What Can We Learn From Monitoring Concrete Temperature?

by P. Taylor and J. Gajda

Synopsis: There is a growing interest in monitoring the temperature of cement paste, mortar and concrete, particularly at early ages. However, there also seems to be confusion about what is being achieved by this activity, and what to do with the information once it is recorded.

This paper outlines the tools and techniques in use, and discusses their applications, benefits and limitations. The discussion will cover concepts such as heat of hydration, maturity, isothermal calorimetry and semi-adiabatic temperature monitoring for assessing setting times, and potential incompatibility between the reactive ingredients (cements, supplementary cementitious materials, and chemical admixtures) in a mixture.

Keywords: heat of hydration; isothermal calorimetry; maturity; setting time; temperature

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INTRODUCTION

There is increasing interest and activity in using temperature monitoring techniques to measure different aspects of cement and concrete hydration. This is because cement develops heat while it hydrates, leading to an increase in temperature. Tracking this heat or temperature provides an effective means of monitoring the progress of the hydration. The heat generated also has implications for design of floors on grade, pavements and mass structures to accommodate the dimensional changes associated with rising and falling temperatures.

Along with the increased activity there is also increasing misunderstanding about the various techniques that are being used and their appropriate applications. This paper discusses the various techniques in use, including their benefits and limitations, and where and how they can be used. The topics covered include:

- Maturity
- Isothermal Calorimetry
- Heat of Hydration
- Setting Time Measurement
- Field Calorimetry

A critical aspect to be noted when considering all of these systems is whether the technique is isothermal, adiabatic or semi-adiabatic – or none of the above. Data collected under one condition may not be transferable or comparable to another condition.

Isothermal tests are controlled at a fixed temperature and often involve measurement of the energy required to maintain that temperature. These data are not representative of the temperature variations experienced in the field, but do provide useful, controlled information about relative hydration kinetics of the systems being investigated. Adiabatic tests are where the samples are sufficiently insulated, or controlled, such that there is no heat transfer to or from the environment. This is representative of concrete about 3 feet below the surface of large concrete elements at early ages, and may lead to very high temperatures. Semi-adiabatic systems are partially insulated, and the heat transfer to the environment is estimated or measured and allowed for. Such tests are often simpler and cheaper to run because the insulation or control systems are much simpler. Other alternatives are simply to track the temperature in the structure, where the environment is not controlled.

MATURITY

The basis for this method is simple: the strength and modulus of elasticity of a concrete specimen are directly related to the quantity of heat developed from the hydrating cementitious materials. The technique is therefore to estimate the strength based on recorded temperatures of the in-place concrete and a model developed from laboratory testing of the same mixture[1].

Maturity methods can and have been used extensively to predict the in-place strength and strength gain of concrete in the field. The practical benefit of this method is that field evaluations of in-place strength can be predicted from simple measurements of the concrete temperature over time. This can lead to efficient usage of forms in structural concrete, and correct timing of saw-cutting in slabs on grade. The theoretical benefit is the ability to accurately predict both the strength and modulus of elasticity of concrete over a wide range of conditions based simply on the temperature development in the modeled concrete. A given maturity model, however, is only applicable to a single mix, and has to be re-calibrated if there are changes in the mix proportions or cementitious materials used. It should be noted that maturity testing does not indicate the quality of the concrete with respect to mix proportions, consolidation or surface finishing. The method also is based on the assumption that the concrete is kept moist, and is crack free.

Maturity testing entails developing a maturity curve (Figure 1) that correlates the development of particular concrete property for a specific concrete mix to both time and temperature. After the maturity curve is developed, the concrete property can be estimated from a measured time-temperature record of the concrete. The maturity function is a mathematical expression to account for the combined effects of time and temperature on the strength development of concrete. The key feature of a maturity function is the representation of how temperature affects the rate of strength development.

There are different approaches to developing the models needed to use maturity effectively. ASTM C 1074 provides procedures for using the measured in-place maturity index to estimate in-place strength (Figure 1). This practice describes two maturity functions. The first, and most popular for use with concrete pavements, is the Nurse-Saul time-temperature function. The other, preferred, maturity equation is the Arrhenius equivalent age function. This function presents maturity in terms of the equivalent age of curing at standard laboratory conditions. Although the equivalent age maturity function presents results in a more understandable format (the equivalent age), the complexity of its equation is likely why this method is less popular than the time-temperature factor method.

