

Durability of Reinforced Concrete Structures in a Petrochemical Complex: a Case Study

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ABSTRACT

Most structures in a petrochemical complex are fully or partially constructed by reinforced concrete and since in this environment various high corrosive materials exist, these structures must possess a durable behaviour during their service life in order to perform satisfactorily. In this study, some reinforced concrete structures of a petrochemical complex in Shiraz city of Iran have been evaluated. First of all, a thorough visual inspection (in order to observe different deterioration mechanisms) accompanied with a comprehensive set of conventional experiments in assessing durability of concrete (such as water absorption, carbonation depths, electrical resistivity, half-cell potential maps) were carried out. It was concluded that a petrochemical complex provides a harsh environment from durability of concrete point of view. Second of all, appropriate repair schemes according to the extent of damages to different units were discussed. At last, some useful recommendations about the maximum w/c ratio and concrete cover of reinforcement for designing structures in such environment were provided.

KEYWORDS

Carbonation depth, Chloride content, Durability, Petrochemical complex, Reinforced concrete.

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1 INTRODUCTION

Most of the structures in a petrochemical complex are fully or partially constructed by reinforced concrete. Therefore, the concrete should be specified with special measures to resist deterioration when placed in a harsh environment to help ensure the long-term performance of such structures. This becomes even more important knowing that in such an environment, in addition to carbonation (ordinary corrosion-induced phenomenon in offshore structures), the rate of concrete deterioration is greater than usual because of the presence of highly aggressive chemicals such as ammonium nitrate and chloride. Moreover, due to the short distances between different units of a petrochemical complex, each unit discharging gases may affect the durability of the concrete in adjacent units.

In the following sections of this paper, the present condition of concrete in three operational units of a petrochemical complex is first investigated, where it will be seen that the different units experienced a high level of deterioration; for this purpose after a complete visual inspection of the structures, common tests such as density, water absorption and electrical resistance were performed on several extracted concrete cores. Secondly, three repair methodologies for these three units will be proposed. Finally, some useful recommendations about the w/c ratio and concrete cover of structures in such environment will be presented. As well, the probable interaction between adjacent units that occurs in a petrochemical complex was also considered.

2 ANALYSES OF DAMAGED STRUCTURES

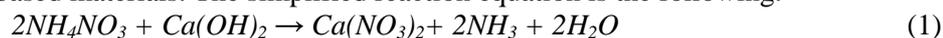
2.1 Ammonium Nitrate Unit

The ammonium nitrate unit is located at the centre of the petrochemical complex and consists of three main parts: (1) Prill tower and its upper structure (Figure 1); (2) Accessing concrete tower which is built to provide accessibility to the prill tower by means of an elevator and staircase; (3) Two steel structures.

Although a protective epoxy coating was applied to concrete surfaces, the prill tower nonetheless showed severe deterioration due to the long time exposure to ammonium nitrate. Damages were mainly softening of concrete (to the extent that even extracting cores from the tower's foundation was not possible) and removal of concrete cover (Figure 2). Therefore a thorough investigation was performed to assess the causes of these damages and also the level of deterioration.

One of the products of a petrochemical complex is chemical fertilizer which is often sold as small particles known as prills. These small particles are produced by converting liquid ammonium nitrate into solid granules. This conversion process is implemented in a tall tower called a prill tower (Figure 1).

Ammonium nitrate is very corrosive to concrete [Schneider & Chen 2004; Schneider & Chen 1999; Schneider & Chen 1998] and continuous exposure of concrete to this chemical leads to dissolution of cement-based materials. The simplified reaction equation is the following:



The reaction products are ammonia and calcium nitrate, which are both easily soluble in water. As a result, in the presence of water or a damp environment and due to the removal of these products, concrete permeability will be increased. Besides, it is clear from the aforementioned chemical reaction that ammonium nitrate decalcifies hardened cement paste due to the removal of calcium hydroxide (Eq. (1)). This results in dissolution of other products of the hardened cement paste and leads to a reduction of the pH-value. Consequently, steel reinforcement corrosion may occur at an accelerated rate. As well, the deterioration of the cement-based material will be intensified and accelerated, when the material suffers under a corrosive attack accompanied by a mechanical load ([Schneider & Chen [2004]).



