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# Corrosion of Beach Concrete Housing in the Yucatan Peninsula

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The Yucatán peninsula is a region surrounded north and west by the Gulf of Mexico, and by the Caribbean Sea in the east. It contains a narrow stripe of sandy soil, in front of the sea, more than a thousand kilometres long. In this region, a large number of small buildings are located whose main structural system employed concrete or masonry walls with reinforced concrete slabs for roofing. The environment in the peninsula has such a high chloride concentration that it places this region as the second in importance for the production of common table salt in Mexico. This resource, which is important for the economy, is the origin of an extremely aggressive environment for the buildings, either by corroding the reinforcing steel or by reaction of the sulphate ions with the hydrated cement paste. The aim of this study was the exploration of the pathologies present in beach houses in order to diagnose the damage and the proper rehabilitation procedure. Concrete properties, as well as chloride concentrations and carbonation depths, were measured from concrete cores obtained from the houses. Results show that the housing infrastructure in this region is continually affected, with heavy losses due to corrosion.

**Keywords:** carbonation, chlorides, corrosion, marine environment, reinforced concrete.

## 1. INTRODUCTION

Damage of concrete structures is occurring faster and more frequently when they are located along the sea coast, exposed to the marine environment. Mexico has more than 10,000 km of shore line in the Gulf of Mexico, the Caribbean Sea and the Pacific Ocean, thus an important part of their buildings and infrastructure is exposed to aggressive marine environments.

In tropical environments, the most important durability problem in reinforced concrete structures is, generally, associated with reinforcing steel corrosion. The main identified causes that onset the electrochemical process are the chloride ions present in the marine environment and the alkalinity loss due to the $CO_2$ present in all environments [1].

Houses are the more vulnerable structures against environmental loading, as they are subject to low level of mechanical loading due to their relatively small dimensions. Thus, their designs, which are generally based on strength criteria, result in elements of small transversal sections and the use of low quality materials [2].

As there is no risk of snowing in this tropical region, houses in southern Mexico are capped using flat roofs. Concrete gained acceptance as the material of choice around the thirties. But it was from mid forties to the late sixties that the roofs were made using flat concrete slabs reinforced in two ways (see Figure 1). From mid sixties prestressed concrete has become the preferred option for roofing.

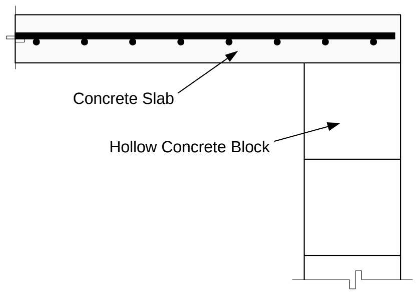


**Figure 1**. Reinforced concrete slab.

In the same manner, walls were stone masonry walls until hollow concrete block gained acceptance in the region. From mid sixties, hollow block masonry wall is the preferred option. Reinforced concrete is used for the headers in windows and doors openings and in the corners of the rooms. In these corners there are two options, based on the applied loads, the regular concrete column reinforced with four bars and stirrups (tie columns), or using a single bar (called rebar) cast inside the hollow of the blocks (see Figure 2).

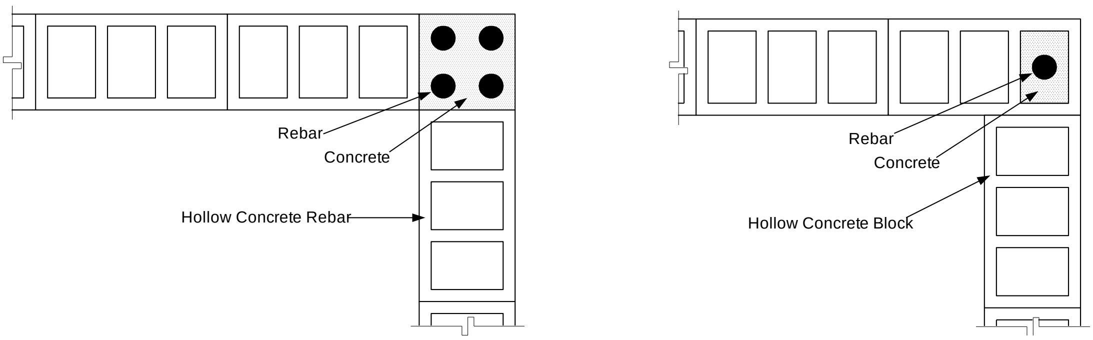


**Figure 2.** Wall corner detail (plant view).

In Mexico, as in most of the Latin-American countries, substitution of damaged infrastructure is generally difficult, as the historical cumulative deficit provoke that the never sufficient resources should be used for new construction in regions with less infrastructure.

