OPEN FORUM
PROBLEMS AND SOLUTIONS

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Delayed Ettringite Formation

Q1: *What is Delayed Ettringite Formation (DEF)?*

A1: Ettringite is the common name for calcium sulfoaluminate hydrate ($3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$), which is produced in all portland cement systems during the early period of hydration from the reaction of the calcium aluminates (C_3A) in the cement with sulfate. If the ettringite formation is delayed until after the concrete has hardened, it may cause expansion and subsequent cracking when exposed to moisture. Delayed ettringite formation (DEF) refers to the development of ettringite within the cement paste system of concrete *after* the concrete has hardened. In many ways, DEF is similar to other forms of sulfate attack that were recognized over 50 years ago; however, for DEF, the source of sulfate is internal, not external, and not the result of using a blend of gypsum or plaster with cement. Researchers have stated that the formation of DEF is related to many factors, including the environment, the cement, the aggregate type, and the curing conditions.

Q2: *How frequent is the DEF problem?*

A2: Despite over 500 papers being written on the topic, it is believed that deterioration of concrete due to DEF is not common. In 1989, severe and rapid deterioration of precast concrete railway ties on the North East Corridor railway line was found, resulting in replacement of the concrete ties between New York and Washington, D.C. DEF has also been observed in Europe, South Africa, and Australia. DEF has occurred in both cast-in-place and precast concretes, and will only happen if sufficient water is present to cause the deleterious later-age expansive reactions. Recently in Texas and Iowa, deterioration of concretes owned by state transportation agencies was observed and the causes were attributed to similar reasons to those described above. However, it is important to note that the Texas DOT reported only seven possible DEF cases out of 40,000 bridges inspected.

Q3: *Why has DEF only recently become a cause for concern?*

A3: There are several reasons why DEF has only recently become a cause for concern. It is believed that changes in portland cement materials have had a major effect on the potential for DEF. A significant amount of research has found that the cement chemistry plays a major role in the risk of DEF. It is also known that fuels and processing used in the manufacture of cement have changed over the last 20 to 30 years. The requirements of early age strengths have led to the use of finer-grained cements. On average, the sulfate (SO_3) and alkali contents of cements have increased. In general, the cement contents of precast concrete have increased and the water-cement ratios have decreased. High-range water-reducing admixtures, which may contain sulfate-containing compounds, are also being used more frequently in precast and cast-in-place concrete. It is also possible that prior cases of DEF were misidentified in the past as other deterioration mechanisms, such as alkali-silica reactivity. However, the more recent use of the scanning electron microscope with attachments that allow identification of atoms in crystals has significantly reduced the possibility for error.

Q4: *What are PCI and others doing about DEF?*

A4: PCI has been aware of the issues surrounding DEF for the last 3 years. Since then, PCI and others have published several papers on the topic and have been involved in discussions with transportation agencies and the Portland Cement Association (PCA). In addition to these discussions, PCI is currently funding a research program by Wiss, Janney, Elstner Associates, Inc. (WJE) to investigate effects of curing temperatures on DEF for cements with different chemistries. This work will investigate the potential for incomplete conversion of sulfate to ettringite, or the decomposition of ettringite, for concretes cured at different temperatures and the potential expansion of the concretes.

Q5: *In the meantime, what common sense rules should precast producers follow to prevent DEF?*

A5: There are three general areas of concern to those involved with the purchase, material supply, and manufacture of concrete:

- Complete curing cycle of the concrete including preset
- Cement chemistry
- Synergism with aggregates

It has been stated by some that the primary cause of DEF is "excessive" heat curing, resulting in the decomposition of the ettringite that is initially produced in portland cement systems during the early 24-hour period of hydration. Subsequently, if the concrete is exposed to substantial amounts of water, the ettringite reforms, leading to destructive expansive forces that crack the concrete members. The conditions for the decomposition of the normal ettringite in concrete have not been well established. This is, in fact, one of the objectives of the current PCI-funded research project. It is believed that problems may be mitigated by allowing adequate preset periods prior to heating, that temperatures commonly used to heat cure concrete are not excessive, and that those cements with a low risk of DEF should be chosen. There is significant research to indicate that excessive heat curing may be a factor only with cements having a composition that falls within certain ranges relating to sulfate and aluminate concentrations.

Studies of failed railway ties have indicated that a significant factor in the development of DEF is the presence of relatively large concentrations of sulfate in the clinker phase of cement manufacture. Some of this sulfate may be very slowly soluble, thus reacting to produce ettringite only after the concrete gets hard.