Figure 1. The ammonium nitrate prill tower.



Figure2. Destruction of concrete cover.

The results of density, compressive strength, water absorption and electrical resistance of concrete cores extracted from the tower are presented in Table 1. It is obvious that concrete of the foundation has a worse quality in comparison with concrete of the tower's body. This also justifies the higher level of deteriorations in the foundation (even sampling from the foundation was not feasible because of loose concrete).

Although, concrete has been decalcified up to about 30 mm from its surface, reinforcement corrosion was negligible along the ammonium nitrate prill tower.

Table 1. Results of different tests on extracted cores from the ammonium nitrate prill tower.

<i>Cores location</i>	<i>Density (Kg/m³)</i>	<i>Half an hour water absorption (%)</i>	<i>Saturated water absorption (%)</i>	<i>Electrical resistance (kΩ-cm)</i>	<i>Compressive strength (MPa)</i>	<i>Carbonation depth (mm)</i>
Ammonium nitrate tower body	2318	1.9	5	4	18	30
Ammonium nitrate tower foundation	2055	4	10	1.5	19	-

2.2 Chloride Unit

The chloride unit is located at the northern part of the petrochemical complex. Most columns of this unit's structures are constructed by reinforced concrete. High concentration of chloride ions in the atmosphere of this unit was the most important finding obtained from the visual inspections; these results served to confirm the high degree of deterioration that was evident on the different concrete elements. Figure 3 presents a column of this unit. It is obvious that the concrete cover has been totally removed and reinforcement corrosion is observed.



Figure 3. A view of supporting columns of the structure of chlorine unit.

Results of different laboratory experiments on the extracted cores with in-situ measurements of carbonation depths are summarized in Table 2. Results confirm the poor condition of the concrete. The depth of carbonation is rather high and according to Figure 4, carbonation phenomenon has pushed the maximum peak of diffused chloride ion from surface of concrete to its depth. Moreover, the concentration of chloride ion at the location of the reinforcement bars (40 mm depth) is far beyond the chloride threshold value ([Pargar et al. [2007]). Therefore, reinforcement corrosion is highly probable. This was in complete agreement with the results of visual inspection and half-cell potential map (changing of absolute potentials along a short distance is an obvious indication of steel corrosion).

Furthermore, according to different measurements, the concrete cover of the columns in this unit was about 4 cm which is clearly not sufficient from a durability point of view given the extremely harsh environment to which the structure has been subjected.

Table 2. Results of different tests on extracted cores from the chloride unit.

Density (Kg/m ³)	Half-hour water absorption (%)	Saturated water absorption (%)	Electrical resistance (kΩ-cm)	Compressive strength (MPa)	Carbonation depth (mm)
2269	2.6	5.5	3.5	15	30

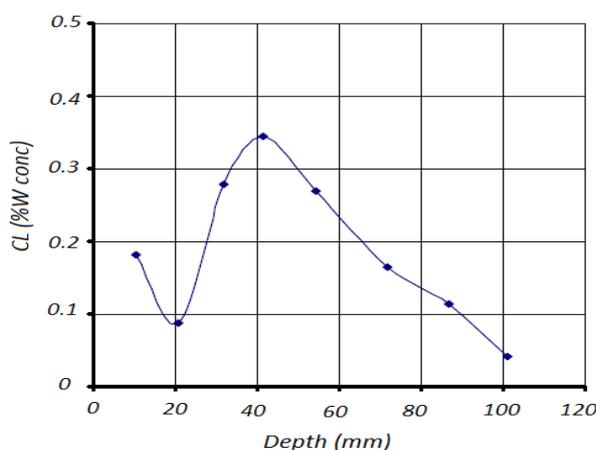


Figure 4. Chloride diffusion profile of a selected column.

