Time of Wetness and HR-T Complex as Tools for Corrosion Risk Evaluation in a Concrete Block Exposed to a Humid Tropical Environment

Tiempo de Humectación y el Complejo HR-T como herramientas para evaluar el riesgo por corrosión en un bloque de concreto expuesto a un ambiente tropical húmedo

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Manuscript Code: 512
Date of Reception/Acceptance: 24.10.2014/01.06.2015

Abstract

Material surface time of wetness (TOW) and temperature (T) are critical variables that influence the corrosion behavior of reinforced steel bars in concrete, and concrete durability. In concrete structures, both variables are indirectly dependent on the atmospheric relative humidity/temperature complex, and specific structural characteristics: concrete composition, water/cement ratio, curing time, geometry and orientation in the environment. Concrete internal TOW and T distribution data were collected using Cu/Au electronic sensors arranged at 15, 40, 65 and 75 mm depths in a concrete block (300 x 300 x 150 mm; w/c 0.5) exposed for one year in a rural-urban humid tropical climate in southeast Mexico. Concrete internal TOW allows structure designers to define concrete cover thickness over steel reinforcement bars. The results indicate that under the tested exposure conditions, the side of the block with the highest TOW values (west) would require a thicker concrete cover than that with lower values (east). Longer TOW can increase the possible permeation of gases such as CO2, and consequent concrete carbonation, as well as lead to loss of the passive state in steel reinforcement and initiation of the corrosion process.

Keywords: Concrete, Tropical Humid Climate, Rural-Urban Environment, Internal Distribution of Time of Wetness, Temperature

Resumen

El tiempo de humectación (TOW) y la temperatura (T) de la superficie de un material son variables críticas que influencian el comportamiento corrosivo del acero de refuerzo en el concreto y su durabilidad. Estos factores tienen una dependencia indirecta del complejo atmosférico humedad relativa/temperatura, debido a las características específicas del concreto: composición, relación agua/cemento (w/c), tiempo de curado, geometría y orientación en el ambiente. Con el objetivo de adquirir datos para la distribución interna del TOW y T, se colocaron sensores electrónicos de Au/Cu a diferentes profundidades de 15, 49, 65 y 75 mm en un bloque de concreto (300x300x150 mm; w/c 0.5), expuesto durante un año en clima rural-urbano tropical húmedo, del sureste de México. El TOW registrado en el bloque de concreto es importante para diseñadores de estructuras, para definir el espesor del concreto sobre el refuerzo. Los resultados obtenidos mostraron que en las condiciones de esta exposición, la cara oeste del concreto debería ser más gruesa que la orientada al este. La existencia de un largo TOW causará una mayor posibilidad de entrada de gases como CO2, lo cual conllevaría a carbonatación del concreto, pérdida de la capa pasiva del acero e inicio de su corrosión.

Palabras Claves: Concreto, Clima Tropical Húmedo, Ambiente Rural-Urbano; Distribución Interna de Tiempo de Humectación, Temperatura

Introduction

Internal humidification of concrete is a consequence of the internal relative humidity-temperature (RH/T) complex. Both parameters respond to the external environment and are those which most affect concrete structure durability. Moisture distribution inside concrete is mainly determined by concrete composition and curing time, and external microclimate (Nilsson, 1996). In new structures, internal moisture controls concrete hardening and curing, consequently affecting permeability to gases, water and aggressive ions.

Low moisture content at early ages produces reduced or defective cement hydration as well as surface porosity and shrinkage that can influence aggressive agent penetration (Parrot, 1988). If RH falls below 80%, cement hydration can actually cease (Enevoldsen et al, 1994). In contrast, the presence of moisture at intermediate and later ages can cause concrete to deteriorate. Pore moisture saturation is one of the factors that controls oxygen availability and therefore corrosion rate. Besides, this fact prevents penetration of gases such as CO2, but favors chloride diffusion. However, if pores are partially saturated carbonation can occur simultaneously with chloride penetration, leading to loss of alkalinity and an increased tendency towards corrosion (Andrade, 1989).

