IMPORTANCE OF CONTROLLING TEMPERATURE RISE DUE TO HEAT OF HYDRATION IN MASSIVE CONCRETE ELEMENTS

Anura NANAYAKKARA
University of Moratuwa

ABSTRACT**:** This paper mainly discusses the deterioration of concrete due to temperature rise in concrete as a result of heat of hydration of cement. When concrete is subjected to high temperature at early age, many physical and chemical changes of the hardened concrete can take place. Recently, severe cracking in some of the pile caps of bridge piers in southern highway project in Sri Lanka was reported. After extensive investigations, it was found that the main cause for cracking in those pile caps was due to an internal chemical reaction known as delayed ettringite formation (DEF). DEF is sometimes referred to as internal sulphate attack which is an internal swelling reaction of the concrete that occurs in the presence of water without any external ingress of sulphate. It is widely accepted that concrete subjected to high temperature at early age and exposed to moisture continuously or intermittently is likely to crack due to DEF. Experimental investigations also revealed that even when the concrete is subjected to high temperature over a short period during early age, there is a possibility of long term strength reduction and increase in permeability. Apart from maximum temperature rise, it is essential to control temperature gradient across thick concrete members like pile caps, deep beams, bridge piers, raft foundations and concrete dams to prevent cracking. There are many factors affecting early age temperature rise in concrete and subsequent cracking and other deterioration of concrete. Therefore it is a basic requirement to specify limiting temperatures for any major concrete construction and strictly adhering to the specification during construction in order to avoid expensive remedial actions to rectify damaged concrete due to thermal effects. Apart from controlling maximum temperature rise in concrete and composition of cement, use of fly ash or slag blended cement is effective in preventing most of the problems associated with temperature rise in concrete.

KEYWORDS: Heat of hydration, Delayed Ettringite Formation

1. INTRODUCTION

Recently, severe cracking in some of the pile caps of bridge piers in southern highway project in Sri Lanka was reported. After extensive investigations, it was concluded that the main cause for cracking in those pile caps was due to “delayed ettingite formation (DEF)”. The crack pattern of damaged concrete due to DEF is random in nature and referred to as “map cracking” (see Figure 1).

Even though DEF was found in many structures, it was not considered as a major problem until identifying DEF in deteriorated steam-cured concrete railway sleepers (Sadananda et al., 2004). It is now widely accepted that high temperature at early age of concrete is a necessary condition for delayed ettringite formation. Therefore this problem can occur in thick concrete members like pile caps, deep beams, bridge piers and raft foundations where core temperature can be very high as a result of heat of hydration of cement (Diamond, 1996). Apart from DEF, there can be several other detrimental effects even when the concrete is subjected to high temperature over a short period during early age which can affect the micro structure of the hardened cement paste.

Even though DEF is fairly a new phenomenon to most of the practicing engineers, other adverse effects due to high temperature rise in concrete are well understood and documented, and can find in any standard concrete technology text book or research reports (Bamforth, 2007). However, basic requirements to prevent these adverse effects, i.e. maximum temperature rise and maximum temperature gradient for large concrete elements, have not been specified in major construction projects in the recent past. As a result, concrete cracking was observed in many of those structures. It could have been avoided and saveed huge sum of money spent on rectification work if correct speciation was adopted in the planning stage of the construction project.

2. HEAT OF HYDRATION OF CEMENT

Extensive researches have been carried out to model the heat of hydration of cement, since it is very important to predict the temperature rise especially in mass concrete structures. Maekawa el al. (1999) has proposed a comprehensive multi-component model for the heat of hydration of cement incorporating exothermic hydration process of each mineral component of cement not only taking into account of interdependency of mineral reactions but also effects of fly ash and blast furnace slag in the case of blended cement. The technical report by CIRIA (Bamforth, 2007) gives a model for predicting the maximum temperature rise, the maximum temperature differential and temperature drop from peak to ambient (T_1) for a given member thickness considering many factors including cement type, formwork type, and thermal properties of concrete. The value T_1 is used in design of water retaining structures based on BS 8007 (BSI, 1987) to limit the crack width in RC members due to early age temperature drop. Approximate values for temperature drop “T_1” can also be obtained from BS 8007 but those are not relevant to local ambient conditions (Nanayakkara, 2003).

