CorrCompilations

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Editor: Malcolm McNeil

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Introduction

The use of concrete in all types of construction is a common practice due to the strength and longevity of concrete. The use of concrete dates back to the Roman Empire. However, concrete has weaknesses and must be protected in many environments. Concrete may be coated for protection and may be used as a coating itself.

The following is a compilation of articles relating to concrete structures and concrete substrates. The articles are categorized under Concrete, Cathodic Protection, Coatings for Concrete, and Corrosion of Concrete and Concrete Reinforcement. These articles come from papers presented at various Corrosion Conferences organized by NACE International and contain a wealth of technical information to help Owners, Engineers, Specifiers, Contractors, and Inspectors in working with many types of concrete structures.

“Long-Term Performance of Concrete Repairs in Complex Conditions”

CORROSION 2013, paper no. 2214

Long-term durability of repairs on existing concrete structures can provide data to support selection of strategies for ongoing remediation and service life extension. This paper describes a study of repair methods for different forms of damage and deterioration on various concrete structures. The study encompasses details of the environmental conditions, concrete materials, and construction issues contributing to the deterioration. The performance of previous repair methods is also analyzed.

Paper No.
2214

NACE INTERNATIONAL CORROSION 2013 CONFERENCE & EXPO

Long-Term Performance of Concrete Repairs in Complex Conditions

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ABSTRACT

Assessment of the long-term durability of concrete repairs on existing structures can provide useful data to support selection of strategies for ongoing remediation and service life extension. Condition surveys of large reinforced concrete storage sheds enabled study of repair methods for different forms of damage and deterioration. Reinforced concrete piles supporting the sheds exhibited multiple deterioration mechanisms and had undergone different repair techniques over 30 years. Deterioration included a combination of reinforcement corrosion, alkali-silica reaction and salt hydration distress (or physical salt attack). Of these, reinforcement corrosion was the greatest concern due to the impact on load bearing capacity of the piles. This paper presents details of the environmental conditions, concrete materials and construction issues contributing to the observed deterioration. In addition the performance of previous repair methods including shotcrete patch repair, protective coatings and cementitious waterproofing slurries is analyzed. The current remediation program is also discussed.

Key words: Reinforcement corrosion, alkali-silica reaction, chlorides, carbonation, repair, shotcrete

INTRODUCTION

Two large reinforced concrete sugar storage sheds are located in Cairns, Australia. The sheds are used to store bulk sugar prior to shipment and are 260 m long and 48 m wide. Each shed is supported on 2,118 reinforced concrete piles. The piles are 500 mm diameter and consist of cast in-situ Franki[(1)] piles below ground to a depth of up to 18 m and a cast in-situ section above ground of 2 m. This type of pile has an enlarged base. The first shed (Shed 1) was constructed in 1964 and the second (Shed 2) in 1972. The sheds are sited on reclaimed tidal land originally consisting of mangrove muds. The site had been filled with pumped dredge spoil prior to development.

The concrete for the piles was specified to have a minimum 28 day compressive strength of 20 MPa (2,900 psi). Above ground the concrete was required to have a minimum cement content of 390 kg/m^3. Concrete was mixed on site during construction.

The piles, particularly on Shed 1, have a history of deterioration, investigations and repairs. A further investigation was recently undertaken and consisted of a detailed condition assessment and development of repair options to extend the life of the piles.

PRIOR INVESTIGATIONS

As part of the current condition assessment, prior investigations were reviewed. In 1983 an extensive investigation into observed deterioration at Shed 1 was conducted and the resultant report[1] provided information on the deterioration history and investigation results. The report discussed the site conditions, condition of piles, prior repairs and the results of concrete, soil and groundwater testing.

According to the 1983 report[1], the first observations of pile deterioration in Shed 1 occurred in 1971, i.e., seven years after construction. Piles were found to have cracking and spalling due to reinforcement corrosion, loss of surface fines just above ground level and gel exudations at or near ground level. Shotcrete patch repairs were performed on 42 piles in 1972. Further deterioration of piles was observed during condition surveys in 1976 and 1982. In 1976 collar encasement type repairs were performed on some piles. By 1983 a further 319 piles were exhibiting cracking and spalling.

The types and causes of concrete deterioration identified in the 1983 investigation report[1] were:

- Reinforcement corrosion due to chloride ingress and carbonation
- Surface deterioration at base of piles due to crystallization of salts
- Alkali-silica reaction (ASR) at base of piles causing weeping of gel

The 1983 investigation included petrographic studies and chloride analysis on core samples, depth of cover and carbonation tests, ultrasonic pulse velocity measurements and analysis of soil and ground water chemistry. The petrographic analysis of concrete core samples confirmed the presence of reactive aggregate and ettringite in voids. The gel deposits were amorphous and predominantly silica.

Analysis of soil samples revealed variable levels of salinity ranging from 1,600 to 21,600 mg/kg. Salinity varied with depth and was highest in the black mud horizon. Chloride concentrations between 3,655 and 6,780 mg/kg were measured. These levels are considered high for soil and aggressive towards embedded steel in concrete. Sulphate concentrations ranged between 90 and 2,300 mg/kg and values greater than 150 mg/kg are considered aggressive (ACI[(2)] 201[2]).

