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Concrete Cracking and Heat of Hydration

The purpose of this PIN is to provide some background information on thermal strains occurring during the setting of concrete and the possibility of cracking in pavements.

When cement is mixed with water, heat is liberated. This heat is called "heat of hydration" and results from the chemical reaction which occurs in setting of concrete between water and cement. This heat causes the concrete first to expand and then to shrink as it cools. If there is a significant temperature gradient through the concrete or the concrete is otherwise restrained, cracking may occur.

Temperature rises of 55ºC have been observed on high cement content mixes. If the temperature rise is significantly high and the concrete undergoes non-uniform or rapid cooling, stresses due to thermal contraction, in conjunction with structural restraint, can result in cracking.

As a "Rule of thumb", the maximum temperature differential between the interior and exterior concrete should not exceed 20ºC to avoid crack development. The potential of thermal cracking is dependent on the tensile strength of concrete at the time, the particular coefficient of thermal expansion, the temperature differential and the restraint applicable.

The greatest rate of heat liberation occurs within the first 24 hours and a large amount of heat evolves within the first three days. Cements with higher contents of tricalcium silicate (C_3S) and tricalcium aluminate (C_3A) as well as higher fineness have higher rates of heat generation than others. Higher fineness provides a greater surface area to be wetted, resulting in the acceleration of the reaction between cement and water. This causes the increase in heat liberation at early ages and hence the commensurate expansion.

Other factors influencing heat development in concrete include the **cement content, water/cement ratio, placing and curing temperature, the presence of mineral and chemical admixtures and the dimensions of the structural element**. As a rough guide, hydration of cement will generate a concrete temperature rise of about **5-7ºC/50kg of cement/m^3** of concrete in 18 to 72 hours. Hence, if a mix has 300 kg/m^3 of cement it could generate 42ºC of heat. If the concrete placement temperature is, say, 30ºC then the interior temperature could be 70ºC+. Mixes with higher w/c ratios have more water and microstructural space available, which in turn results in an increased rate of heat development. Research has shown that increasing the w/c ratio from 0.4 to 0.6 results in an increase of 11% of the heat of hydration. Hence, the internal temperature in this example could approach 80ºC. To avoid cracking, the surface temperature of the concrete should be maintained at a temperature of 20ºC less! As this is impractical, control of the other factors of influence should be considered.

Higher temperatures greatly accelerate the heat of hydration and the rate of heat liberation at early stages. It should be noted that chemical admixtures accelerate this process whereas mineral admixtures such as fly ash can significantly reduce the rate and amount of heat development.

The key to reducing temperature related cracking is to recognise when it may occur and what are the factors influencing it and then to take steps to minimise it. (Overseas, for important structures, a Thermal Control Plan is actually specified).

The following provides some background info for consideration:

1 The ingredients of cement are:
   - Dicalcium silicate **–** **C_2S** 7 – 32%
     Slow acting, low heat generation, best long term strength and durability
   - Tricalcium silicate **–** **C_3S** 45 – 75%
     Quicker acting, more heat generated, good strength and durability but not as good as C_2S
   - Tricalcium aluminate **–** **C_3A** 0 – 13%
     Very rapid reaction, high heat generation, responsible for early (but not high) strength and setting, easily attacked by chemicals
   - Tetracalcium aluminoferrite **– C_4AF** 0 – 18%
     Relatively little influence on properties of concrete, present because it is needed during manufacture.

2 C_3A is the most reactive ingredient. Max heat in 10 – 20 hours.

3 In the US for GP cement the C_3S + C_3A proportion is limited to 58%; for low heat cement to 32%.

4 For normal cements the fineness is 320 -380 m^2/kg; For rapid hardening 450 – 650 m^2/kg.

5 The variations in the Coefficient of Thermal Expansion of various aggregates are:
   Limestone aggregate – 6.8 μm/ºC
   Basalt aggregate - 8.6 μm/ºC
   Granite aggregate - 9.6 μm/ºC
   Sand and gravel -10.8 μm/ºC
   Quartz aggregate - 12.2 μm/ºC

6 For winter casting – consider high C_3S + fine grind cement for higher heat + possibly a higher w/c ratio.

7 For summer casting – consider low C_3S + coarse grind cement + low w/c ratio.

References

1 PCA Concrete Technology Vol 18/2
2 Concrete Mix design, QC and Specification, Ken Day
3 Use of Pavement Anchors in Concrete Pavements, A Tinni, RJ Stubbs (1994)