Equivalent age is expected to result in more accurate results when large temperature changes occur in the field. However, the time-temperature method is easier to apply and has been successfully used for estimating the in-place strength of paving concrete. Each of these functions requires preliminary testing to relate to the strength of concrete. Each method has a constant that can be assumed or for accuracy determined for the specific mix (ASTM C 1074). In the temperature time factor, a datum temperature below which hydration is minimal is assumed to be 0°C, or can be determined experimentally. In the equivalent age method, activation energy is assumed to be 33500 J/mol, or can be calculated.

ASTM C 918 uses the maturity method of monitoring temperature of cylinders cured in accordance with standard methods outlined in ASTM C 31 (AASHTO T 23). Cylinders are tested at early ages beyond 24 hours, and the concrete temperature history is used to compute the maturity index at the time of test. Using historic data, a prediction equation is developed to project the strength at later ages based on the maturity index and early-age strength tests[2].

Maturity can be determined with commercially available test equipment (Figure 2), or with standard temperature-logging equipment and an understanding of maturity. In either case, temperature sensors must be placed at critical locations in the concrete. For most pavement placements, this will be either at the top or bottom surfaces. When in doubt, use the lower of the maturities from sensors at the top and bottom surfaces. For mass and structural concrete, sensors are placed at the surface for maturity applications.

Commercially-available test equipment (maturity meters) log the concrete temperature as a function of time, and presents the current maturity (time temperature factor or equivalent age) of the concrete. There are two primary types of maturity meters. The first type uses temperature sensors in the concrete and has logging equipment outside the concrete. The second type combines the temperature sensor and logging equipment in a single package, which is embedded in the concrete. Wires extend from the sensor to outside the concrete. These wires must be periodically connected to a hand-held reader so that the maturity data from the sensor can be read. Wireless equipment is also available. Maturity can also be calculated from temperature sensors (such as thermocouples, thermometers, or thermistors) that are embedded in the concrete. The time interval should be selected to adequately resolve temperature changes in the concrete. In most cases, hourly time intervals are adequate.

ISOTHERMAL CALORIMETRY

In isothermal calorimetry testing, a small paste sample is maintained at a fixed temperature. The rate of heat evolution is monitored and plotted in units of specific power (rate of energy transfer per unit mass) versus time. The shape of the curve is descriptive of the hydration kinetics of the paste[3]. An example is shown in Figure 3 showing the retardation effects or increased water reducing admixture dosage.

By varying the materials in the paste and their proportions, the effects of supplementary cementitious materials, chemical admixtures, cement composition, and batching sequence can be addressed. The technique is also useful for determining whether the system being tested contains sufficient sulfates, which influence time of set and early rate of hydration.

An isothermal heat conduction calorimeter consists of a heat sink that has two heat flow sensors and a sample holder attached to each sensor. A freshly prepared mixture is placed in a container in contact with one of holders and a thermally inert material is placed in contact with the other. The heat released by the reacting cementitious sample passes across a sensor into the heat sink. The output from the calorimeter is the difference between the outputs from the sample heat flow sensor and the inert heat flow sensor. The measurement therefore takes place at essentially constant temperature.

The relative hydration performance of test mixtures are compared with appropriate control mixtures. The procedure and apparatus can be used to assess potential incompatibilities including:

- Effect of addition of sulfate on the setting time of a mixture. This can be used to indicate whether a cementitious system (including admixtures and supplementary cementitious materials) has the optimum amount of sulfate.
- Relation between the time of maximum alite heat evolution and the time of sulfate depletion. This relationship may be used as an indicator for the overall sulfate balance of each mixture.
- Acceleration of aluminate hydration before setting as a function of admixture type and dosage.
- Retardation of the alite hydration as a function of admixture type and dosage.
- Effect of supplementary cementitious materials type and dosage relative setting time at constant temperature.
- The rate of heat evolution from cementitious pastes as well as combinations of cements with chemical and mineral admixtures.

The equipment is relatively expensive and the data are sensitive to procedures in the laboratory. The method in preparation at ASTM calls for mixtures to be prepared outside the machine because precision is improved if mixing is complete and if it is uniform between mixtures. This approach does mean that the first readings are taken 5 to 10 minutes after water is added to the cement, thus losing some of the data associated with aluminate reactions. This is generally considered acceptable in order to gain better data about the silicate reactions. The initial peak is also associated with the heat of wetting the dry materials, and poor correlation has been found between this first peak and the physical performance of the cementitious system[4]. Some calorimeters allow internal mixing if the data are required for determination of heat of hydration (see following section) or other purposes.

