The heat produced by concrete during concrete curing is called heat of hydration. This exothermic reaction occurs when water and cement react. The amount of heat produced during the reaction is mostly related to the composition (Table 1) and fineness of the cement.

The Five Phases of Heat Evolution in Concrete

Heat evolution in concrete is a very complex and extensively researched topic. To simplify this process, the heat evolution over time can be separated into five distinguished phases. The heat profile can change depending on the type of cement. Typical hydration for Type I cement is graphically represented in the figure below.

Table 1: Portland cement composition

Portland Cement Phases	**Abbreviation (Chemical Formula)**
Dicalcium silicate	C_2S
Tricalcium silicate	C_3S
Tricalcium aluminate	C_3A
Tetracalcium aluminoferrite	C_4AF
Calcium sulphate *	CaSO4, $CaSO_4 \cdot 2H_2O$ (gypsum), $CaSO_4 \cdot ½H_2O$

*Calcium sulphate only represent~10% of the cement mass. The other four phases are the principal compounds of the Portland cement and their individual mass fraction changes based on the type of cement.

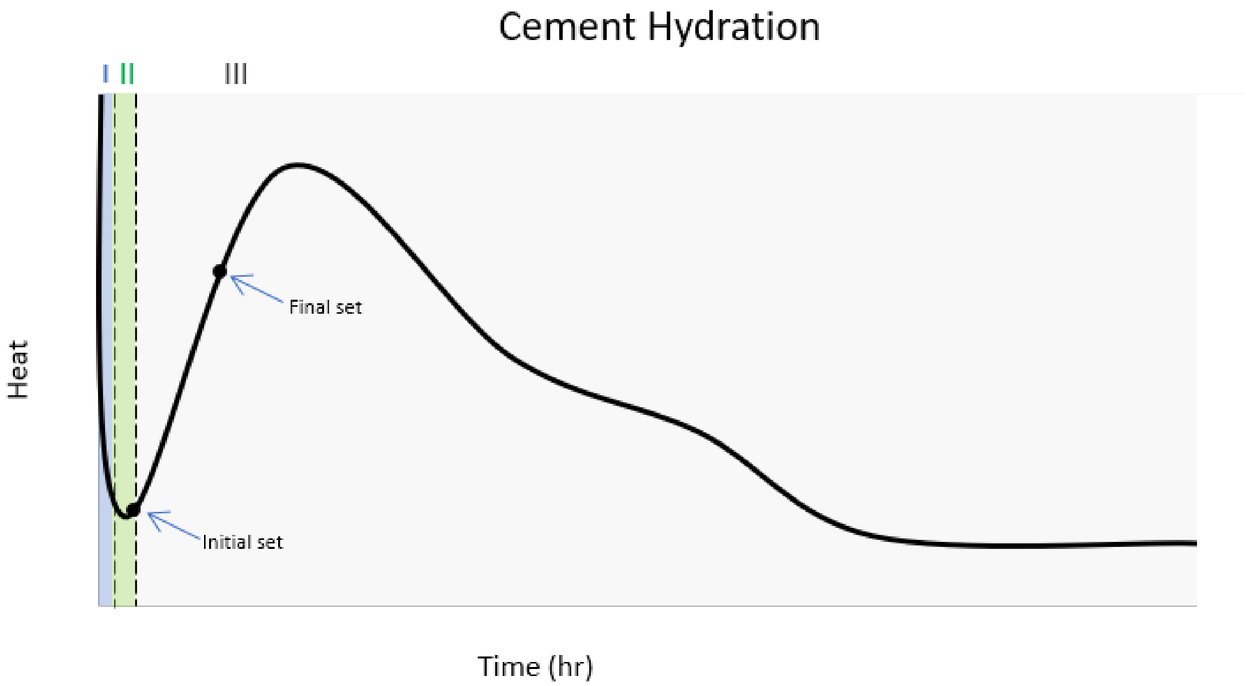

Figure 1: Heat of hydration for Type 1 cement

Phase I: Pre-Induction

A short time after the water comes into contact with the cement, there is a sharp increase in temperature, which happens very quickly (within a couple minutes). During this period, the primary reactive phases of the concrete are the aluminate phases (C_3A and C_4AF). The aluminate and ferrite phases react with the calcium and sulphate ions to produce ettringite, which precipitates on the surface of the cement particles. During this phase, at a lesser extent, the silicate phases (mainly C_3S) will also react in very small fractions compared to their total volume and form a very thin layer of calcium-silicate-hydrate (C-S-H).

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Phase II: Dormant Period

This phase is also known as the induction phase. During this period, the rate of hydration is significantly slowed down. Traditionally, this is believed to be due to the precipitation of the aforementioned compounds on the surface of the cement particles, which leads to a diffusion barrier between cement particles and water. Nevertheless, there is significant debate on the physical and chemical reasons behind the occurrence of this stage and the methods to predict it.

This is the period at which the fresh concrete is being transported and placed since it has not yet hardened and is still workable (plastic and fluid). The length of the dormant period has been shown to vary depending on multiple factors (cement type, admixtures, w/cm). The end of the dormant period is typically characterized by the initial set.