In a particular level, owners acquire their houses by credit which they will pay during the most part of their productive life. Therefore, repair of damaged houses due to unexpected or premature deterioration is very hard to afford. This in turn diminishes the occupant's security and the service quality of the house.

The objective of this work was to study de corrosion of houses built in the coast of the Yucatan Peninsula, in order to diagnose the damage and the proper rehabilitation procedure.

## 2. METHODOLOGY

The north and east coasts of the Yucatán Peninsula were searched in order to identify places where houses were concentrated. The main data of the climate for each studied place were obtained from the National Meteorological Service [3].

Once the places were identified, single houses and developments were explored in order to observe the damage from the environmental loading; individual houses were selected based on the observed damage. In each of the selected houses, a general damage inspection was done and the structural concrete elements were chosen in order to take samples and perform further tests. All the samples, concrete powder, and electrochemical measurements were taken from the same area of the concrete elements; the studied area was located 1.5m above foundation.

Among those tests, concrete cover was measured as well as the carbonation depth; the latter was performed by measuring the pH reduction using an acid base indicator [4].

Concrete porosity and density were determined in lab from samples taken on the field [5]. To avoid excessive damage to the houses, compressive strength was estimated by means of the non destructive technique known as rebound hammer [6]; in spite of its inaccuracy to predict the actual concrete's compressive strength in carbonated concrete elements, this test is a good indicator of the material's homogeneity.

Corrosion of reinforcing steel was evaluated by means of electrochemical techniques using a commercially available corrosion meter employing a guard-ring sensor: concrete resistance, half-cell potentials [7] and corrosion rates [8].

In each concrete element studied, concrete powder was collected at five different depths (from cero to five cm) in order to determine the amount of total chlorides by means of a chloride ion selective electrode. Chloride extraction was performed according to ASTM C-1152 [9].

## 3. RESULTS AND DISCUSSION

The locations were selected following two criteria. In the north of the peninsula, along the Gulf of Mexico coast, four ports were chosen: Celestun (CE), Progreso (PR), Chabihau (CB), and Dzilam-Bravo (DB). In those ports the main activity is fishing, and the fishers' houses, in general, are not close to the sea, as the narrow sandy strip is full with summer houses, which are inhabited only from spring to summer by people coming from inland. In this case, the locations are almost rural, and the houses have been built individually by their owners.

In the east of the peninsula, along the Caribbean Sea, two cities were chosen: Cancun (CA) and Chetumal (CT); the first one is the most important tourist place in southern Mexico and most of their inhabitants are working in tourism; meanwhile, the latter one is a border town where the main activity is commerce. In both cases, the towns are urban and the houses belong to developments built, mainly, with public funds. Figure 3 shows the location of the selected places, and Table 1 the main meteorological variables.

Based on the town size and the dwellers disposition to lend their houses to take samples of the material, houses were selected in each location, from one house (in Celestun) up to five (Cancun and Chetumal). Table 2 presents the main characteristics of the studied structures.

All the houses studied, with the exception of those from Chetumal, were built with masonry walls, made of concrete blocks, confined by reinforced concrete elements (tie columns and bond beams); those houses from Chetumal were built with reinforced concrete walls. In addition, the masonry walls of the houses from Cancun were over-reinforced with small rebars every three lanes of concrete blocks, following a seismic design. All the roofing consists of ribbed concrete slabs made with small prestressed concrete beams and small concrete or polystyrene vaults (Cancun and Chetumal).

