EVALUATION OF FACTORS PERTAINING TO DELAYED ETTRINGITE FORMATION IN STEAM CURED PRECAST CONCRETE MEMBERS

JOHNSON MAK, KIRK VESSALAS, PAUL THOMAS,
Centre for Built Infrastructure Research, University of Technology, Sydney

DAKSH BAWEJA,
Engineered Material Solutions, Sydney

SUMMARY

Precast prestressed concrete structural beam elements are widely used in infrastructure projects to achieve design efficiencies. Such beams are produced under tight manufacturing requirements where early age concrete strength criteria are paramount to facilitate early age stress transfer between tendons and the concrete. Concrete for such applications requires a relatively high binder content and the application of steam curing. Due to the high heat and therefore high temperatures generated within the sections, concerns have been expressed as to the risk of delayed ettringite formation (DEF) in the concrete. The implicit factors relating to probable occurrence of DEF in precast concrete elements are examined and applied to the determination of the susceptibility of precast concrete members to DEF. The main factors contributing to DEF identified include the chemical composition of cement used in mix design, in particular, the SO$_3$ content, SO$_3$/Al$_2$O$_3$ molar ratio and Na$_2$O equivalent, the use of supplementary cementitious materials (SCMs), the temperature profile applied during steam curing process of member and the moisture exchange of the member whilst in service. Based on limits associated with these factors, T-Roff girders were analysed in this paper and are concluded to have low susceptibility to DEF; a combination of low SO$_3$/Al$_2$O$_3$ molar ratio of 0.45, low SO$_3$ content of 0.23%, low Na$_2$O equivalent of 0.5% in cement and the use of 25% fly ash reduces the susceptibility to DEF. The relatively high curing temperature (up to 90°C) used initially in manufacture caused some concern for DEF at later stages. However, it is known that a combination of all factors is required for DEF and, therefore, susceptibility of DEF in girders is assessed to be low or mitigated.
INTRODUCTION

In order to develop the high concrete strength requirements for achieving stress transfer in precast concrete beams (typically 40 MPa) accelerated curing at elevated temperature is carried out. The use of high temperatures in curing can lead to the phenomenon known as delayed ettringite formation (DEF) which is associated with high curing temperatures which are exacerbated by the heat produced during the hydration of the binder.

DEF is known to cause volumetric expansion in concrete leading to cracking and spalling of a member and, hence, a compromise in structural integrity (Sahu & Thaulow 2004). This poses not only a safety concern but also a concern financially in terms of repair costs given that the beams are required to have a design life of 100 years. In this paper, an overview of theory of DEF in concrete members is described. The factors influencing DEF in concrete members are discussed and used to estimate the susceptibility of DEF in precast concrete members cured at elevated temperature. The susceptibility of DEF in the girders used for the manufacture of beam elements used in typical infrastructure projects is summarised based on the analysis presented.

THEORY OF DEF

DEF is not a well understood phenomenon due to the complexity associated with hydration in the cementitious system within the concrete matrix. The probable mechanisms of DEF formation and factors contributing to DEF have been described in the literature; however, conjecture amongst researchers on issues such as crystal growth theory (Cohen 1983) and swelling theory (Mehta 1973) can be found. Ettringite belongs to the family of alumina ferric oxide trisulfate (AFt) phases and is defined as a crystalline calcium sulfoaluminate hydrate product of Portland cement (PC) hydration with a general formula of 3(CaO)∙Al₂O₃∙3CaSO₄∙32H₂O. Ettringite has a needle-like crystal structure with Figure 1 showing synthetically prepared ettringite crystals viewed under scanning electron microscopy (Bollmann & Stark 1997).

