomplished by solving the Fourier equation

\[
k \nabla \cdot (\nabla T) + \dot{Q} = \rho c \dot{T}
\]

(1)

where \( \dot{Q} \) is the rate of internal heat generated by the cement hydration, reproduced by the Arrhenius-type law:

\[
\dot{Q} = a f(\alpha) e^{-\frac{E_a}{RT}}
\]

(2)

where \( E_a \) is the activation energy, \( R \) is the universal gas constant, \( a \) is the maximum value of the heat production rate and \( f(\alpha) \) describes the evolution of the normalized heat production rate. The latter is a function of the degree of heat development \( \alpha \) - which is calculated by dividing the heat released at a given instant \( Q(t) \) by the total heat that can be released by concrete upon hydration completion \( Q_{pot} \).
In terms of the boundary conditions for Eq. (1), convection and radiation phenomena are expressed together through the equation

\[ q = h(T_b - T_d) \] (3)

where \( q \) is the heat flux per unit area, \( h \) is the combined convection-radiation transfer coefficient, \( T_b \) is the boundary surface temperature, and \( T_d \) is the air temperature.

For further details regarding implementation through the Finite Element Method (FEM), as well as to the algorithm for solving the resulting non-linear system of equations, see ref. [4].

4.2 Mechanical problem

Focus is given here to the aspects in which the mechanical analyses of concrete at early ages differ from classical transient approaches for hardened concrete. As temperatures vary during the period of analysis, and mechanical properties of concrete endure a continuous growth, a transient analysis is required to compute the local strains and stresses in concrete. This analysis is usually implemented with the same time advancing scheme adopted for the thermal problem, from which it receives, at each time-step, the nodal temperatures. Therefore, at each time-step it is possible to compute the volumetric strains, and to update the mechanical properties of concrete (Young’s modulus and tensile strength) based on a local equivalent age \( t_{eq} \)

\[ t_{eq} = \int_0^t e^{-\frac{T_{ref}}{E_0(\tau)}} \left( \frac{1}{\tau - \tau_{ref}} \right) d\tau \] (6)

where \( T_{ref} \) stands for the reference temperature (usually 20ºC).

Another issue with relevance for evaluation of stresses concerns the pronounced concrete creep that occurs during the early ages, causing large stress dissipations. One of the most suitable laws for reproducing early age basic creep, adopted in our applications, is the Double Power Law [7]

\[ J(t, \tau) = \frac{1}{E_0(\tau)} + \frac{\phi_1}{E_0(\tau)} \left( \frac{1}{\tau - \tau_{ref}} \right) \tau^{-m} (t - \tau)^n \] (7)

where \( J(t, \tau) \) is the compliance function at time \( t \) for a load applied at instant \( \tau \), \( E_0(\tau) \) is the asymptotic elastic modulus (corresponding to short term loads), and \( \phi_1, m \) and \( n \) are material parameters.

Therefore, at any instant it is possible to compare the local stress state with the local tensile strength \( f_{ct} \) of concrete, and therefore to compute the cracking risk at the actual location.

4.3 Application 1: laboratory experiment

As a preliminary illustration of how information obtained from early age concrete monitoring can be combined with numerical simulations, in Fig. 1 it is possible to compare the distribution of temperatures on a concrete cube with edges 0.40m long captured by a thermography camera (left), or computed numerically via the FEM. A rather close resemblance was obtained for the surface distributions of temperatures, as it can be observed.
4.4 In-situ field applications

Application 2: wind tower RC foundation

The cracking risk of wind tower RC foundation has been assessed as an industry demand. In the RC foundation, with a 16.5×16.5m² insertion in plan, the tower itself was a circular hollow section steel mast, and for the perfect clamping of the tower onto the RC foundation there was a 2.3m tall steel ring, partially cast inside concrete, as depicted in Fig. 2a. A monitoring campaign was undertaken to measure relevant temperature evolutions using 5 PT100 sensors. The calculated temperature field at the age of 56h is depicted in Fig. 2b. In Fig. 2c the numerical predictions agree fairly well with the field assessment measurements, with deviations that never overcome 4°C. Even though this example did not encompass strain measurements or in-depth mechanical characterization, the numerically estimated stresses indicated a low risk of cracking, consistent with the in-situ absence of cracking.

Application 3: Pretarouca concrete gravity dam

Another field application concerns to the Pretarouca concrete gravity dam, built in the north of Portugal, and reproduced in Fig. 3a. Experimental and numerical simulation campaigns were undertaken to check the behaviour of this large concrete structure, and issues like the construction phasing and the thermal stresses developed at early ages were addressed. Figs 3b,c illustrate some details concerning the installation of the adopted vibrating wire strain gages for monitoring the strains and temperatures in concrete (a total of 39 sensors was installed on the concrete body, at mid-height of the dam). An in-depth laboratory program has been conducted for concrete, including measurements of the compressive and tensile strengths, the E-modulus evolution, the creep and shrinkage at early ages, and the calorimetric testing.
The FE mesh for the final stage of construction is depicted in Fig. 4a (each colour reproduces a different material). In Fig. 4b it is possible to observe the numerical results corresponding to two consecutive phases during the sequence of construction (1h before and 41h after the largest gallery becomes closed on the top), at about mid-height of the dam: the distributions of temperatures (on the left) and the ‘layered’ pattern of the $\sigma_x$ stresses (on the right) are some of the typical results that can be obtained. Similar distributions for the $\sigma_y$ and $\tau_{xy}$ stresses, and for the local tensile strength of concrete $f_{ct}$, were also obtained (not represented here just for reasons of conciseness).

![Figure 3: a) Pretarouca dam; b) and c) installation of vibrating wire strain gages](image1)

![Figure 4: a) FE mesh; b) temperatures and stresses](image2)

Comparison of the calculated temperatures at the various points of the dam where measurements from thermal sensors were available was performed as well. A typical example of such comparison is reproduced in Fig. 5a, where deviations are shown to be very low. The strains collected from the vibrating wire strain gages were zeroed at the end of casting, and their outputs were corrected for the effects of temperature. The resulting total strains were then compared with the numerically predicted ones, similarly as in the case reproduced in Fig. 5b. Coherence between the numerical predictions and the actual measurements of concrete strains is reasonably good, although rather less accurate than observed for the temperatures.
Other applications

Within this scientific domain we have tackled several other cases of early age behaviour of concrete structures, involving in-situ monitoring, which cannot be described here. Some of the most relevant ones are however enumerated in the following list: (i) a highly restrained slab [8]; (ii) a precast beam subject to heat curing [2] - Fig. 6a; (iii) a tetrapod for coastal protection [9] - Fig. 6b; and (iv) a dam spillway with air-cooling pipes [10] - Fig. 6c.

5. CONCLUSIONS

This paper summarized the accumulated experience of the research groups from the University of Minho and the University of Porto, in view of their holistic approach to the numerical simulation of concrete structural behaviour since early ages. Even though several limitations and challenges have been identified throughout the paper, it is considered that the current state of knowledge provides an adequate capacity for the numerical simulation of cracking risk in massive concrete structures.

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