Cement & Concrete Composites **18** (1996) 157–159

Guest Editorial

In recent years, a number of failures of concrete products precast at elevated temperatures have been reported. They have been characterised by cracking after some years of service in environments exposed to the weather, and have occurred notably, though not exclusively, with railway sleepers. Petrological and SEM investigations have shown the presence of abundant ettringite at paste–aggregate boundaries and elsewhere. The pioneering work of Ludwig and his collaborators,[1–3] confirmed by other investigators, has shown that any ettringite formed prior to curing at temperatures of or above about 70°C is destroyed during the heat treatment, and that the damage is associated with the formation, or reformation of this phase during the subsequent service at ambient temperature. The term 'delayed ettringite formation', or DEF, is widely taken to denote this phenomenon, but some investigators, including some contributing to this issue, have used it more widely, to include the late formation of ettringite in material that has been cured at ordinary temperature.

I am grateful to Professor Swamy for his invitation to edit this issue of *Cement and Concrete Composites*, in which some aspects of DEF are addressed. One of these concerns the part played by the aggregate. Studies on deteriorated field concretes in which DEF has been detected have shown that this effect is very often accompanied by alkali silica reaction (ASR). Shayan and Ivanusec describe the results of a laboratory investigation on the association between the two effects. Mortars cured at 75°C and subsequently stored at 40°C expanded significantly only if the alkali content and aggregate were such as to have produced ASR, in which case DEF augmented the expansion. These results accord with the observations on field concretes and also with those of Diamond and Ong,[4] who found that a limestone mortar did not expand significantly after curing at 95°C. However, if reactive silica was added to the mix, marked expansion occurred, initially from ASR, and was later exacerbated by the effect of DEF. The expansion from DEF was attributed largely to the deposition of ettringite in ASR-induced cracks.

The effect of varying the cement is examined in the papers by Kelham, Odler and Chen, and Glasser. Kelham reports expansion data for mortars made with five different clinkers and various combinations of SO_3 content, sulfate source and added KOH or K_2SO_4. No expansions were observed with a sulfate resisting clinker, but there was little difference in behaviour between the other clinkers. Expansions increased notably with fineness of grinding and on addition of alkali, whether as KOH or as K_2SO_4, and passed through a maximum at 4% SO_3. Kelham noted that the main effects that increase expanson are all ones that increase early strength. Other workers have offered explanations of the effects of SO_3 and of alkali, but the effect of fineness has received less attention. Among hypotheses that deserve exploration may be mentioned the effects on DEF of the degree of hydration during the elevated temperature curing.

Odler and Chen studied expansion and ettringite contents in pastes made from four different cements that had been cured at 90°C and subsequently stored at ambient temperature. Significant expansion occurred only with a cement that was high in both SO_3 (4·9%) and C_3A. Kelham similarly found that expansion increased with these quantities separately (up to 4% in the case of SO_3). These results contrast with earlier conclusions that expansion increases with the ratio of SO_3 to Al_2O_3 or of $(SO_3)^2$ to Al_2O_3 present in C_3A.[2,3] Odler and Chen's results are also of interest in showing that expansion takes place with pastes, as well as with mortars or concretes, though more slowly than in the latter cases. Lawrence[5] has also found this.

Glasser approaches DEF mainly from the standpoint of thermodynamic modelling and pore fluid analysis. His results provide explanations both of the existence of a pessimum SO_3 content and of the increase in expansion with alkali content. An important point noted is that the commonly observed disappearance of ettringite at temperatures above about 70°C does not necessarily imply thermodynamic instability; in fact, ettringite remains stable up to about 100°C, and its disappearance at lower temperatures is due to increasing solubility. This accords with an earlier observation by Heinz and Ludwig.[2] In his conclusions, he draws attention to several areas requiring further investigation and concludes that the best guidance for avoiding DEF in concrete cured at elevated temperatures is to use a low alkali cement or perhaps one that releases its alkali only slowly, with the lowest practicable curing temperazture, and to limit the contents of Al_2O_3 or SO_3 or both.

Kuzel reports new experimental work confirming and extending earlier findings that monosulfate in cement pastes react with CO_2 or CO_3^{2-} to form ettringite and hemi- or monocarbonate. Some 0·5% of CO_2 in the cement sufficed to complete the conversion. This observation almost certainly explains the fact that, while laboratory studies on cement pastes commonly show that the ettringite formed during early hydration is subsequently replaced by monosulfate, petrographic and SEM studies on field concretes, both sound and otherwise, commonly show the presence of ettringite. Kuzel found that, if a paste made from cement almost free from CO_2 and protected from CO_2 during hydration was subsequently exposed to CO_2, ettringite was formed; calcite was only detected when carbonation had proceeded further. He considered that damage in field concretes through this reaction was a theoretical possibility, but that it was probably unlikely to occur unless the concrete had been cured above 80°C, thereby forming monosulfate; commercial cements were normally high enough in CO_2 to ensure the formation of ettringite if hydration occurred at lower temperatures.

Diamond's paper deals mainly with two issues that may prompt considerable discussion. First, he reports that microstructural features identical to those seen in deteriorated concretes that have undergone DEF following steam curing may also be seen in ones that have not been steam cured. He concludes that damage from DEF can occur in normally cured concrete, and considers that this can often be attributed to high contents of SO_3 (4–5%) in the cement and, more specifically, in the clinker. The second issue discussed by Diamond concerns the mechanism of expansion from DEF. He presents evidence in support of the view that expansion and cracking from this cause are caused by local and inhomogeneous crystal growth pressures and not, as some others have proposed, by uniform expansion of the paste. Shayan and Ivanusec also discuss this question.

Among questions raised by Diamond's paper that deserve further investigation the following may be mentioned:

(i) Is 4–5% of SO_3 in a cement sufficient to produce expansion in a normally cured concrete, and, if so, how quickly does that expansion occur? Data reported by Kelham in this issue indicate that it is not.
(ii) In clinkers with high SO_3 contents, such as those mentioned by Diamond, in what phase(s) is the sulfate present and how quickly is the sulfate released during hydration?
(iii) Is the presence of ettringite in cracks, etc., evidence that the growth of that ettringite has either initiated or expanded those cracks?

Further studies on these questions would be of much interest.

It remains for me only to thank all the authors who have contributed to this issue.

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