It is important to differentiate between early ettringite and delayed ettringite formation as this can have an impact on precast concrete beam manufacture. Early ettringite formation (EEF) is a normal hydration product of PC and is usually formed homogeneously within hours of hydration (during the plastic state). This form of ettringite is not considered to be deleterious whether in the expansive or non-expansive form as the plastic state of the paste is able to

Figure 1 – Needle Like Ettringite Crystals (Bollmann & Stark 1997)
accommodate volumetric expansion. Early ettringite formation has been reported by Taylor (2009) to be beneficial by acting as a retarder when gypsum (CaSO$_4$·2H$_2$O) reacts with anhydrous calcium aluminate (3(CaO)·Al$_2$O$_3$) during the hydration process resulting in EEF:

$$3(CaO)·Al_2O_3 + 3(CaSO_4·2H_2O) + 26 H_2O \rightarrow 3(CaO)·Al_2O_3·3CaSO_4·32H_2O$$

(1)

Yan et al. (2004) noted that the expansive properties of EEF can be beneficial to concrete by providing compensation for deformation resulting from early age shrinkage effects. Early ettringite can decompose if the conditions are favourable, and reform at a later stage during the hardened state resulting in DEF. DEF can be a cause of deterioration of the concrete matrix due to volumetric expansion. It is formed heterogeneously and distributes itself, most commonly, in crack tips that exist from the presence of microcracking. Importantly, DEF may not necessarily result in deterioration as DEF may be expansive or non-expansive, the former being a durability concern and the latter considered benign.

DEF can further be classified in two areas depending on the sulphate source. Internal sulphate attack (ISA) arises when the sulphate contained within the PC or aggregate contributes to the DEF. In contrast, external sulphate attack (ESA) contributes to DEF by sourcing sulphate from the environment such as soil and ground water encasing the in-situ member. In this investigation, expansive DEF with a sulphate sourced internally (i.e. from within the concrete itself) will be the focus of attention.

**FACTORS INFLUENCING DEF**

In order for precast concrete to achieve high early strength, the application of high temperature curing and the manipulation of binder composition and properties are required. However, the application of a heat treatment and the modification of the binder composition may lead to an increase in the susceptibility to DEF. As the mechanisms of DEF are complex and in dispute in the literature, a simplistic approach to DEF prediction based on key factors in the manufacture of precast concrete elements is used to assess susceptibility of a precast concrete member to DEF. Factors that are deemed to contribute to DEF have been classified in three separate categories as primary, secondary and tertiary factors. Primary factors encompass the mix design of the precast concrete, that is, composition and physical properties of the raw material components and the composition of the binder used to produce the concrete. Secondary factors relate to the manufacturing technique employed, with the most significant factor being the temperatures attained within a precast concrete element during steam curing. Tertiary factors include the serviceability of the concrete, that is, the environment in which the precast concrete is placed in-service including exposure to moisture. The primary and secondary factors are part of manufacturing control and will be the principal focus of this investigation for conceptualising the susceptibility to DEF. Table 1 summarises the key factors contributing to DEF in descending order of their significance.

**Primary Factors Influencing DEF**

The formation of ettringite (3(CaO)·Al$_2$O$_3$·3CaSO$_4$·32H$_2$O) requires the release of calcium, aluminium and sulphate ions into micropore waters. As aluminium and calcium ions are released into the pore waters during the PC hydration processes, the role of sulphate ions has been identified as the most important controllable factor (Tosun 2006; Zhang et al. 2002a; Lawrence 1995). Sulphate is a key ingredient for the formation of ettringite; hence, composition limits have been imposed by manufacturing standards. AS3972 2010 has limit of 3.5% sulphate by weight as an example. Sulphates present in PC can be broadly categorised into two types:
2004 high alkali content (>1%) also may recrystallise conversely, if the alkali is leached alkali content governed by the alkali influenced assumptions made by the Bogue’s method made in the Bogue’s manufacturing process for example, has been reported to influence the proportion of oxide components (e.g. in B)

The range of

however, have been reported in the literature (For example, Heinz & Ludwig 1987, Heinz et al. 1989), although lower ratios have also been reported (Tracy et al. 2004).