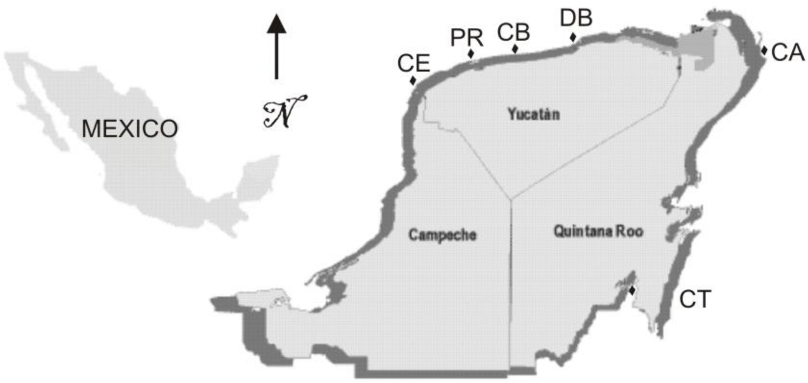


**Figure 3.** Location of the studied sites.

**Table 1.** Characteristics of the climate in the places studied.

| Place | Average maximum temperature (°C) | Average minimum temperature (°C) | Annual pluvial precipitation (mm) | Annual evaporation (mm) |
|---|---|---|---|---|
| Celestun (CE) | 32.4 | 20.4 | 787.1 | 1,921.8 |
| Progreso (PR)* | 30.4 | 21.1 | 687.6 | 1,657.6 |
| Chabihau (CB)** | 31.7 | 21.3 | 594.7 | 1,896.3 |
| Dzilam-Bravo (DB) | 31.4 | 17.1 | 702.2 | 1,769.9 |
| Cancún (CA) | 31.0 | 23.2 | 1,337.7 | n. a. |
| Chetumal (CT) | 31.4 | 22.4 | 1,327.4 | 1,803.7 |

* Station located at 5km. ** Station located at 14km.

**Table 2.** Characteristics of the studied structures.

| Place | Age (years) | Concrete Element | Cross section (cm) | Steel diameter (mm) |
|---|---|---|---|---|
| Celestun (CE) | 30 | Tie column | 25 x 25 | 13 |
| Progreso (PR) 1 | 17 | Tie column | 25 x 25 | 13 |
| Progreso (PR) 2 | 25 | Beam | 40 x 20 | 13 |
| Chabihau (CB)1 | 22 | Tie column | 15 x 15 | 10 |
| Chabihau (CB) 2 | 20 | Tie column | 15 x 15 | 10 |
| Dzilam-Bravo (DB) 1 | 23 | Column | 25 x 25 | 13 |
| Cancún (CA) 1, 2, 3, 4 & 5 | 27 | Bond beam | 14 x 22 | 10 |
| Chetumal (CT) 1, 2, 3, 4 & 5 | 15 | Wall | 12 (width) | 6 |

The general inspection showed common damage in the concrete elements of the houses; either by reinforcing corrosion or by sulphate attack. The reinforcing steel for seismic protection was corroded. Figure 4 presents some examples of the observed damage. Except for isolated cases, houses from Chetumal have no apparent damage.

Damage in wall, Cancun (CA).

Damage in outside ceiling, Chetumal (CT).

Damage in beam, Dzilam Bravo (DB).

Damage in wall, Chabihau (CB).

**Figure 4.** Damages observed in the different houses and localities.

The apparent estimated concrete strength, based on the rebound hammer, for the different houses was in the range from 30 MPa to 10 MPa, which involved the expected range for this type of construction [10]. Even though it has been documented that concrete carbonation usually increases the number of the bounces of the hammer, this technique showed clearly the great variability of the concrete employed in these houses.

Concrete porosity was in the range from 17 to 38%; these values represent the spectrum of possible variability of concrete quality used in this type of structures. Although concrete porosity was high, most of the values were in the expected range (up to 30%) due to the high porosity of the crushed limestone aggregate used in this region [11]. These results help to establish that total porosity measurement is not always a good indicator of the concrete durability.

Concrete cover was in the range 20 to 74 mm, which was, in most of the cases, fully carbonated. Table 3 presents the concrete characterization of the studied concrete elements.

Table 4 presents the results from the electrochemical measurements performed in order to evaluate de reinforcing steel corrosion: corrosion rates, half-cell potentials and concrete resistance.