Figure1 Map cracking in a pile cap

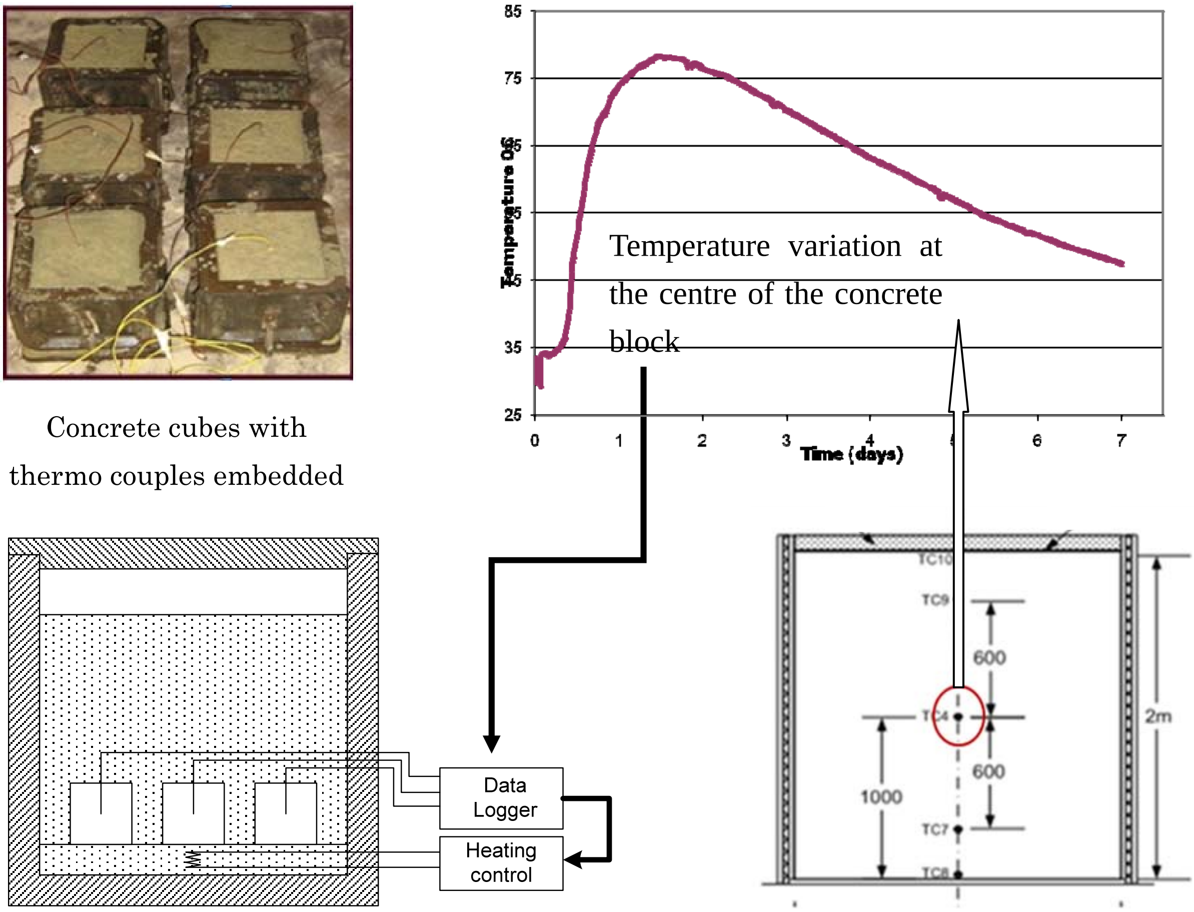
There are three possible effects of excessive temperature rise in concrete due to heat of hydration of cement.

1. *Development of tensile stress in concrete due to contraction under internal/external restrain during temperature drop.*

This effect is adequately considered in structural design of reinforced concrete structures. It is common practice to specify allowable temperature differentials during post construction period to control crack width of early-age thermal cracking. These limits depend on many factors such as thermal properties of aggregate, tensile strain capacity of concrete and degree of restraint. Typical limit for the maximum temperature differential within a single pour is 20 °C (Bamaforth, 2007).

2. *Change in microstructure of hydrated cement paste.*

It is a well established fact that the durability depends on the permeability of concrete. When the concrete is subjected elevated temperature even due to heat of hydration of cement, there can be many changes in the micro structure of the hydrated cement paste. Investigations carried out by Seishi Goto et al. (1981), revealed the total porosity of cement paste samples cured at 60 °C is smaller than those cured at 27 °C. However, pore volume of larger pores (larger than 750 Å) is greater in cement paste cured at 60 °C than those cured at 27 °C. Since permeability of cement pastes is mostly determined by the volume of the larger



Concrete cubes with thermo couples embedded

Temperature controlled curing tank

2 m thick concrete block

Figure 2 Temperature match curing

pores rather than by total porosity, cement paste samples cured at elevated temperature showed higher permeability (Seishi Goto et al., 1981).