Groundwater analysis taken at a depth of 1.5 m showed magnesium concentrations between 17 and 165 mg/L, chloride concentrations between 452 and 3,030 mg/L and sulphate concentrations between 48 and 71 mg/L. Of these, the elevated chloride concentrations are a concern for concrete durability, with sulphates of lesser concern. The magnesium concentrations were insufficient to be an issue. The groundwater pH ranged between 7.9 and 8.0 indicating slightly alkaline conditions.

Concrete core samples were taken from several piles at various depths below ground level. Each core was crushed and the aggregate and matrix were sorted by hand. The matrix was further ground and mixed with water at a 1:5 ratio for the determination of water soluble cations and anions, pH and total soluble salts. Analysis showed chloride ions with concentrations up to 8,200 µg/g (0.82% by weight of concrete). Elevated concentrations were detected at depths up to 150 mm from the external surface and this is a reflection of the chloride ions being transported up the piles by capillary action rather than external penetration. Testing of the 1:5 slurry from the cores using a pH electrode indicated that pH values of concrete piles below ground were typically above 12. Only one core showed a reduction in pH from the outer 0-50 mm to a depth of 100-150 mm. In this case the pH was 10.75 at the outer layer and 12.09 deeper into the pile.

The depth of carbonation causing loss of alkalinity was measured on concrete cores using a phenolphthalein indicator solution. It was found that carbonation of atmospherically exposed concrete had occurred to a depth of 15 mm by 1983. There was no other source of exposure besides atmospheric carbon dioxide that would cause loss of alkalinity in the above ground concrete. The sheltered environment for the above ground concrete would also favor carbonation. Phenolphthalein indicator tests on cores taken from piles below ground did not detect alkalinity loss. This was consistent with the pH tests.

The 1983 core samples showed significant variations in depth of cover from 20 to 135 mm. Depth of concrete cover tests with a covermeter on cracked piles showed that 19 out of 90 (21%) had cover less than 30 mm on one side and greater cover on the other side. The cover measurements imply that reinforcement cages within the pile forms were frequently displaced and resulted in uneven cover.

Ultrasonic pulse velocity measurements on piles above ground ranged between 3,700 and 4,350 m/sec and suggest variability in concrete quality. The lower values were measured on porous concrete. Rebound hammer tests were performed on piles below ground and the inferred compressive strength of the concrete was around 40 MPa (5,800 psi). This is higher than the target strength of 20 MPa.

In 1987 further investigations were performed and documented in a report[3]. Reinforcement corrosion due to chlorides was confirmed as the principal cause of deterioration, with ASR being secondary. The report recommended removal of deteriorated concrete to a depth of at least 2 cm behind the reinforcement, surface preparation by sand blasting and application of shotcrete to a saturated surface dry substrate. This was to be followed by curing in the form of wrapping the piles in wet burlap and polyethylene sheeting for two weeks. The use of 50/50 slag cement in the repairs was recommended for additional durability. The report also noted that the reinforcement corrosion issues were related to the reinforcement cage being offset with resultant low cover to one side. Therefore, it was recommended that asymmetric repairs be undertaken to ensure that sufficient cover was achieved in the repaired area.

CONDITION ASSESSMENT

Visual Inspection

Shed 1

The recent condition assessment found that all of the Shed 1 piles exhibited gel exudations due to ASR and exposed aggregate at the base. Examples of these features are depicted in Figures 1 and 2. The exudations were a white-brown color and typically located in the lower 150 mm of the piles, although up to 300-400 mm from the soil level in the worst affected piles. The tendency for ASR to be more prevalent at the base of the piles corresponds with higher moisture conditions close to the soil level.

The exposed aggregate on the surface of the piles was also typically in the lower 150 mm and the piles had a clear “tidal appearance”. In some cases the deterioration extended up to 500 mm above the soil level. The presence of exposed aggregate is primarily attributed to salt hydration distress associated with uptake of salts from the soil as previously identified. Salt hydration distress refers to accumulation and crystallization of expansive salts in the surface pores of concrete and is also termed “physical salt attack” or “salt crystallization”.

Numerous piles showed cracking, delamination and spalling due to reinforcement corrosion. The total percentage of affected piles was 6.1%. A typical example is shown in Figure 3. Reinforcement corrosion generally occurred 0.5-1.5 m above the soil level and was primarily due to a combination of wicking of chloride ions from the soil and carbonation. Some of the piles had been manually exposed below the soil level. Inspection of the below ground section of these piles did not reveal indications of reinforcement corrosion.

Shed 2

In general, the piles supporting Shed 2 were in significantly better condition than those for Shed 1. There was no evidence of reinforcement corrosion or related damage. There was still evidence of ASR, sulphate attack and salt hydration distress at the base of the piles. However, the degree of deterioration was not as severe as that for Shed 1 and was rated as “slight”. The superior performance of the Shed 2 piles compared with Shed 1 was attributed to higher quality concrete and uniform depth of cover above 50 mm. The main concern with the Shed 2 piles was subsidence and geotechnical issues but these are beyond the scope of this paper.

Figure 1: ASR Gel Exudations at Base of a Shed 1 Pile (arrowed)