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PETROGRAPHIC EXAMINATION AND CHEMICAL ANALYSIS OF THE LUCINDA JETTY PRESTRESSED CONCRETE ROADWAY

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ABSTRACT

The 5.76 km long jetty at Lucinda Bulk Sugar Terminal, N. Queensland, Australia, was commissioned in 1979. The jetty serves as an outloading facility for bulk raw sugar which is transported off-shore on a conveyor belt housed in a gallery. Along the gallery is a roadway which provides access to the off-shore wharf structure. Each of the 288 twenty metre long roadway spans consists of six 0.60 m by 0.60 m hollow prestressed box girders which are joined by transverse post-tensioning bars.

Within a few years after completion, longitudinal cracking became evident, and this development has since continued, resulting in extensive cracking in the top and bottom surfaces of the roadway. The cause of the cracking is alkali-silica reactions. The reactive aggregate is a volcanic rhyolitic tuff coarse aggregate.

The jetty roadway is the longest known prestressed concrete structure in the world suffering from alkali-silica reactions. It is characteristic of the reactions that their intensity is highly variable within elements and between elements and spans. Girders or parts of girders may exhibit little or no damage while in other places the reactions have caused the exudation of significant amounts of viscous gel which has been sampled for analysis.

The present paper describes some of the observations which have resulted from petrographic examination and chemical analysis of samples extracted from the concrete roadway. These studies have revealed new aspects of gel chemistry and reactivity of aggregates.

1. INTRODUCTION

In 1979, the new bulk sugar outloading facilities at Lucinda Bulk Sugar Terminal, N. Queensland, Australia stood completed and was taken into use. The jetty serves as an outloading facility for bulk raw sugar which is transported off-shore on a conveyor belt housed in a gallery. The bulk sugar conveyor system altogether comprises a tail-end structure, located at the shore line, the jetty and the off-shore berthing wharf. Figure 1 is a view of the jetty from the off-shore wharf looking due west.

Along the gallery is a 3.60 m wide roadway which provides access to the off-shore wharf structure. Each of the 288 twenty metre long spans which make up the roadway consists of six 0.60 m by 0.60 m hollow prestressed box girders which are joined by transverse post-tensioning bars. At six locations along the jetty, the width of the roadway is increased to 8.20 m (14 girders) to allow for the passage of traffic.

Figure 1 A view of the Lucinda Jetty from the off-shore warf.

Within a few years after the facilities were taken into use, longitudinal cracking became visible in the top surface of the jetty. This cracking has since developed further and has become evident on the underside of the roadway. As a consequence of the cracking and resulting volume expansion of the roadway, jamming against transversal restraints such as hold-down brackets at expansion joints, angle brackets at the headstocks etc. became evident, and considerable remedial action has been required to relieve the stresses and accomodate the expansion.

Having been the subject of reports dating back to 1980, several hypotheses had been proposed regarding the origin of cracking of the more than 1750 beams forming the roadway. Theories included opening of cracks which were due to plastic settlement during manufacture of the beams, expansion of insufficiently burned lime in the cement, and alkali-silica reactions.

In 1986, The Sugar Board, Brisbane, Queensland, Australia, commissioned G.M. Idorn Consult A/S (with Rambøll & Hannemann as subcontractor) to carry out a thorough investigation into the cause and likely consequences of the cracking. Extensive field investigations, petrographic examinations and chemical analyses of extracted cores demonstrated that alkali-silica reactions are the cause of the cracking and that the reactive aggregate is a volcanic rhyolitic tuff. In the following, a description is given of results of the studies of the manifestation of the alkali-silica reactions. Reference is also made to Holm, Idorn & Braestrup, [1] who describe in detail the overall approach to the investigation.

2. THE CLIMATIC CONDITIONS

Located approximately 18 degrees south of the Equator, Lucinda experiences tropical climatic conditions. Annual ambient temperatures range from typically 15°C during winter and 35°C during summer. The annual precipitation is approximately 3000 mm, frequently occurring as rain falls of high intensity. However, most often, the sun shines from a clear sky. Combined with the geographic location, this causes considerable heating of the top surface of the concrete. Thermocouples embedded app. 3 cm below the top surface of the concrete have indicated concrete temperatures as high as 60°C. Conversely, temperatures indicated by thermocouples embedded app. 6 cm from the bottom surface of the roadway rarely exceed 35°C.