As a result of micro structural changes in concrete subjected to elevated temperature at early age can affect the mechanical properties of concrete as well. Figure 2 shows a test carried out to investigate the effect of high temperature generated at the core of a 2 m thick concrete block (insulated sides and top surface) on strength development. Grade 40 concrete with a cement content of 485 kg/m^3 was used to cast the concrete block. The maximum recorded temperature at the centre of the block was 78 °C. Concrete cubes were cast with the same concrete and cured in water whose temperature was matched with the in-situ temperature obtained at the centre of the concrete block using thermocouples placed in the concrete cubes. Figure 3 shows the compressive strength results of cubes cured in a curing tank where temperature was matched to the temperature at the centre of a 2 m thick block and cubes cured at room temperature. It clearly shows that even though the early age strength was greater in cubes subjected to high temperature than cubes cured at room temperature, there was a clear reduction in strength at 28 days when the concrete was subjected to elevated temperature even for few hours.

3. *Change of composition of hydrated products*

At high temperature (> 70 °C), ettringite (one product of hydration of cement), transforms to monosulphate at very early stage of hydration and once the concrete has hardened, under permanently or intermittently wet condition, monosulphate converts to ettrintgite. This is known as delayed ettringite formation (DEF). Since ettringite takes up more space than monosulphate from which it forms, the transformation is an expansive reaction causing cracking in concrete.

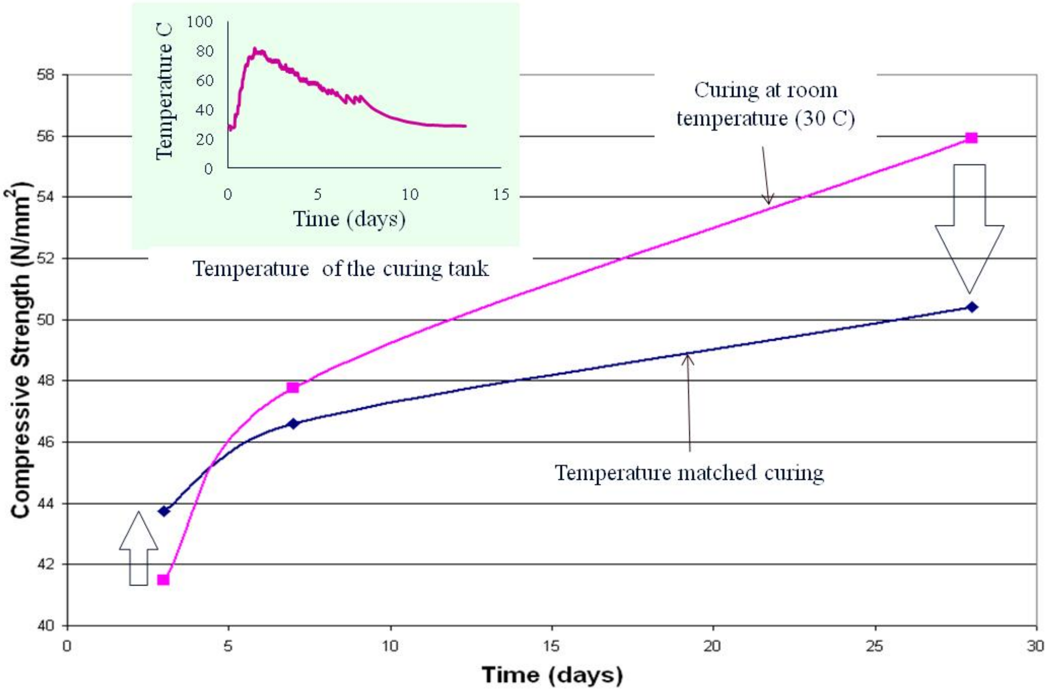


Figure 3 Effect of high temperature at early age on compressive strength development

3. DELAYED ETTRINGITE FORMATION

3.1 Previous reported cases

There are several reported cases of deterioration of in-situ as well as precast concrete mainly due to DEF in other countries. Lawrence et al. (1999) found that the main cause for premature deterioration of large number of precast concrete box beams in Texas was DEF. A study by Ceary (2007) found that DEF as the primary cause for deterioration of cast in situ elements of several bridges in Maryland. An investigation by Michael Thomas at el. (2008) revealed that sole cause for cracking of cast in situ bridge column in southern U.S.A. after 15 years of construction was due to DEF. There are several cases of cracking in in-situ concrete elements including abutments, wing walls, bridge beams and foundations owing to DEF have been identified in UK. They are of large sections (at least 600 mm) and were made using high cement content (~500kg/m3) (Hobbs, 1999).