Phase III and IV: Strength Gain

In this phase, the concrete starts to harden and gain strength. The heat generated during this phase can last for multiple hours and is caused mostly by the reaction of the calcium silicates (mainly C_3S and to a lesser extent C_2S). The reaction of the calcium silicate creates "second-stage" calcium silicate hydrate (C-S-H), which is the main reaction product that provides strength to the cement paste. Depending on the type of cement, it is also possible to observe a third, lower heat peak from the renewed activity of C_3A.

Phase V: Steady State

The temperature stabilizes with the ambient temperature. The hydration process will significantly slow down but will not completely stop. Hydration can continue for months, years, or even decades provided that there is sufficient water and free silicates to hydrate, but the strength gain will be minimal during such a period of time.

Why Monitor Concrete Temperature?

In Phase II, the temperature of concrete can be measured as the concrete is poured. The temperature measurement is typically done to make sure the concrete is in compliance with certain specifications that define a certain allowable temperature range. Typical specifications require the temperature of the concrete during placement to be within a range of 10°C to 32°C (50°F to 90°F). However, different specified limits are provided depending on the element size and ambient conditions (ACI 301, 207). The temperature the concrete exhibits during placement affects the temperature of concrete during the next hydration phase.

Monitoring the temperature of the concrete during phase III and IV is a quality control component that is regularly being performed. The main reason behind this measurement is to ensure the concrete does not reach temperatures that are too high or too low to allow proper strength development and durability of the concrete. Another reason for monitoring concrete curing temperature during this phase is to evaluate the in-place strength, where the rate of hydration is the principal behind the maturity method (ASTM C 1074).

Cold-Weather Concreting

If the ambient temperature is too low, the hydration of the cement will significantly slow down or will completely stop until the temperature increases again. In other words, there will be a significant reduction or an end to the strength development. If the concrete temperature reaches freezing before reaching a certain strength (3.5 MPa/500 psi) (ACI 306), the concrete will have a reduced overall strength. This will also cause cracking as the concrete does not have sufficient strength to resist the expansion of water due to the formation of ice.

To ensure proper strength development and avoid cracking of the concrete, the general guidelines suggest that the concrete temperature must be maintained higher than a certain temperature for a specific amount of time (>5°C (40°F) for 48hrs) (ACI 306).

> Learn About Monitoring Your Concrete’s Curing Temperatures Here!

Hot-Weather Concreting

Generally, a limit of 70°C (160°F) is specified for the concrete temperature during hydration. If the temperature of the concrete during hydration is too high, it will cause the concrete to have high early strength but consequently gain less strength in the later stage and exhibit lower durability. Furthermore, it has been observed that such temperatures interfere with the formation of ettringite in the initial stage and subsequently its formation in the later stages is promoted; which causes an expansive reaction and subsequent cracking.

Additionally, high-temperature issues are of concern, especially in mass concrete pours, where the core temperature can be very high due to the mass effect, while the surface temperature is lower. This causes a temperature gradient between the surface and the core, if the differential in temperature is too large it causes thermal cracking.

Mitigating Improper Concrete Hydration Temperatures

Multiple methods currently exist to mitigate the adverse effect of improper hydration temperatures. Two approaches, or a combination of both, can be taken to control the temperature during the dormant and strength-gain phase of the hydration process. One approach is to control the surrounding elements or mix constituents' temperature. The second approach is to optimize the mix design.

Concrete Temperature Control During Mixing and Curing

The temperature when the concrete is placed can be somewhat controlled by using cold water for the mix, cooling down aggregates using ice, or pouring at night when temperatures are naturally lower.

In cold weather, the temperature of the concrete can be controlled by providing appropriate curing conditions such as with the use of heating systems. High curing temperatures can also be controlled in the mass pour with cooling pipes.

Concrete Temperature Control During Mix Design

An effective approach to controlling heat generation during cement hydration is to have a mix design that is suited to the application and the ambient conditions. Here are some things to consider:

- Selecting the appropriate cement type changes the heat of hydration generated. Compared to Type I cement, Type III generates more heat while Type II generates moderate heat, and Type IV generates less than the others;
- Adjusting the finesse of the cement (a finer cement will generate more heat);
- Using supplementary cementitious materials (SCMs) is also an effective means of reducing the heat generated during hydration. Replacing a portion of the cement with, for instance, slag or fly ash, reduces the amount of reactive material in the early stages; in turn, this reduces the amount of heat generated and delays concrete strength gain; and
- Adding other types of admixtures such as retarders and accelerators (however, these mixtures will not typically affect heat generation; rather they will be used to control the length of the dormant period).

Keep in mind that appropriate curing is crucial to ensuring that the concrete has enough moisture to hydrate properly. Overall, the general contractor, engineer, and ready-mix supplier need to be in good communication with each other, test concrete temperatures regularly to avoid extremes during mixing, pouring, and curing, and have a plan in place in case temperatures do drop or exceed the recommended limits.

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