HEAT OF HYDRATION

Reactions involving cementitious materials are exothermic, leading to a rise in temperature. The relative rates of heat generation provide useful information on the hydration kinetics of the systems as discussed above. Another effect of this temperature rise is that measures have to be taken to prevent cracking resulting from dimensional changes associated with the temperature changes. Knowledge of the heat generated by the system is a required input parameter in numerical models (ACI 207) used to predict the risk of thermally related cracking. Heat of hydration is expressed in units of energy per unit mass at fixed time intervals (e.g. kJ/kg at 7 days). Additionally, ASTM C 150 imposes optional maximum limits on the heat of hydration of Type II and IV cements, based on measurement of the heat of solution in accordance with ASTM C 186.

ASTM C 186 is not considered an ideal test because the precision is poor[5], it is costly, not all laboratories have the required equipment and such standard equipment is not commercially available. Investigations are underway to develop alternative methods of measuring heat of hydration of cementitious materials. Such approaches include

- Isothermal conduction calorimetry (using the same calorimeter discussed above)
- Adiabatic calorimetry using mortar or concrete samples in an adiabatic chamber
- Semi-adiabatic calorimetry using simpler equipment and allowing for energy loss from the chamber.

All of these approaches have strong points and limitations, with the use of the isothermal conduction calorimeter reportedly showing most promise. This test is suitable for testing paste samples for a relatively short period because it does tie up a calorimeter for the length of the test. An advantage is that data collection is at frequent time intervals, leading to a smoother curve than in the incremental C 186 approach, where normally only two ages are used. Work is still required to better understand the precision and bias of the method, and to ensure that existing limits are still appropriate. Examples of comparative data for the same sample are shown in Figure 4.

SETTING TIME

One clear indication of when silicate reactions are starting (indicating setting) is a rapid increase in temperature at the end of the dormant period. Devices that measure the temperature of the in-situ concrete or laboratory samples allow the time of set to be determined at relatively low cost (Figure 5). Work is ongoing at ASTM to standardize such an approach including a round robin of a draft method conducted in 2005. Correlation with initial set is relatively simple, and is either taken at the point of inflection of a time-temperature plot, or the point when the second derivative of such a plot is at zero.

Attempts to determine the final set are less successful, with attention being focused on the slope of the first derivative of the time – temperature curve. This lack of correlation is not surprising because the current ASTM C 403 definition of final set is based on an arbitrary figure of pressure applied through a penetrometer rather than any parameter associated with the hydration kinetics of the system. The rate of hydration will vary between different systems and the time taken to achieve a given resistance to pressure may not be related to the slope of a time-temperature plot. Data has shown that final set occurs between the top of the time-temperature curve and about half way up the curve (Figure 6)[4]. For a given mix, correlation between initial set and final set was reasonable, therefore final set can be predicted based on the initial set value.

Tracking data using sensors embedded in a structure will allow better timing of activities such as saw-cutting joints in pavements and floors on grade. In the laboratory it is easy to automate data collection, therefore staff do not have to work a late shift if mixtures are made late in the day.

FIELD CALORIMETRY

There are many variations of field calorimeter in use, from simple thermocouples inserted in a concrete slab or cylinder, up to multi-celled semi-adiabatic systems with computer based data-loggers (Figure 7). The selection of the equipment will depend on the application and the data to be collected. Potential applications are those discussed above, and include:

- Collection of data for maturity monitoring
- Field assessment of potential incompatibilities between mix ingredients[6]
- Tracking uniformity of delivered materials using control charts of peak temperature and/or time of set
- Monitoring time of set for field batches

In general, the data collected from such systems is less precise than that from more expensive laboratory equipment, but it is easily transportable, and for many applications, the data are good enough to provide useful information about the performance of the system under investigation. Examples of such data are shown in Figure 8.

SUMMARY

A large amount of useful data can be collected by monitoring the temperatures of cementitious systems. These data are useful for characterizing the materials in the systems, investigating interactions between them, tracking uniformity, timing finishing activities that are governed by the time of set and monitoring strength development. The range of applications is wide, and the types of equipment available are varied. This paper has set out to clearly describe the different techniques that can be used, their applications, strengths and limitations.