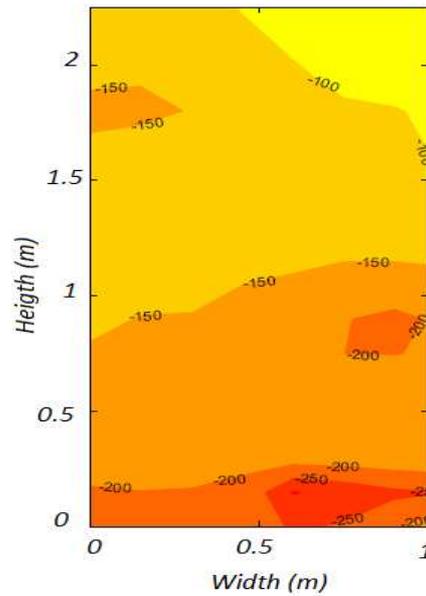


Figure 5. Half cell potential map of a selected column.

2.3 Cooling Tower Unit

This unit is located at the north western part of the petrochemical complex and next to the Chloride unit. The function of this unit is to reduce the temperature of water gathering from cooling systems of different units by spraying it from the top to the bottom of the cooling tower. As the drops of hot water fall, they evidently lose temperature. Therefore, high humidity conditions exist where water is sprayed and the concrete is thus almost near the saturation limit for large areas of this structure. Concrete elements of this unit consisting of peripheral frames such as columns, beams and walls are pre-fabricated and the columns rest on pedestals that are almost two meters in height (Figure 6).



Figure 6. A view of the cooling tower unit.

In some of the columns and walls of this unit, longitudinal cracks with almost 2 mm size were observed (Figure 7).

In Table 3 average test results of concrete cores extracted from the cooling tower unit and also carbonation depth measurement are presented. As shown, the water absorption factor is high and specific electrical resistance of concrete is low. These results together with those obtained for compressive strength and depth of carbonation indicate an inappropriate quality of concrete used in this complex.

Various studies have suggested that different half-cell potential ranges should be considered instead of absolute potential values in order to determine the locations of “high-probability” corrosion activity within a reinforced concrete structure [RILEM TC 154-EMC 2003]. Figure 8 displays half-cell potential contours of a wall which exhibited many longitudinal cracks that likely originated from reinforcement corrosion. In this figure, high fluctuations of potential values in both ends of the wall were observed which is indicative of a high likelihood of the presence of steel corrosion.



Figure 7. Longitudinal vertical cracks of almost 2 mm size in a selected column.

As it was mentioned earlier, this unit is located beside the chloride unit and because of the high concentration of chloride ions in the atmosphere of the latter unit; the chloride-induced corrosion also threatens the durability of concrete in the cooling towers unit. Figure 9 provides an overview about the penetrating chloride ion to the concrete on a western wall of the cooling tower unit. As was the case in Figure 4, the existence of carbonation phenomenon is apparent since the maximum peak of the curve is transferred from surface of the concrete to its depth. Chloride content is somehow high. At the location of bars (40 mm depth) chloride content of approximately 0.06% by weight of concrete which is very close to chloride threshold value is observed. Meanwhile, results of chloride profile of the farther units from the chloride unit showed a little amount of diffused Chloride. Therefore, the hypothesis of occurring interactions between adjacent units is highly presumable and should be considered in designing or at least allocating sufficient distances between different units.

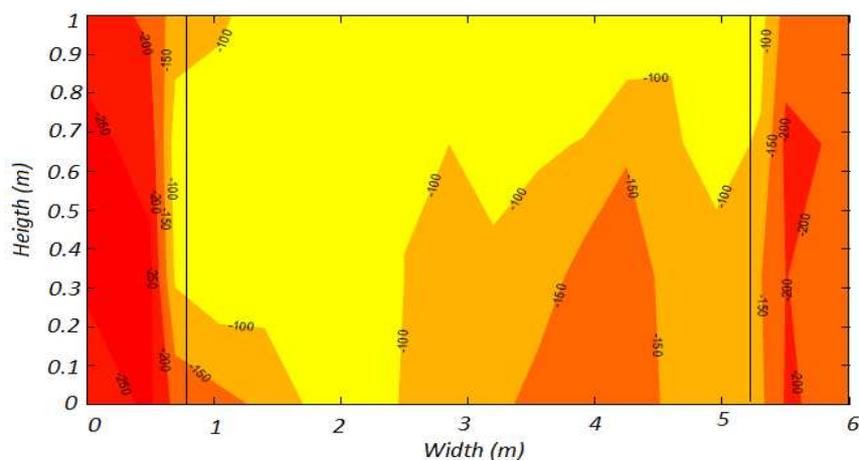
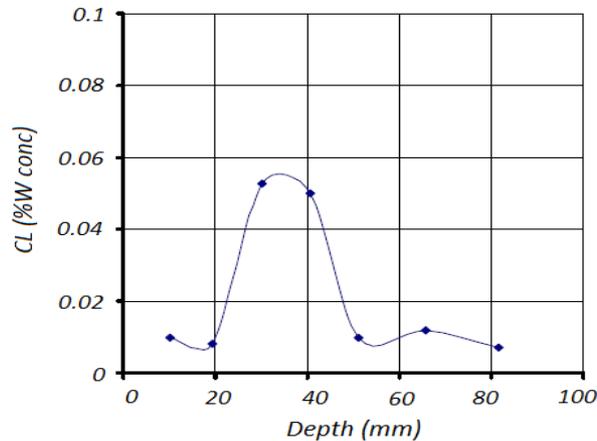