3.2 Formation of Ettringite

Out of the four main compounds of cement, $2CaO.SiO_2$ (C_2S), $3CaO.SiO_2$ (C_3S), $3CaO.Al_2O_3$ (C_3A), $4CaO.Al_2O_3.Fe_2O_3$ (C_4AF), tricalcium alumunate (C_3A) is the one responsible for the formation of ettringite. When C_3A reacts with water in the presence of gypsum, the ettringite ($C_3A.3CaSO_4.H_{32}$) is formed. C_4AF also reacts with gypsum and produce ($C_3(AF).3CaSO_4.H_{32}$). These reactions are not only exothermic, like reactions of all other compounds in cement with water, but also create volume expansion. Since these reactions occur at very early stage of cement hydration, i.e. fresh stage of concrete, the volume expansion will not create any destruction. These reactions continue until all the available amount of calcium sulphate had been consumed. Under this condition, the ettringite formed initially reacts with additional amount of tricalcium aluminate to form monosulphate as the product of reaction (Hewlett, P. C., 1988). About 9.5 % gypsum (i.e. 4.4 % of SO_3) would be necessary, for example, to transform 5% C_3A fully into ettringite. However, in most of the cement standards limit the sulphate content to a maximum of 2.5 to 3 %, depending on the C_3A content of cement (SLSI 107). Therefore, monosulphate is always formed.

Ettringite is not a stable phase at high temperature and it converts to form monosulphate hyrdrate releasing sulphate ions if the early age temperature is higher than 70 °C (Taylor et al.,2001, Colleparadi, 2003). These sulphate ions will be absorbed into C-S-H gel which is the main product of hydration of C_2S and C_3S. Once the concrete has hardened, under permanently or intermittently wet condition, monosulpahte reacts with these sulphate ions and converts to ettrintgite. This is known as delayed ettringite formation (DEF). Since ettringite takes up more space than monosulphate from which it forms, the transformation is an expansive reaction causing cracking in concrete. This can be considered as a internal sulphate attack induced by exposure to heat. Therefore it was proposed at the International RILEM TC 186-ISA Workshop that DEF should be correctly known as “Heat Induced Internal Sulphate Attack" (Scrivener, 2005). According to Hobbs (reported in (Keith, 2001)), time of appearance of cracking due to DEF may vary from 2- 20 years depending on number of factors associated with cement composition, initial curing condition, design detailing, workmanship and exposure environment.

3.3 Mechanism of cracking due to DEF

One suggested mechanism is known as “Uniform Paste Expansion Theory”. According to this theory, expansion is taking place uniformly and isotropically in the paste phase since monosulphate is intimately mixed with C-S-H (S. Diamond, 1996, Taylor, 2001). Due to the expansion of paste phase a gap is created around aggregate particles. Subsequently ettringite and also $Ca(OH)_2$ recrystallises in these cracks and gaps around the aggregates (see Figure 4). However, this may not generate any significant expansive pressures (Diamond, 1996). Figure 5 clearly shows the formation of a rim around aggregate particle in DEF affected concrete sample supporting this mechanism.

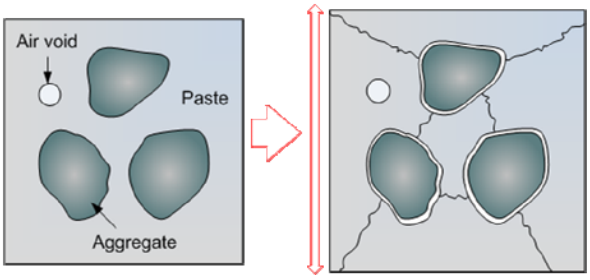


Figure 4 Diagrammatic representation of expansion of mortar or concrete by DEF (Taylor,

The other predominant theory with respect to DEF is “Ettringite Crystal Growth Theory”. According to this theory, expansion is attributed due to pressure exerted by the growing ettringite crystals in the micro cracks between cement paste and the aggregate. Since there is evidence to support both theories, both mechanisms may be possible and depending on the environmental condition one may be more prevalent. However, it should be noted that there is no agreement among researchers regarding the mechanism(s) for DEF and the cause(s) of expansion but all agreed that expansion is taking place in concrete subjected to high temperature at early age due to DEF.

If a thick concrete member is considered, only the core of the member is subjected to high temperature, more than 70°C. Therefore DEF is taking place in the core of the section causing expansion of the core which can produce cracks on the surface layer of thick concrete members as shown in Figure1.