3. FIELD EVIDENCE OF DAMAGE

In 1984 the entire top surface of the jetty roadway and the wharf received a bituminous overlay for the purpose of reducing the ingress of water into the cracks in the top surface of the beams. Sofar it has not been possible to identify any influence of the bitumen on the progress of damage.

Figure 2 Photograph of the underside of the Lucinda Jetty. The concrete beams are partly covered with alkali-silica gel and calcite.

The manifestation of deterioration, as evidenced by deposits and cracking on the underside of the roadway, is highly variable, as illustrated in Figure 2. Thus, spans with extensive deposits may be observed immediately adjacent to spans which appear free of damage. Within a given six-girder assembly of a span, undamaged as well as heavily cracked and stained undersides of individual girders may be observed. Even within a given girder, considerable variability in damage may be observed.

On the underside of the tail-end structure, where the clearance between the water level and the underside of the roadway is reduced, and waves of warm, salty water frequently hit the bottom surface of the roadway, viscous, transparent gel exudes from micro-fissures in the concrete in sufficient amounts to be scraped off with a pocket knife and collected for further studies. This abundance of gel products is probably unique - based on available published case histories.

Upon removal in selected areas of the bitumen coating, the extensive level of cracking of the top surface of the beams became evident, as illustrated in Figure 3. Structural analysis and load testing, nevertheless, demonstrated predictable behaviour and high strength reserves [1], a finding which is corroborated by other accounts of load testing of structures subjected to deleterious alkali-silica reactions [2]. A comprehensive monitoring programme established at the jetty [1] has further demonstrated that while longitudinal expansion of the girders is modest, transverse expansion of the girder assemblies is about 70 times as high.

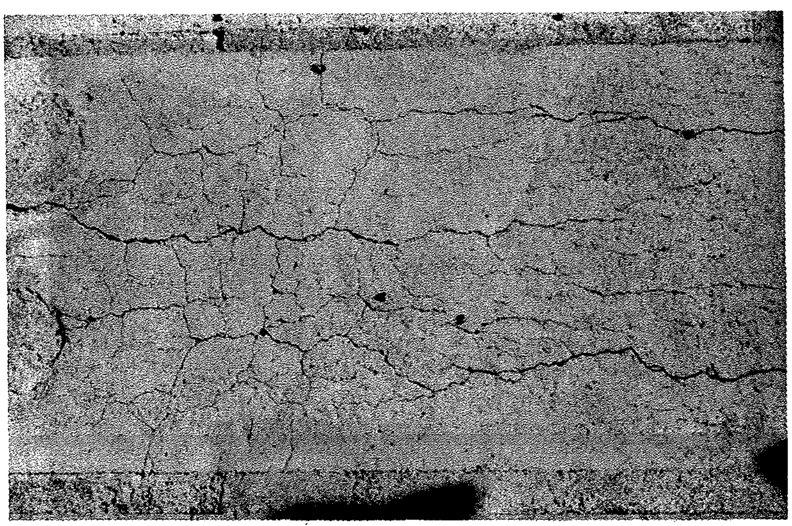

Figure 3 After removing the bitumen coating and sand blasting the concrete surface the extensive cracking of the beams became evident.

4. THE PRESTRESSED GIRDERS

Approximately half of the girders for the jetty roadway were cast in a pre-casting yard which was established at the site especially for this purpose. The coarse aggregate used for these girders was quarried locally at nearby Mt. Cordelia. The other half of the girders were manufactured by a precaster in Townsville and trucked the approximately 100 km to Lucinda. These latter girders were cast using locally available coarse aggregate quarried at Roseneath. In both instances, the fine aggregate was local quartz sand, while the cement was a relatively high-alkali ordinary Portland cement. In-situ strength testing and testing of extracted cores typically indicated compressive strengths in the range of 45 - 65 MPa.

5. PETROGRAPHIC EXAMINATION

Petrographic examination of core samples was performed using fluorescent thin-section microscopy. Using this technique, 20 micron thick slices of concrete are prepared from samples of concrete which have previously been impregnated with an epoxy containing a fluorescent dye. In the petrographic microscope, the crack pattern caused by alkali-silica reactions as well as other features of porosity may be clearly viewed.