Figure 8. Half cell potential map of a the western wall of the cooling tower unit.

Table 3. Results of different tests on extracted cores from the cooling tower units.

Density (Kg/m ³)	Half-hour water absorption (%)	Saturated water absorption (%)	Electrical resistance (kΩ-cm)	Compressive strength (MPa)	Carbonation depth (mm)
2185	2.5	7.4	4	17	30

**Figure 9.** Chloride diffusion profile of a selected wall.

3 PROPOSED REPAIR METHODOLOGIES

- 1) For the ammonium nitrate unit in which the concrete was decalcified to a depth of 30 mm from its surface but for which reinforcement corrosion was not observed, the best repair scheme would be to remove concrete up to 30 mm depth and replacing with a high quality and compatible repair material [Vaysburd et al. 2004; Moragn 1996]. This should be followed by placing a protective and breathable coating on the exposed surfaces.
- 2) As was the case for the ammonium nitrate unit, for the cooling tower units the best repair method would be local patch repairs. But in some locations of these units, reinforcement corrosion was observed and in some regions the chloride content in proximity to the reinforcement was around the threshold value. Therefore, not only must the contaminated concrete be substituted by high quality and compatible concrete, but the corroded reinforcements must also be replaced by new rebars.
- 3) Most parts of the concrete structure of the chloride unit are contaminated by chloride ions far beyond the threshold value and up to 8 cm depth from its surface; reinforcement corrosion was observed to be well developed. Therefore it would be more cost-effective to build a new chloride unit than perform repair operations; in any case, durability parameters should be taken in to account.

4 CONCLUSIONS AND RECOMMENDATIONS

In this study the durability of some reinforced concrete structures forming part of a petrochemical complex and which showed early signs of deterioration since their construction were investigated. Results indicated various levels of deterioration due to different exposure conditions. The study was useful in that the results help further emphasize that environment conditions in which a structure is to perform should be thoroughly reviewed during design process to subsequently ensure satisfactory performance of such structures during its lifetime. Disregarding basic principles of durable structural design, may in fact lead to over expenditures for premature repairs during its utilization simply to ensure that it is maintained in an operational mode.

The investigations carried out in this study helped confirm that a concrete cover of 4 cm was not adequate for the aggressive environment in which this petrochemical complex operates. In addition, results of water absorption, electrical resistivity and compressive strength tests suggest that the w/c ratio used in the mix design was too high.

In conclusion, it is recommended that the petrochemical complex environment be considered as a harsh environment from durability of concrete point of view. Since there is no specific code and recommendations in this case, given value of nominal concrete cover (65 mm) provided in ACI 357R84 for a wall located in splash and atmospheric zone is highly recommended. It should be noted that concrete covers of reinforcement should not be significantly greater than the prescribed value to restrict the width of possible cracks. This would be more critical for those members in flexure. Moreover the concrete must be of low permeability therefore the w/c ratio must not be taken too high; a maximum w/c ratio of 0.4 is recommended (this is the value given in ACI 201.2R-01 for class 3 exposure to sulphate attack).

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