The Al₂O₃ content and availability also plays an important role in DEF. Al₂O₃ is mostly sourced from the hydration of C₃A present in cement. For ettringite formation to occur, the appropriate stoichiometric SO₃/Al₂O₃ ratio is required. A range of minimum SO₃/Al₂O₃ ratios, however, have been reported in the literature for DEF susceptible cements: SO₃/Al₂O₃ molar ratio exceeding 0.7 and a (SO₃)²/Al₂O₃ molar ratio exceeding 2.0 has been reported to be necessary for DEF (Heinz & Ludwig 1987, Heinz et al. 1989), although lower ratios have also been reported (Tracy et al. 2004).

The range of SO₃/Al₂O₃ ratios indicating susceptibility to DEF may result from shortcomings in Bogue calculations (AS2350.2 2006 and ASTM C114-11b 2001) which do not take minor oxide components (e.g. magnesium oxide) and the alkali content into account. Alkali content, for example, has been reported to influence the proportion of C₃A generated in the clinker manufacturing process thus affecting the availability of Al₂O₃ (Horkoss et al. 2011). The assumptions made by the Bogue’s method may, therefore, give an inaccurate representation of the available C₃A and, hence, result in an incorrect indication of the susceptibility for DEF.

The solubilities of sulphates, in particular ettringite, affecting the propensity to DEF is also influenced by the pH of the pore solution (Collepardi 2003). The pH of the pore solution is governed by the alkali (Na₂O and K₂O equivalent (AS2350.2 2006)) content. An increase in alkali content (increase in pH) will lead to an increase in the solubility of ettringite. Conversely, if the alkali is leached (resulting in a drop in pH) from the concrete, ettringite may recrystallise and induce deterioration of a concrete member due to DEF. ASTM150/C150M (2012) specifies that the alkali content in PC should not exceed 0.6% as a high alkali content (>1%) also exacerbates cracking caused by drying shrinkage (Tracy et al. 2004) and in the presence of a reactive aggregate may also cause the alkali silica reaction (ASR) resulting in microcracking (Ichikawa 2009). The formation of microcracks will increase

<table>
<thead>
<tr>
<th>Primary Factors</th>
<th>Secondary Factors</th>
<th>Tertiary Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. SO₃ content and SO₃/Al₂O₃ molar ratio</td>
<td>1. Elevated temperature curing</td>
<td>1. Exposure to moisture</td>
</tr>
<tr>
<td>2. Na₂O equivalent</td>
<td>2. Microcracking</td>
<td>2. Sulphate attack from the environment</td>
</tr>
<tr>
<td>3. SCM (chemical composition of SCM)</td>
<td>3. The geometric design of concrete</td>
<td></td>
</tr>
<tr>
<td>4. C₃A and C₃S content</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Binder fineness/ specific surface area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. MgO content</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Water:Binder ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Aggregate type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Use of admixtures</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) Added sulphates – such as gypsum, hemihydrate and anhydrite
2) Clinker sulphates – such as arcanite, aphaltalite, calcium langbeinite, and thenardite

Aggregates may also be contaminated with sulphates increasing the total sulphate content of the concrete (Hime 1996). In general, added sulphates such as gypsum dissolve rapidly and contribute to EEF whereas clinker sulphates are relatively insoluble and are unavailable for EEF, but may contribute to DEF (Collepardi 2003, Tosun 2006). As a result, cements and concretes with the same reported SO₃ content may have significantly different susceptibilities to DEF.

Table 1 – Primary, Secondary and Tertiary Factors Directly Influencing DEF (shown in descending order according to significance level)
the permeability of a concrete member accelerating DEF as it facilitates the diffusion of the reactant ions (\(\text{Ca}^{2+}, \text{Al}^{3+}\) and \(\text{SO}_4^{2-}\)) required for DEF.