A detailed investigation of the petrographic manifestations of distress in the concrete from the Lucinda jetty is presented by Andersen & Thaulow [3]. These investigations show that alkali-silica reactions are the cause of cracking and consequent expansion. The examinations have further identified the source of the reactive silica to be the coarse aggregate, a volcanic rhyolitic tuff. Cracks are seen penetrating such coarse aggregate particles and deposits of at least three distinct types of gel have been identified in the cracks immediately inside and outside the perimeter of the aggregate particles. Figure 4 is a micrograph of a reacted coarse aggregate particle depicting the different types of gel.

Fluorescence microscopy has shown that although of similar composition, the coarse aggregates exhibit a considerable difference in porosity and that the alkali-silica reactions predominantly occur in the porous fraction. These observations suggest that it is the inherent porosity and hence specific surface of the aggregates which controls their reactivity and hence the irregular distribution of alkali-silica reactions in the jetty.

Accelerated testing of concrete cores from the roadway by immersion into a 50°C hot saturated NaCl solution (The Danish TI-B 51 reactivity test) has shown variable continued expansion. This also suggests that the distribution of alkali-silica reactions in the structure is controlled by the susceptibility of the coarse aggregates towards alkali-silica reactions rather than for instance by differences in the climatic exposure along the jetty.

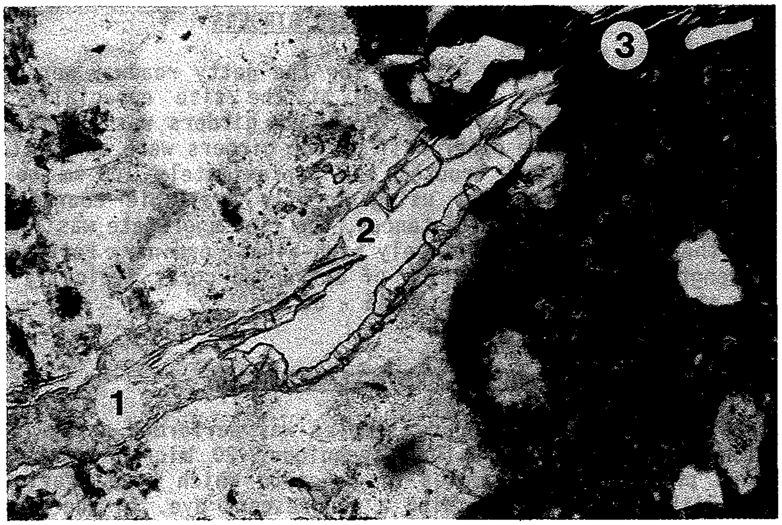

Figure 4 Micrograph of part of the light coloured, reacted coarse aggregate particle (left). Three types of gel are seen:
1. Crystalline "gel" inside a crack in the aggregate.
2. Amorphous gel lining crack in aggregate and in the paste.
3. Dark layered gel in crack in the paste.

Field of view 2.5 x 4 mm.

6. CHEMICAL ANALYSES

Samples of gel collected from the underside of the tail-end structure and gel observed in thin-sections at the perimeter of cracked aggregate particles have been studied by SEM and EDX. The SEM studies show that the gel within the cracked particles is crystalline with a rosette-like appearance, Figure 5. Similar appearances of gel have been described by Mather & Buck [4] and Regourd et al [5]. Close to the paste/aggregate interface but inside the aggregate the gel exhibits transparent, amorphous appearance, and further out within the hardened cement paste, the gel tends to have a non-transparent, grained and layered appearance.

The results from the EDX examinations of the different types of gel are presented in Table 1. These analyses show several interesting features.

The composition of the crystalline rosette-like gel and the transparent, amorphous gel are identical, with a molar (Na+K)/Si of 0.3:1 and a Ca/Si ratio of 0.25:1. The non-transparent, grained gel further out in the cement paste is presently being examined by EDX but analyses from other case studies of gel deposits of a similar appearance show a molar (Na+K)/Si ratio of 0.01:1 and a Ca/Si ratio of 1.45:1. This type of gel has a significantly higher relative content of calcium and a lower relative content of alkalies when compared to the other two types of gel.

