Engineering and architectural progress in the US related to environment conditions

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My presentation relates to vivid examples of how environmental conditions have influenced the lifespan of structures in the United States, including concrete and materials other than concrete.

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Wiss, Janney, Elstner Associates, Inc (WJE) undertakes 3000 to 4000 investigations a year dealing dominantly with buildings, bridges, and construction materials that exhibit poor performance. However, concrete materials generally stand the test of time, but not always, the subject of some of my presentation today.

As a result of our many bridge failure investigations, the National Transportation Safety Board (NTSB) requested that WJE re-assemble the 747 TWA Flight 800. The final media reports lead the public to conclude that the environment in the fuel tank was aggressive to the long-term performance of the electrical wiring system, and eventually, after many years of service, the wire coating in the fuel tank deteriorated and created the conditions for an explosion.

Another example of harsh chemical environments that have created severe deterioration has been seen in our studies of over 1000 buildings and 700,000m^2 of plywood roofing in the United States where normal wood framing and plywood have been chemically treated to provide fire-resistant qualities.

These chemical treatments created severe deterioration of the wood, as well as, in some cases, brittle failures. The result is structural failures at early ages as well as at more-mature ages. We were recently contacted by European clients who believe similar wood failures are now occurring in Europe. Our laboratories have identified the chemical composition of the treatments, the degree of strength loss, and eventually repair or replacement methods.

Long-term sagging of specific post-tensioned concrete bridges has been a problem. The Parrott's Ferry Bridge in California was a lightweight concrete bridge with a 625mm sag at midspan. This was the longest lightweight concrete bridge of its type. Equally unique was the Palau (Koror) Bridge that had a 1200mm sag prior to repairs several years ago. This Palau bridge was also a record span bridge when constructed.

Both of these WJE-investigated bridges were unique in their record spans and both had unique environments that played a major role in long-term creep and shrinkage. As you may realise, the Palau Bridge collapsed shortly after a major repair with supplemental post-tensioning to stabilise the sagging.

Through the years WJE has noted that record spanning structures seem to be problematic.

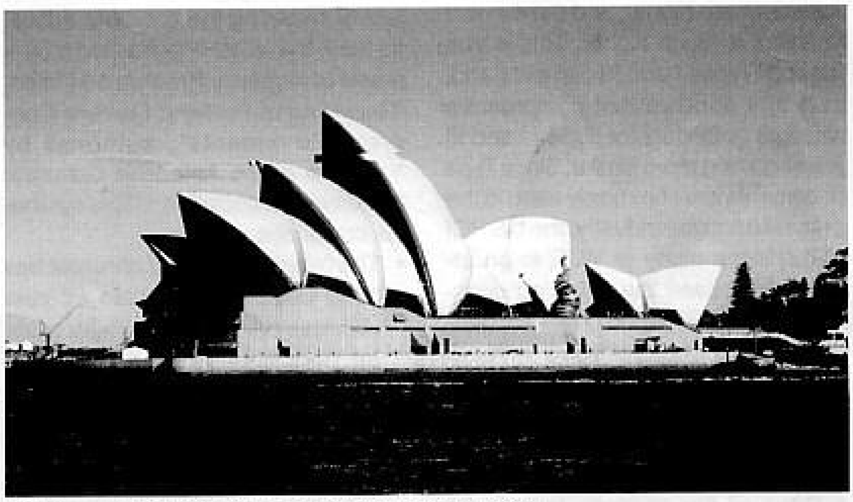
Since essentially all concrete deterioration requires water to produce the harmful deterioration, it is still appropriate to remind everyone once again of the dramatic usefulness of silane sealers. These penetrating sealers dramatically reduce the ingress of rainwater and saltwater into concrete. While the National Cooperative Highway Research Program (NCHRP) Report No 244 was published in 1981[1], the use of silanes to prolong the service life of concrete structures continues. While the use of high-performance, low permeability concrete is becoming popular, conventional concrete structures can have the same low permeability characteristics as high-performance concrete by using multiple coats of 40% or 100% solids penetrating silane sealers. The concrete from the Sydney Opera House was evaluated by WJE using severe weathering tests on concrete cores extracted from the shell roof. One, two, and three applications of silane were evaluated. The data show a 10mm silane penetration with three coats applied at 15-minute intervals. Following accelerated ultraviolet weathering tests and severe saltwater ponding tests, the data show 75% and 100% reduction of absorbed chloride ion into the 0 to 10mm and 10mm to 20mm depths, respectively, when compared to the control concrete from the shell roofs. Such 75% to 100% reductions in chloride ion are not even possible with high performance concrete in their 0 to 10mm depths[2]. Therefore, the continuing use of silanes to provide longer service life for conventional concretes in severe water and saltwater environments is certainly recommended.