The use of supplementary cementitious materials (SCMs) such as Class F fly ash (ASTM C618 2012) has been reported to significantly reduce or inhibit DEF when greater than 20% is used for partial replacement of PC in precast concrete subjected to a curing temperature >70°C (Ramlochan et al. 2003). SCMs such as fly ash exhibit a wide range of chemical compositions and physical shape and size. Under the specifications for Class F fly ash, the fly ash may contain up to a 5% \(\text{SO}_3\) content and the \(\text{Al}_2\text{O}_3\) content is typically 25% suggesting a potential source of aluminium and sulphate ions for DEF. The fineness of the fly ash, however, decreases pore size through a pore blocking mechanism resulting in a denser less permeable structure reducing the potential for DEF (Chindaprasirt et al. 2007).

### Secondary Factors Influencing DEF

DEF has been related to the curing of precast concrete elements at elevated temperatures (circa >70°C) (Tosun 2006, Escadeillas et al. 2007, Yang et al. 1999, Barbarulo et al. 2005, Skalny et al. 2002). The significance of heat curing has led to the term “heat-induced internal sulphate attack” to describe DEF specifically in heat cured precast concrete elements (Leklou et al. 2009) and is exacerbated by the heat of hydration of the \(\text{C}_3\text{A}\) and \(\text{C}_2\text{S}\) present for early age strength (Hooton et al. 2005).

The temperature has a significant influence on the early cement hydration with respect to the formation of the C-S-H gel and the formation of EEF (Barbarulo et al. 2007, 2005). The first reaction involves the hydration of \(\text{C}_3\text{A}\) resulting in the crystallisation of early ettringite due to the presence of sulphate ions from the rapidly dissolving gypsum which is responsible for early set. The second reaction involves hydration of \(\text{C}_2\text{S}\) resulting in the formation of the calcium-silicate-hydrate (C-S-H) gel, which is responsible for the strength of the binder. The EEF is effectively inhibited at elevated temperatures due to the increased solubility of the sulphates and as ettringite is thermally unstable above circa 70°C, although the exact temperature at which ettringite decomposes is under debate (Taylor et al. 2001). There are several pathways for the mechanisms of decomposition of ettringite. To generalise, the three major pathways are:-

1. Sulphate ions from the dissolution of ettringite is adsorbed on the C-S-H gel
2. The conversion of ettringite to the AFm phase (e.g. monosulfate)
3. The conversion of ettringite to meta-ettringite

The solubility of ettringite increases with temperature resulting in the dissolution of the ettringite and the adsorption of the sulphate ions onto the C-S-H gel (Barbarulo et al. 2007). The adsorption of sulphate ions on the supersaturated C-S-H gel is, however, a reversible reaction. The C-S-H gel acts as a buffer for sulphate ions that are subsequently released under favourable conditions or as the temperature returns to ambient post cure and in service. The release of sulphate ions is a slow process and allows for the slow crystallisation of ettringite in the DEF process (Barbarulo et al. 2007). The sulphate ions are released into the pore solution during the hardened state of the concrete. The sulphate rich pore solution is then able to diffuse to sites with free aluminate and calcium ions within the concrete matrix and results in the preferential nucleation of ettringite at crack tips resulting in cracking of the concrete.

Other sulphate ion sources such as gypsum may also be adsorbed. It has been shown (Fu et al. 1995) that sulphate adsorption in the C-S-H gel is significantly increased at a critical temperature of 70 °C resulting in the rapid depletion of gypsum and the supersaturation of sulphate in the gel which effectively inhibits EEF. Ettringite may also be converted to the
alumina ferric oxide monosulfate (AFm) phase. Calcium monosulfoaluminate (henceforward referred to as monosulfate) which is the most prominent representative of the AFm phase is formed as it is more stable than ettringite at elevated temperatures (Shimada & Young 2004). The reaction of ettringite to monosulfate is shown in Eq. (2).

\[
3(\text{CaO})\cdot\text{Al}_2\text{O}_3\cdot3\text{CaSO}_4\cdot32\text{H}_2\text{O} \rightarrow 3(\text{CaO})\cdot\text{Al}_2\text{O}_3\cdot\text{CaSO}_4\cdot12\text{H}_2\text{O} + 2(\text{CaSO}_4\cdot2\text{H}_2\text{O}) + 16 \text{H}_2\text{O} \tag{2}
\]

The reaction of ettringite to monosulfate is a reversible reaction. The reformation of ettringite may, therefore, occur when the concrete is cooled down to ambient temperature.