A 3 percent limit on SO_3 content has been suggested, but such a limit may be below optimum for high compressive strength for many cements, particularly for Type III cements. Others suggest that magnesium, sodium and potassium contents may be contributing factors. In the PCI-sponsored research program, the cement ingredients and chemical interactions will be studied. Tests, such as the Duggan Test developed by Duggan and Scott to investigate the potential expansion of concrete or ASTM C 265 to determine the amount of unreacted sulfate content in concrete after 1 day in water, should be considered; however, any new test method needs to be correlated with test results.

Alkali silica reactions (ASR) were found in DEF-distressed concrete railway ties (sleepers) produced in Germany, Finland, the United States, Australia, and South Africa. It appears highly unlikely that all the producers of millions of ties in these countries around the world would somehow select aggregates known to be alkali reactive. Several published papers conclude that a synergism exists between ASR and DEF. That is, ASR may promote DEF or vice versa. Thus, more care in aggregate selection is required, especially in avoiding reactive aggregates.

Concern has been raised that concretes with relatively low water-cement ratios are more susceptible to DEF than concretes with high water-cement ratios, and that the use of sulfonated water-reducing admixtures may contribute to the problem. Both low water-cement ratios and the consequent use of high-range water-reducing admixtures are normally required for high strength concretes.

One researcher has suggested that DEF is promoted by three factors, namely, cement chemistry, high curing temperatures, and pre-existing micro-cracking in the concrete. If these three conditions exist simultaneously, then there is a greater likelihood that cracking of the concrete due to DEF may occur. The PCI Parking Structures Committee recommends that in parking structures exposed to high humidity levels, such as supporting a cooling tower, the immediate surface areas be treated with a silane sealer.

Q6: *Where can more information on DEF be found?*

A6: A good starting point for further information on DEF is a paper by William Hime published in the July-August 1996 PCI JOURNAL titled "Delayed Ettringite Formation — A Concern for Precast Concrete?" Information on DEF has also been published by ACI, ASTM, and other technical journals. Care should be taken when reading research papers on DEF, as some articles do not reflect precast concrete practices where a proper preset period determined by ASTM C403 is commonly used. Research funded by PCI and other organizations is aimed at determining those factors that increase the risk of DEF. At this time, many of the fundamental questions regarding DEF remain unanswered.

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Openings in Precast, Prestressed Concrete Members

Q1: *As precast producers, we sometimes need to manufacture precast, prestressed concrete members with openings. Can you furnish me with some pertinent references that are especially applicable to such members? (Erin Pratt, Spancrete of California, Irwindale, California)*

A1: The most important consideration in dealing with members with holes or openings is that the section has sufficient structural capacity to sustain and transfer loads, and that the area around the opening has enough reinforcement to resist the high stress concentrations. The soon to be published Fifth Edition of the PCI Design Handbook offers some design guidance for treating openings in decks and webs in Chapter 4 (Sections 4.10.2 and 4.10.3). Also, the new PCI Manual for the Design of Hollow Core Slabs offers some advice for openings in hollow-core slabs (see Section 3.3, pp. 3.8, 3.9, and 3.10). It should be emphasized, however, that the situation in hollow-core slabs is much different from that of openings in stemmed members such as beams or double tees.

The following papers from the PCI JOURNAL are good references on the subject of openings in precast, prestressed concrete members:

1. Ragan, H. S., and Warwaruk, J., "Tee Members with Large Web Openings," PCI JOURNAL, V. 12, No. 4, July-August 1967, pp. 52-65.
2. Barney, George B., Corley, W. Gene, Hanson, John M., and Parmelee, Richard A., "Behavior and Design of Prestressed Concrete Beams with Large Web Openings," PCI JOURNAL, V. 22, No. 6, November-December 1977, pp. 32-60.
3. Kennedy, John B., and Abdalla, Hany, "Design Against Cracking at Openings in Prestressed Concrete Beams," PCI JOURNAL, V. 40, No. 6, November-December 1995, pp. 60-75.
4. Arumugasaamy, Panchy, Fischer, Larry G., Savage, John M., and Tadros, Maher K., "Behavior and Design of Double Tees with Web Openings," PCI JOURNAL, V. 41, No. 1, January-February 1996, pp. 46-62.
5. Mackertich, Seroj, and Aswad, Alex, "Lateral Deformations of Perforated Shear Walls for Low and Mid-Rise Buildings," PCI JOURNAL, V. 42, No. 1, January-February 1997, pp. 30-41.

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