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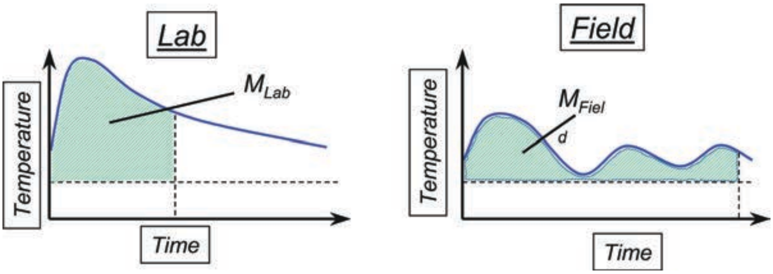

Figure 1—Maturity of the field concrete is equivalent to maturity of the laboratory concrete when the area under the curves is the same.

Figure 2—An example of a maturity logger.

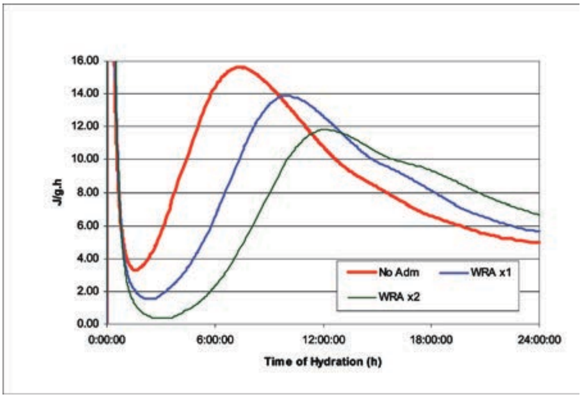

Figure 3—Example of isothermal calorimetry plots illustrating the retarding effect of increased dosage of a water reducing admixture. Highest temperature and earliest set is with the plain mixture, with lower peak and longer setting with increasing WRA dosage.

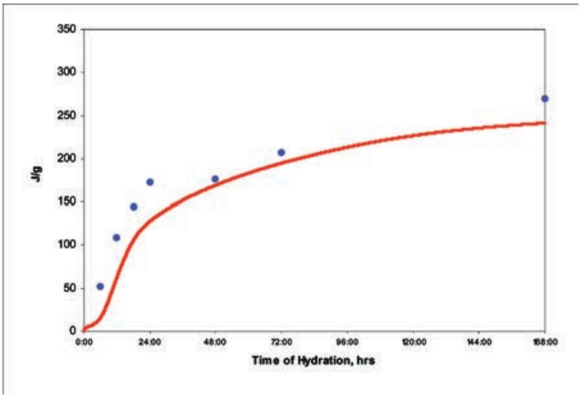

Figure 4—Example of data collected using ASTM C 186 heat of solution (dots) and an isothermal calorimeter (line) for the same cement sample.

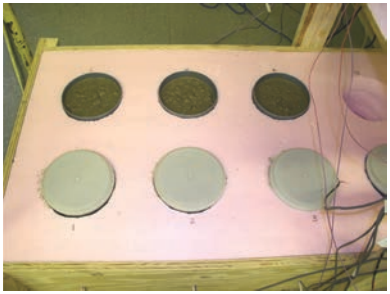

Figure 5—Example of equipment used to measure setting time by monitoring temperature rise.

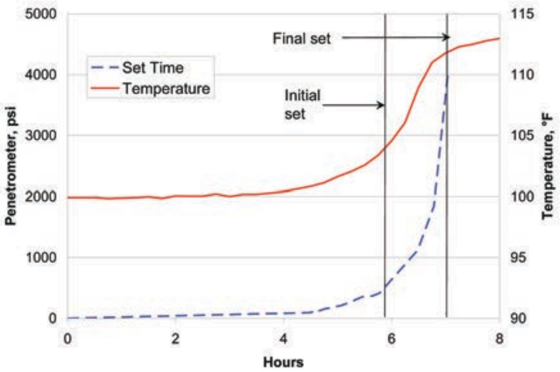

Figure 6—Data of semi-adiabatic temperature rise compared with penetrometer readings for the same concrete mixture (Taylor et al., 2006).

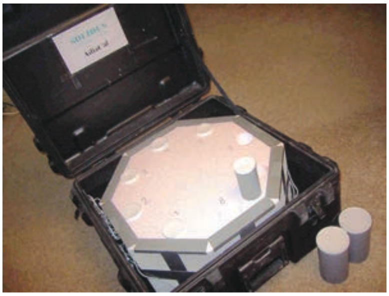

Figure 7—Field Calorimeter (Courtesy of Paul Sandberg, Grace).