At extreme temperatures above 100°C, ettringite can be converted into meta-ettringite; partially dehydroxylated products of ettringite (products with variable stoichiometry for the hydrate) (Zhou & Glasser 2001, Zhou et al. 2004). The decomposition of ettringite is a stepwise process and the hydrated water content can range from 30 to 10 water molecules in the structure. Meta-ettringite can reform as ettringite at ambient temperatures and can induce damage due to DEF.

Although curing temperature is known to play a critical role in DEF, the use of elevated temperature curing is only one feature which is responsible for the heat required to cause the reactions described. The initial hydration reaction of the binder also contributes to the evolved heat resulting in significantly higher temperatures in the core of precast concrete element increasing the susceptibility to DEF.

Tertiary Factors Influencing DEF

The in-service environment has a great impact on the susceptibility of DEF in a concrete member. The exposure of a precast concrete element to moisture is a critical factor for DEF (Sahu & Thaulow 2004, Bouzabata et al. 2012). Bouzabata et al. (2012) reported that concrete members immersed in water showed greatly accelerated the DEF. Similarly, Sahu & Thaulow (2004) reported, in a case study on precast railway ties, that only ties which were exposed to moisture expanded and developed cracks due to DEF. In addition, the members that were exposed to a dynamic water supply (i.e. the renewal of storage water) contributed to a more rapid and increased expansion. Shimada & Young (2004) suggested that acceleration of DEF due the leaching of alkali under dynamic water supply as the solubility of ettringite reduces at a lower alkalinity occurs. Additionally, ground waters can also be an external source of sulphate ions (ESA) resulting in DEF (Zhang et al. 2012, Sarkar et al. 2010, Haynes et al. 1996).

Microcracking in a precast member is also a concern for the susceptibility to DEF due to the increased permeation of water in the concrete element (Diamond 2000). Microcracking can be caused by ASR or thermal shock, freeze-thaw cycling and dynamic loading with the subsequent DEF occurring at on the crack tips aiding crack propagation through volume expansion. Microcracking as a prerequisite for DEF is, however, controversial (Petrov & Tagnit-Hamou 2004) and a study by Fu & Beaudoin (1996) indicated that the presence of microcracking provides sufficient volume for the accommodation of the expansion from DEF removing deleterious volume expansion.

SUSCEPTIBILITY OF STEAM CURED CONCRETE MEMBERS TO DEF

A number of factors are important in contributing to DEF, but there is conjecture on the threshold limits of some factors such as the $\text{SO}_3$ content. It is also apparent that as the concrete environment is a complex heterogeneous system, a single factor by itself does not
accurately predict the susceptibility to DEF. Kelham (1996) and Zhang et al. (2002b) have both attempted to rationalise these factors and determine a DEF index to predict the susceptibility to DEF based on binder composition, in particular, key factors such as SO$_3$ content, SO$_3$/Al$_2$O$_3$ molar ratio and Na$_2$O equivalent content. However, these methods have yielded limited success as they only approximate the hydrating cement environment. The current testing methods available (such as the autoclave expansion test in accordance with (ASTMC151/C151M 2009)) for qualifying DEF in concrete members are also ineffective. Features such as expansion and cracking are often interpreted as DEF, even though they may be caused by other factors such as ASR. In addition, microscopic techniques may incorrectly qualify that DEF has occurred due to the presence of ettringite formed around crack tips. Prudence is, therefore, required when interpreting ettringite as a normal hydration product and whether the ettringite observed is in fact responsible for contributing to the deterioration of the concrete in the first place.