For the houses along the north coast (CE, PR, CB, and DB), half cell potentials were indicating active corrosion. This was supported also by the low resistance values of the concrete cover obtained with the guard-ring sensor. However, corrosion rates were very low, indicating passive corrosion. This behaviour was attributed to the lack of moisture inside the concrete at the time of testing, as the concrete samples were almost dried at the beginning of the porosity test.

**Table 3.** Concrete characterization.

| Place | Concrete cover (mm) | Carbonation depth (mm) | Rebound hammer (MPa) | Concrete porosity (%) | Concret e density ($g/cm^3$) |
|---|---|---|---|---|---|
| Celestun (CE) | 26 | 20 | 20 | 17 | 2.2 |
| Progreso (PR) 1 | 30 | 45 | <10 | 21 | 2.1 |
| Progreso (PR) 2 | 25 | 47 | 28 | 19 | 2.1 |
| Chabihau (CB) 1 | 20 | 28 | 22 | 20 | 2.0 |
| Chabihau (CB) 2 | 30 | 30 | 20 | n. a. | 2.2 |
| Dzilam-Bravo (DB) | 32 | 28 | 20 | 22 | 2.0 |
| Cancun (CA) 1 | 44 | >50 | 18 | 29 | 2.4 |
| Cancun (CA) 2 | 58 | >50 | 15 | 28 | 2.4 |
| Cancun (CA) 3 | 50 | >50 | <10 | 38 | 2.3 |
| Cancun (CA) 4 | 20 | >50 | 23 | 29 | 2.7 |
| Cancun (CA) 5 | 20 | >50 | 19 | 25 | 2.5 |
| Chetumal (CT) 1 | 60 | 36 | 15 | 26 | 1.9 |
| Chetumal (CT) 2 | 76 | n. a. | 13 | 36 | 2.0 |
| Chetumal (CT) 3 | 74 | 55 | 12 | 29 | 2.0 |
| Chetumal (CT) 4 | 56 | 45 | 10 | 29 | 2.1 |
| Chetumal (CT) 5 | 54 | >60 | 13 | 28 | 2.2 |

In the case of Cancun, results were mixed as concrete resistance was high in most of them; half-cell potentials were passive in two cases but active in the other two. Corrosion rate was high only in CA 5 in good agreement with the low resistance measured.

In the case of Chetumal, results were mixed also, as the half-cell potentials were most of them active, but corrosion rates were passive with the exception of CT 4, which presented the lowest resistance value.

**Table 4.** Electrochemical measurements.

| Place | Corrosion rate ($\mu A/cm^2$) | Half-cell potential (mV) | Concrete Resistance (kΩ) |
|---|---|---|---|
| Celestun (CE) | 0.015 | -145 | 8.9 |
| Progreso (PR) 1 | 0.011 | -322 | 1.1 |
| Progreso (PR) 2 | 0.019 | -264 | 5.8 |
| Chabihau (CB) 1 | 0.010 | -266 | 1.8 |
| Chabihau (CB) 2 | 0.015 | -431 | 4.3 |
| Dzilam-Bravo (DB) | 0.090 | -462 | 3.7 |
| Cancun (CA) 1 | 0.010 | -344 | 31 |
| Cancun (CA) 2 | 0.011 | -136 | 31 |
| Cancun (CA) 3 | n. a. | n. a. | n. a. |
| Cancun (CA) 4 | 0.005 | -357 | 88 |
| Cancun (CA) 5 | 0.549 | -196 | 3 |
| Chetumal (CT) 1 | 0.031 | -250 | 16 |
| Chetumal (CT) 2 | 0.043 | -216 | 18 |
| Chetumal (CT) 3 | 0.020 | -386 | 27 |
| Chetumal (CT) 4 | 1.154 | -333 | 0.5 |
| Chetumal (CT) 5 | n. a. | -515 | n. a. |

Figure 5 presents the chloride penetration profiles for the houses found in the north coast of the Yucatan peninsula, directly exposed to the Gulf of Mexico Sea. Data for CB 1 corresponds to the second y axis. Figure 6 presents the chloride penetration profiles for the houses exposed in the northern part of the Caribbean Sea. Figure 7 presents the chloride penetration profiles for the houses located in Chetumal, exposed to the southern part of the Caribbean Sea. In these figures, each data point represents the average concentration plotted in the middle of the range where the powder was collected, e. g., at 5 mm for the 0 to 10 mm range.