The fastest growing portion of our business is in the curtainwall area, since so many have problems. While architectural precast concrete wall panels have stood the test of time, other newly developing curtainwall systems have not stood the test of time. Common problems have been sealant failures; cracking of the architectural layer; water and air infiltration due to poorly manufactured systems. It appears that owners are pressing architects to use these less costly and unproven systems.

Common to many problematic systems is the use of a light-gauge steel stud framing system as used with glass fibre reinforced concrete (GFRC) wall panels. GFRC panels have behaved properly in the United States when the 15mm to 20mm-thick skin is solely GFRC. However, when a composite GFRC skin utilises ceramic tile, clay brick tile, terra cotta, and thin exposed aggregate face mix concrete veneers bonded to the GFRC backup material, bowing, cracking and water and air infiltration have occurred[3]. Extensive jobsite strain-relief tests and wind-load tests were undertaken between 1987 and 1993 to determine the causes for the poor behaviour of these two-layer composite GFRC skins attached to steel stud framing. The 1993 Third Edition of the PCI GFRC Recommended Practice deals with these incompatibility issues.

Other curtainwall systems that also use steel stud framing and which claim to be cementitious have been even more unserviceable. Examples are thin brick on plastic forms; ceramic tile faced wood fibre reinforced portland cement board; ceramic tile fibre-reinforced skin glued to a cement-based board and polymer-faced skin on gypsum board. These and other ultra-lightweight curtainwall systems have extreme incompatibility issues created by thermal and moisture environmental factors. Many have early age failures from uncalculated stresses due to thermal and moisture change issues, and not from calculated wind and gravity load stresses.

The most severe environmental factor in the United States is chloride exposure[4], not just to exposed bridges, buildings, wharfs, and other ocean-exposed structures, but also from the use of admixed chloride in concrete buildings that have no exterior exposure to saltwater[5]. This internal chloride is added by contractors as an accelerator.



WJE has carried out tests on concrete cores extracted from the shell roof of the Sydney Opera House.

Two critical corrosion issues need to be clearly understood and both explain why corrosion of conventional reinforcing bars has created massive worldwide corrosion. They are as follows:

- A metal loss of only about 0.013mm to 0.10mm from the bar surface will create cracking of the concrete at the corroding bar surface[6].
- It requires only about $0.50kg/m^3$ to $0.80kg/m^3$ of acid-soluble chloride, externally applied or internally admixed to initiate the corrosion process with conventional rebar[5,7].

Both of these numbers are extremely low, therefore, the reason for the need for corrosion-resistant rebars with an acid-soluble chloride threshold of about $18kg/m^3$, such as with 316 stainless, is obvious[7].

Due to the severe saltwater exposure in different environments, high-performance, low permeability concretes have become more common. However, their use has created detrimental issues. One is the lack of constructability with such low w/c ratio concretes, followed by cracking due to construction issues and restraint to thermal and shrinkage volume changes. These issues are not commonly addressed in design and specifications and numerous lawsuits have resulted.