Therefore, for the assessment of the susceptibility of a concrete to DEF, a conservative estimate of the chemical and physical limits for DEF need to be established until the processes involved in DEF are better understood. For this initial analysis of the susceptibility of the concrete composition and curing conditions used in the manufacture of T-Roff girder sections, the following conservative limits for DEF susceptibility were used.

- In order to minimise the decomposition of and promote EEF (which is likely to recrystallise as DEF resulting in DEF related failure) curing temperatures of <70°C should be used.
- In order to minimise the potential for DEF:
  - the SO$_3$ content of the concrete element should be 3.5% by weight,
  - the [SO$_3$/Al$_2$O$_3$] ratio < 0.7 and
  - the [SO$_3$]/[Al$_2$O$_3$] < 2.0.

**EVALUATION OF THE SUSCEPTIBILITY OF STEAM CURED CONCRETE ELEMENTS TO DEF**

In this study, data collected from a pretensioned precast concrete T-Roff girder used for construction in a major Australian project were analysed for the susceptibility to DEF. Typical dimensions of the girders are 1,500H x 20,000L x 1,000D mm. A schematic cross section of the girder is shown in Figure 2 listing the dimensions and the location of the pretension strands. The girders were steam cured by raising the curing tank temperature to 65°C). The total duration of curing was 18 hours and included 2.5 hours of pre-cure at ambient temperature followed by steam heating at a heating rate of 25°C per hour for 1.5 hours followed by an isotherm at 55°C for 9 h before natural cooling to ambient temperature. The girder was then taken out of the curing tank and removed from the mould.

The chemical composition and physical properties of the PC used in the concrete mix design of the girders shown in Table 2 are compared with the limits outlined above for susceptibility to DEF. The binder fineness was calculated with the Blaine method while the C$_3$A and C$_3$S contents were calculated using the Bogue’s method. All chemical composition calculations were reported in accordance with (AS2350.2 2006). The SCM content and its chemical composition are shown in Table.
Table 2 – Concrete girder PC composition.

<table>
<thead>
<tr>
<th>Component</th>
<th>Cement/Concrete Property</th>
<th>Proposed DEF Model Threshold Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement Type</td>
<td>AS3972 2010 Type SL GP</td>
<td></td>
</tr>
<tr>
<td>Cement fineness (m²/kg)</td>
<td>350</td>
<td>&lt;420</td>
</tr>
<tr>
<td>CaO</td>
<td>64.4</td>
<td>N/A</td>
</tr>
<tr>
<td>SiO₂</td>
<td>19.6</td>
<td>N/A</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>5.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>3.5</td>
<td>N/A</td>
</tr>
<tr>
<td>C₃A (Bogue’s)</td>
<td>7.7</td>
<td>&lt;8</td>
</tr>
<tr>
<td>C₃S (Bogue’s)</td>
<td>63.9</td>
<td>&lt;58</td>
</tr>
<tr>
<td>SO₃</td>
<td>2.3</td>
<td>&lt;3.5</td>
</tr>
<tr>
<td>MgO</td>
<td>1.04</td>
<td>&lt;4.5</td>
</tr>
<tr>
<td>Na₂O equivalent</td>
<td>0.5</td>
<td>&lt;0.6</td>
</tr>
<tr>
<td>SO₃/Al₂O₃ molar ratio</td>
<td>0.45</td>
<td>&lt;0.7</td>
</tr>
<tr>
<td>(SO₃)²/Al₂O₃ molar ratio</td>
<td>1.04</td>
<td>&lt;2.0</td>
</tr>
<tr>
<td>w/c ratio</td>
<td>0.39</td>
<td>&lt;0.4</td>
</tr>
</tbody>
</table>

Figure 2 – Typical T-Roff Girder Section
Table 3 – Fly ash composition.