According to the ACI [12], the chloride threshold goes from 0.6 to 0.9 $kg/m^3$ of concrete (equivalent to 0.17 to 0.26 cement percent by weight) although the CEB accepts 1.4 $kg/m^3$ of concrete (equivalent to 0.40 cement percent by weight). Only PR 2 and CB 2 are in-between those ACI values in Figure 5, supporting the half-cell potential measurements. Another oddity is the fact that there was a higher chloride concentration inside the concrete element than in the outer layers. This has been observed in chloride analysis from a very high w/c concrete specimen (w/c about 0.80). Therefore, due to the high porosity of the concrete element (high w/c ratio coupled with highly porous aggregate), the chloride concentration is higher at the core of the element, with fluctuations in the outer layers. Nevertheless, chloride concentrations from house CB 1 were three times above the values measured in the other houses. It was found that this particular house was twice flooded (up to 1.6 m above floor level) with sea water during hurricanes Gilbert (1988) and Isidore (2002) storm surges.

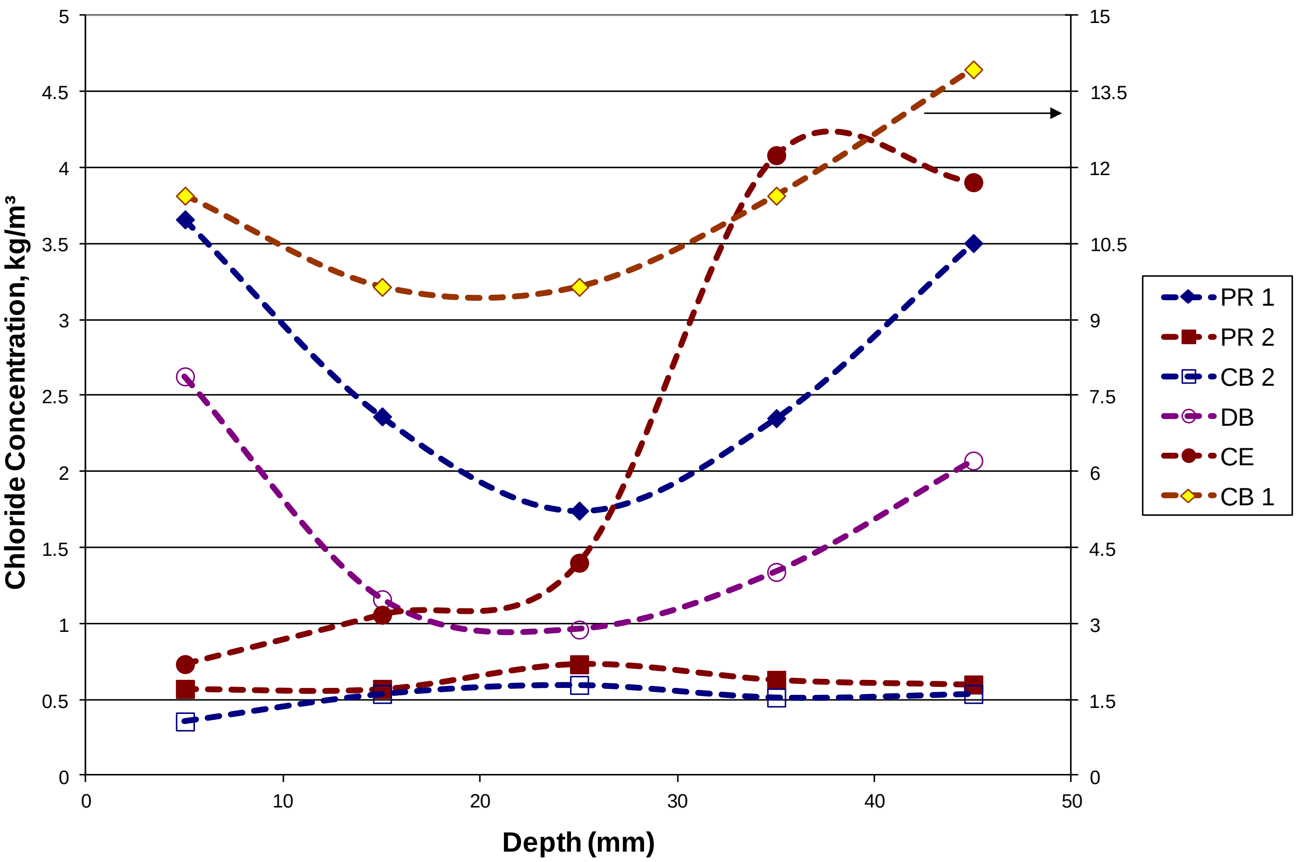


**Figure 5.** Chloride concentration from Celestun (CE), Progreso (PR), Chabihau (CB) and Dzilam-Bravo (DB) houses, in kg/m$^3$ of concrete.

Similar patterns were observed in the houses from Cancun (Figure 6). Most of the chloride concentration profiles were beyond the chloride threshold at rebar depth. The higher concentrations were observed in CA 3 and CA 5, in agreement with the corrosion rates observed, and particularly for CA 3, with the low concrete quality employed (Table 3).

In the case of the houses from Chetumal (Figure 7), all the concentrations were between the chloride values suggested by the ACI for corrosion onset. We have to take into account that these houses were not as old as the other houses. However, besides chloride ingress, concrete carbonation may be playing a very important role. In the north coast, only CE and DB have carbonation depths lower than concrete covers. In Cancun, only CA 2 may have a carbonation depth lower than the concrete cover. In the case of Chetumal, carbonation depth is beyond the concrete cover measured in CT 5. Therefore, the actual damage may not be attributed only to chloride induced corrosion, but may be due to a synergetic effect between chloride attack and concrete carbonation. In the Yucatan peninsula, concrete carbonation was measured previously in concrete buildings under marine [13] and non marine environments [14]. In both cases, it was found that the concrete properties were not enough to avoid carbonation during their expected service life of the structures. Even tough, concrete properties were twice as better as the concrete employed in these houses. The fact that carbonation front is reaching the concrete cover before the expected service life is an indication that concrete design based only on compressive strength can not guarantee proper durability of the structure.