Figure 5 SEM micrograph of crystalline "gel" with a platy morphology. This type is found inside cracks in reacted coarse aggregate particles. Magnification 2700 times.

The gel which has been exuded onto the surface of the roadway as jelly-like droplets has an average molar (Na+K)/Si ratio of 0.26:1 and no detectable calcium.

The gel analyses from the aggregate particles indicate that the gel tends to take up calcium when it enters the hardened cement paste in the concrete. A similar uptake of calcium away from the reacting aggregate particle has formerly been described by Thaulow & Knudsen [6]. Thin-section studies further confirm this observation as the finely dissiminated calcium hydroxide which is normally present in the cement paste is depleted in the vicinity of cracks filled with gel.

Furthermore, it appears that the high calcium gel must have been rather rigid as later generations of cracking caused by alkali-silica reactions in the concrete are often noticed to cause brittle fractures in the Ca-rich gel. Kawamura et al. [7] have shown that the microhardness of gel increases with an increasing calcium content. Accordingly, it is also to be expected that the viscosity of the gel will increase with an increasing calcium content thus transforming an earlier fluid, Ca-low gel into a solid and rigid C-S-H gel which is compositionally very similar to hydrated cement paste (Mather & Buck,[4])

The cement paste in contact with a gel filled crack may be considered as a reaction zone formed by reaction between C-S-H with calcium hydroxide and alkali silica gel with a varying calcium content. The end product of this reaction will be an alkali enriched calcium silicate hydrate free of solid calcium hydroxide.

Table 1

Average EDX analyses of the contents of Na, K, Ca and Si in the four different gel types. The numbers 1-3 refer to the gel types shown in Figure 4 while Gel No. 4 is an analysis of a sample of gel taken from the underside of the roadway. The figures are reported as atomic percentages.

	Na	K	Ca	Si
Gel No. 1	3.2	16.1	16.1	64.5
Gel No. 2	3.2	16.1	16.1	64.5
Gel No. 3	0.0	0.6	58.8	40.5
Gel No. 4	19.4	1.4	0.0	79.9

The width of the zone of converted C-S-H will be determined by the amount of gel in the crack. An observation that supports this hypothesis is that the optical properties of this zone are the same as the optical properties of cement paste with pozzolan addition.

The low content of calcium in the gel which have been exuded on the underside of the roadway is rather surprising. If this gel was originally formed within reacting aggregate particles in the concrete and subsequently channelled through cracks in the hardened cement paste and onto the surface, one would expect it to take up calcium from the surroundings during its passage. This has apparently not happened. Due to the resulting low calcium content, the gel possesses a very low viscosity which has enabled it to emerge on the underside of the roadway as small, transparent droplets.

The deposition of an almost pure alkali-silica gel on the underside of the jetty has occurred continously during the monitoring period which has now lasted approximately 2 years. The phenomenom can thus not be ascribed to any special event, for instance during the initial development of alkali-silica reactions in the construction, but must be assumed to be a natural part of the continously reacting system between the pore fluids of the cement paste and reactive silica in the aggregates.

7. CONCLUDING REMARKS

The field and laboratory studies of the Lucinda Jetty Roadway have provided an excellent example of the complexity of alkali-silica reactions. The extreme variability in the manifestations of cracking in the structure may thus partly be explained by variations in the inherent porosity of aggregate particles which are otherwise similar. The gel produced during the alkali-silica reactions is shown to have varying composition and appearance depending on its location in the concrete. For instance, it appears that a low amount of calcium causes the gel to be very fluid which again causes it to be exuded onto the concrete surface. On the other hand, a high content of calcium gives the gel binding properties much similar to the hydrated cement paste. These observations suggest that it is only within a narrow range in calcium content that a gel possesses the right viscosity as to be expansive and deleterious to the concrete.

Finally, it is to be said that the large physical and chemical variability of the alkali-silica reactions in the Lucinda jetty point to field investigations of structures affected by alkali-silica reactions as being a most important laboratory in which more knowledge regarding the nature and consequences of alkali-silica reactions may be obtained.

8. ACKNOWLEDGEMENTS

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