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly ash % in Binder</td>
<td>25</td>
</tr>
<tr>
<td>CaO</td>
<td>4.5</td>
</tr>
<tr>
<td>SiO₂</td>
<td>51.3</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>24.6</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>12.7</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.3</td>
</tr>
<tr>
<td>MgO</td>
<td>1.8</td>
</tr>
<tr>
<td>Na₂O equivalent</td>
<td>1.04</td>
</tr>
</tbody>
</table>

The temperature at various points in the girder and in the curing tank were monitored during manufacture for the steam curing process and are schematically shown in Figure 3 where the cross section of the precast girder is represented by the cylindrical shape and the points A to E represent the location of the installed thermocouples. The descriptions of the locations of the thermocouples corresponding to the thermocouple temperatures listed in the legend in Figure 4 are:

- Core temperature “A” – Core Temp1: the centre most point of the cross section of the girder.
- Surface temperature “B” – 100 mm below the surface at any point (one or more thermocouples have been used)
- Steam zone “C” – temperature of the steam jets, up to 6 steam zone thermocouples have been used
- Curing tank “D” – internal temperature of the curing tank
- Ambient temperature “E” – external temperature of the curing tank

A maximum core temperature of 90°C and a maximum surface temperature of 80°C was reached during the manufacturing process. These temperatures are above the limit of stability for EEF suggesting that there is a potential for DEF especially if the chemical conditions, in particular, the sulphate ion concentrations present, are conducive to the formation of DEF. Therefore, the susceptibility to DEF must be determined from the limits of chemical composition, in particular, the sulphate ion concentration.

The absolute SO₃ content of 2.3% for the shrinkage limited PC (Table 2) is below the threshold limit of 3.5% suggesting that the cement used does not have the sulphate present to initiate DEF. The partial replacement of 25% fly ash, however, alters the chemical and physical composition of the binder (Table 3). A SO₃ content of 0.3% will result in a reduction of the sulphate content. FA also contains 24.6% Al₂O₃. This alumina, however, is unreactive and tightly bound in the aluminosilicate network so is considered to not contribute to the aluminium ions in solution. The susceptibility of the precast girders may, therefore, be estimated from the from the SO₃ and Al₂O₃ content of the PC (Table 3). Inspection of Table 2 suggest that despite the elevated core temperature of the girder in manufacture, the low SO₃ content of the PC suggests a low potential for DEF.
Figure 3 – Schematic representation of the curing tank containing the girder indicating the thermocouple locations.

Figure 4 – Typical temperature profile recorded during girder manufacture.
CONCLUSIONS

There are many factors affecting DEF. A conservative and simplified approach was applied primarily focusing on the sulphate (SO₃) content of the concrete as a low sulphate content is linked to a low potential for DEF. The concrete used in the girder investigated contained a sulphate content far below the estimated limits suggesting that these girders are not likely to be susceptible to DEF. However, it should be noted that the cement environment is complex and there is much contradictory data reported in the literature. In order to confirm these preliminary findings and to develop an understanding of the processes involved an investigation into DEF has been instituted.

ACKNOWLEDGEMENTS

Work presented in this paper is being conducted at the University of Technology in Sydney, Australia with support from Humes, a division of Holcim Australia. The authors acknowledge the support of Brett Beaver, Concrete Material Technologist for Humes in providing the support information used in this publication.

REFERENCES

AS2350.2 2006, Methods of testing portland, blended and masonry cements Method 2: Chemical composition, Standards Australia Limited, Australia.
ASTMC618 2012, Standard Specification for Coal Fly Ash and Raw or Calcinated Natural Pozzlan for Use in Concrete, ASTM Standards, United States.


Zhang, Z., Olek, J. & Diamond, S. 2002b, 'Studies on delayed ettringite formation in heat-cured mortars: II. Characteristics of cement that may be susceptible to DEF', *Cement and Concrete Research*, vol. 32, no. 11, pp. 1737-42.