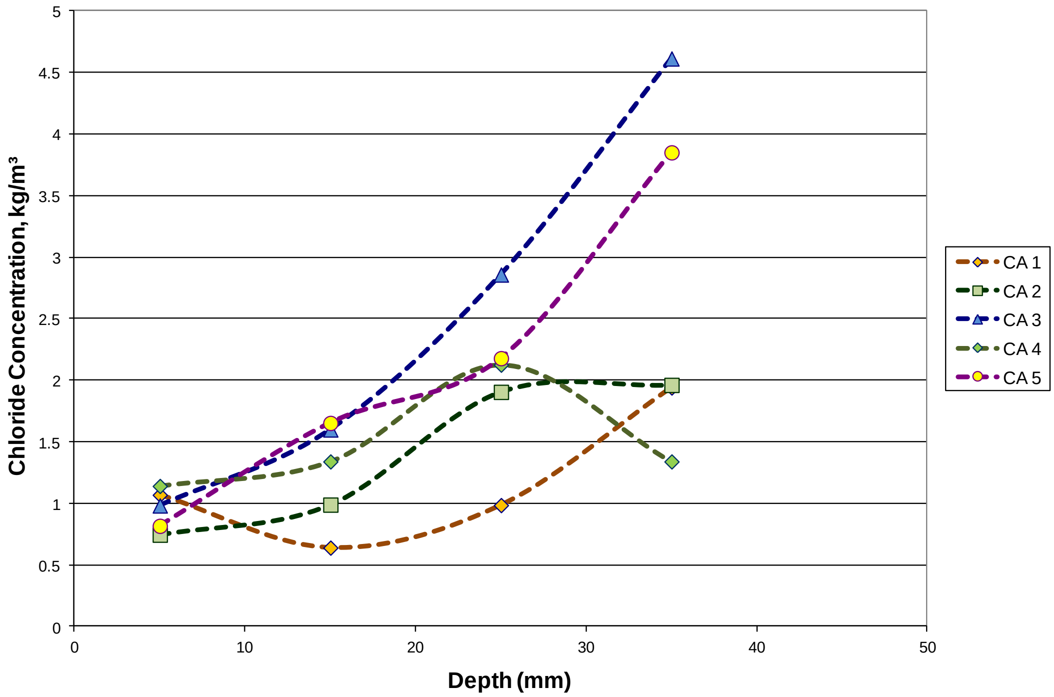


**Figure 6.** Chloride concentration from Cancun (CA) houses, kg/m$^3$ of concrete.

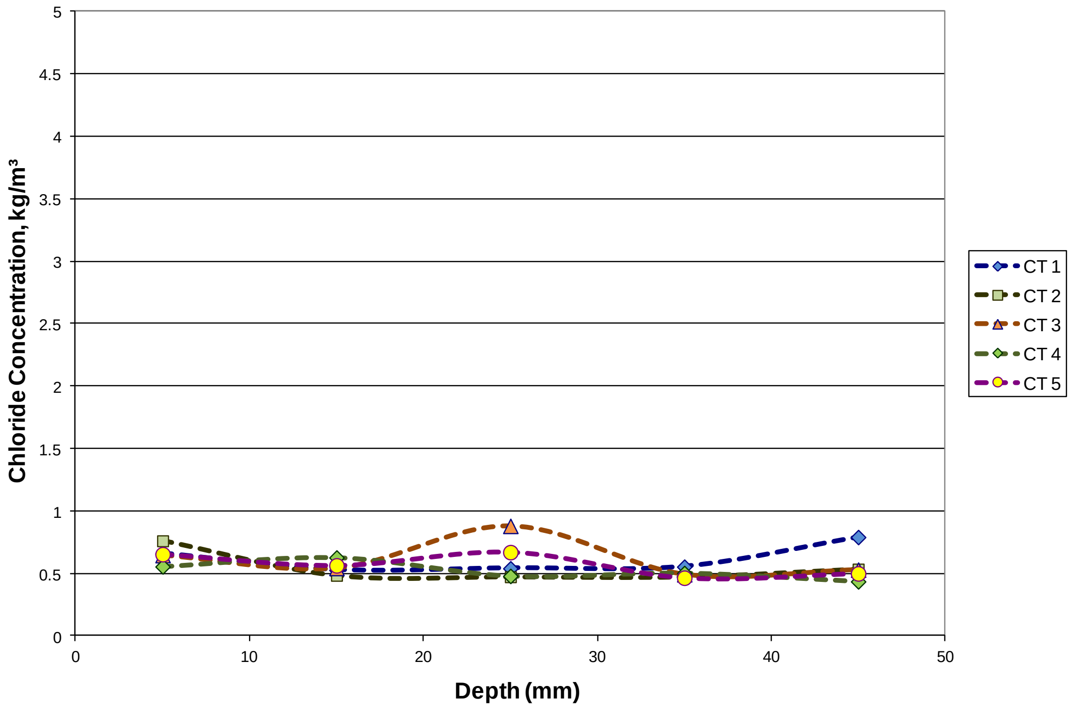


**Figure 7.** Chloride concentration from Chetumal (CT) houses, kg/m$^3$ of concrete.

In summary, houses built along the north coast of the peninsula are exposed to lower precipitation than those built along the east coast, especially in Chetumal. This may result in higher carbonation rates and chloride deposition at the surface. Also, predominant winds are from the east and the north, therefore, houses built in the north are more exposed than those in the south, i. e., Chetumal. Nevertheless, the concrete quality employed is not enough to withstand chloride penetration and concrete carbonation in order to ensure the expected service life.

## 4. CONCLUSIONS

The environmental loading along the Yucatan peninsula is causing early damage in concrete elements from houses with less than 30 years of building.

The use of steel reinforcement from seismic design without additional protection was counteractive for the durability of the concrete elements as it corroded damaging the masonry walls.

Durability criteria together with strength criteria should be the standard for concrete design in order to avoid corrosion of the reinforcing steel during the expected service life for houses along the coast of the Yucatan peninsula.

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