Bridge deck cracking is epidemic in the United States and, as a result, a restrained ring test was developed and used by WJE during a 3-year NCHRP study on bridge deck cracking[8]. The test provided a good correlation between bridge-site ring test cracking behaviour and the actual cracking of the bridge deck under the same environmental conditions. This ring test demonstrates that "cracking tendency" correlates to the high modulus of elasticity, low creep, and high strength of high-performance concrete.

Another issue with high-performance concrete relates to engineers and specifiers who desire to use non-air-entrained concrete to achieve even higher strength. While freezing and thawing may not be a significant Australian issue, tests on extremely low w/c ratio concretes with w/c ratios of 0.22 to 0.29 and compressive strengths of 75MPa to 90 MPa exhibited poor laboratory freeze/thaw resistance during ASTM C666 tests. It was equally disturbing that similar non-air-entrained concretes performed both poorly or well when tested by two different test methods used by AASHTO and ASTM.

The final technical environmental issue to be briefly discussed is that of DEF or delayed ettringite formation, a subject that was already created over 500 technical papers. From an environmental view, the actions of the US Environmental Protection Agency

(EPA) against smokestack emission from the portland cement and lime manufacturing industries not only help create the conditions for more acid-rain[9,10], but also created higher sulfate and alkali contents in manufactured portland cement. As emissions were more regulated, cement chemistry changed. This change in basic cement chemistry was clearly seen in the 1994 ASTM paper "Survey of North American Portland Cements: 1994", by R F Gebhardt[11]. This review of 387 different cements clearly show that, when compared to the last survey in 1953-1954, the amounts of sulfate and alkali are higher, and the cement fineness is much higher. This is true for both Types I and III cements and, in fact, it appears that compressive strength potentials for Types I and III are becoming more similar. Since Type III cements are commonly used in the precast concrete industry, the US PCI is funding a study at WJE in an attempt to answer the following questions about DEF when under accelerated heat curing conditions with cements of today.

Under heat curing conditions of 23°C, 54°C, 66°C, and 82°C, with a proper preset period:

- Does all the ettringite form in 24 hours, or is it possible that significant ettringite may form at a later time?
- Are all cements equally affected by curing temperatures from 23°C to 82°C or are some more stable?
- What is the range of sulfate contents and does this value relate to the amount of ettringite formed in the first 24 hours?

It is noteworthy that a recent paper by D B McDonald[12] showed that the work by Kelham[13] on five different production clinkers with added SO_3 found no significant expansion for most of the mortars cured at 20°C, 70°C, or 80°C, but found significant expansion at 90°C. Kelham then developed an equation that related expansion to cement chemistry, SO_3, C_3A, C_2S, MgO, and Na_2O_e. When McDonald used this Kelham-developed equation with the 178 cements from 1953-1954 and then with the 359 cements from the 1994 ASTM cement survey data, it appeared that a vastly greater percentage of Type III 1994 cements could be more susceptible to DEF when cured at 90°C than for those cements produced in 1950.

It is noteworthy that WJE has laboratory test techniques to clearly differentiate between DEF, ASP, and DEF when in combination with ASR. It is equally important to note that DEF appears to be a minor deterioration mechanism at this rime and it is believed that the ongoing research will identify ff there are indeed specific curing temperatures that must be avoided and/or if other factors must be avoided, such as cement chemistry.

When one thinks about deteriorated or aged concrete structures, the subject of recycling the concrete arises. In 1989, the NCHRP published a Synthesis of Highway Practice 154 titled, "Recycling of Portland Cement Concrete Pavements", authored by Yrjanson of the American Concrete Pavement Association[14]. This synthesis concludes:

- The recycled crushed concrete has been used as aggregate for new concrete pavements, as aggregate for new open-graded base and subbase layers and as aggregate for cement-treated base.
- Even D-cracked concrete pavement has been recycled as aggregate for new pavement with improvement in the D-cracking potential after recycling.
- Projects in Michigan, Minnesota, Iowa, North Dakota, Wisconsin, Wyoming and Oklahoma were reviewed.

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