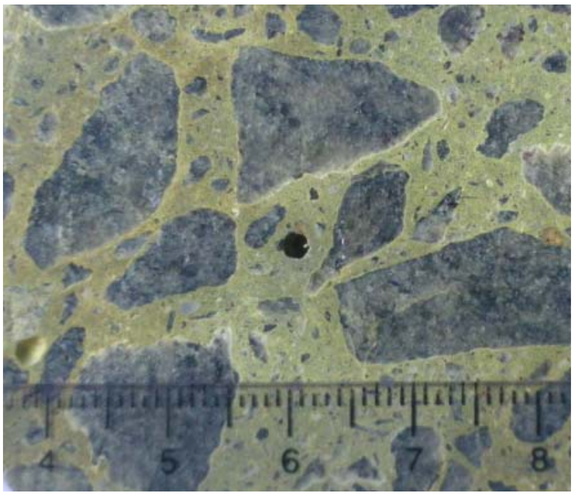


Figure 5 Formation of a rim around aggregate in DEF affected concrete

4. CONCLUDING REMARKS

Construction industry always prefers cement with accelerated early strength development without realizing the consequences of such cement. Because of the demand for such cements, cement manufactures adjusted their technologies to fulfill the market requirement. This was achieved by changing the composition of cement (increased amounts of C_3S and C_3A, increased amounts of sulphate and increased proportion of alkali sulphates) and increasing the fineness to accelerate early strength development (Aitcin, 2008). This has resulted in high temperature rise, leading to modification of microstructure and hydration chemistry which can affect mechanical properties and durability of concrete. Therefore it is important to control temperature rise of concrete with modern day cement, especially in construction of large structures.

In addition to the maximum temperature rise, temperature gradient across thick concrete section is also very important in controlling thermal cracking on the surface of the element. Full scale mock-ups are very useful for providing data on temperature profile for identifying the precautions needed to control temperature gradient. Apart from controlling the maximum temperature rise in concrete and composition of cement, use of fly ash or slag blended cement is effective in preventing most of the problems associated with temperature rise in concrete.

REFERENCES

Aitcin, Pierre-Claude, 2008, *Binders for durable and sustainable concrete,* Taylor & Francis, Milton Park, Abingdon, Oxon, 500 p.

Bamforth, P.B., Early-age thermal crack control in concrete, CIRIA C 660, 2007.

BS 8007:1987, Code of practice for Design of concrete structures for retaining aqueous liquids, BSI

Ceary M.S., 2007, Characterization of delayed ettringite formation in Maryland bridges, PhD Dissertation submitted to the Faculty of the Graduate School of the University of Maryland.

Colleparadi M, 2003, A state-of-the-art review on delayed ettringite attack on concrete, Cement & Concrete Composites, 25: 401-407.

Diamond S, Delayed Ettringite Formation, 1996, Processes and Problems, *Cement and Concrete Composites*, 18: 205-215.

Hewlett, P. C., 1988, *Lea's Chemistry of cement and concrete, Fourth edition*, Elsevier, 1057 p.

Hobbs, D.W., 1999, Expansion and cracking in concrete associated with delayed ettringite formation. In Ettringite – The sometimes host of destruction, Ed: Erlin, B. ACI Report SP-177, 1999. (Reported in Keith Quillin, 2001).

Keith Quillin, 2001, Delayed ettringite formation: in-situ concrete, *Information Paper, IP 11/01, BRE Centre for Concrete Construction*.

Lawrence B., Moody E., Guillemette R., Carrasquillo R., 1999, Evaluation and Mitigating Measures for Premature Concrete Distress in Texas Department of Transportation Concrete Elements, *Journal of Cement, Concrete and Aggregates(CCA),* Volume 21, Issue 1: 73-81.

M. Thomas, K. Folliard, T Drimals, T. Ramlochan, 2008, Diagnosing delayed ettringite formation in concrete structures, *Cement and Concrete Research,* 38:841-847.

Maekawa K., Chaube R., Kishi T., 1999, *Modelling of concrete performance - Hydration, Microstructure formation and Mass Transport,* E & FN Spon,308 p.

Sadananda Sahu, Niels Thaulow, 2004, Delayed ettringite formation in Swedish concrete railroad ties, *Cement and Concrete Research,* 34 :1675–1681.

Scrivener K., Skalny P., 2005, Conclusions of the International RILEM TC 186-ISA Workshop on Internal Sulfate Attack and Delayed Ettringite Formation, *Materials and Structures,* 38: 659-663.

Seishi Goto, Della M. Roya, 1981, The effect of w/c ratio and curing temperature on the permeability of hardened cement paste, *Cement and Concrete Research*, 11(4): 575-579.

Taylor HFW, C Famy, KL Scrivener, 2001, Delayed ettringite formation, *Cement and concrete research,* 31: 683-693.