Carbonation can affect concrete cover permeability since the reaction involves modifications to cement paste matrix pore structure (Parrot, 1988). Water generally plays a vital role in chemical reactions in concrete and associated deterioration processes (Nilsson, 1996). In response to the above dynamic, a number of studies have been done on concrete internal RH to correlate environmental conditions to concrete durability and steel reinforcement corrosion onset. Laboratory in situ measurements have been done of RH profiles in partially sealed, 100 mm concrete cubes submerged in sea water at 20 and 50 mm depth (Nilsson, 1996).

The mechanism of moisture penetration into the concrete was found to be different than in a structure exposed to atmospheric conditions. In addition, curing time and the water/cement ratio (w/c) were found to have little influence on internal RH profiles (Parrot, 1991). A critical RH may exist for steel corrosion onset (Enevoldsen et al., 1994), perhaps 80% under laboratory conditions and 70% in field conditions. Finally, when a concrete contains chlorides, external environment RH is normally lower than internal RH (Andrade et al., 1996).

Despite identification of these basic responses, correlating internal RH to steel reinforcement corrosion rate and external RH remains a challenge (Parrot, 1991). Many authors have also found it difficult to correlate concrete internal and ambient external RH (Andrade et al., 1996). Immense research effort has been exerted to quantify how internal RH relates to other factors and the results suggest that RH cannot be used alone. Time of wetness (TOW) is actually a more accurate parameter for representing the reinforcement corrosion and concrete deterioration processes. It is the Time of wetness is the time during which wetness (condensation) occurs on surface exposed to environment On the other hand, relative humidity can be defined as the percentage of the ratio of water vapor pressure in the atmosphere to dew point water vapor pressure at the same temperature. [ec. 1]

The same RH value can be produced at different saturation levels. In contrast, TOW considers all the means by which an electrolyte solution remains on a metallic surface. Therefore TOW allows an accurate quantification of the duration of the electrochemical corrosion process, and explicitly indicates when mass transport and charge transfer, or electrochemical corrosion are possible.

$$RH=\frac{\text{Saturated } H_2O \text{ vapor pressure at dew point}}{\text{Saturated } H_2O \text{ vapor pressure at ambient temperature}} \times 100 \qquad [1]$$

The present study demonstrates the influence of different environmental parameters associated with a humid tropical climate (T, RH, rainfall, solar radiation) on T and TOW registered at different depths within a concrete block. The influence of block geometry and orientation vs. the sun on the RH-T complex and TOW are also addressed.

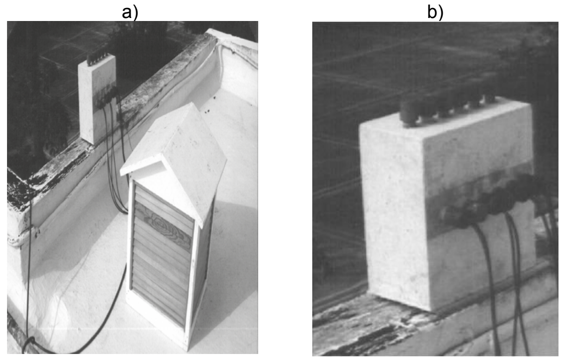
Experimental Procedure

Specimen design

Figure 1 presents an overview of exposed concrete block and electric data collection system for RH-T. A concrete block (300 x 300 x 150 mm) was made using type I Portland cement, aggregates and potable water at a 0.5 w/c. Six humidity chambers were placed inside the block at a depth of 75 mm from the thinner concrete block wall (Section A-A’, Figure 2). These helped to document the effects of the external RH-T daily complex and solar radiation on internal RH-T complex and TOW values.

This arrangement also allowed observation of environmental influence on block edges. An additional six PVC connections were embedded in the concrete block at different depths (15, 25, 40, 65 and 75 mm) to detect the influence of concrete permeability. Unlike other experimental block designs (Andrade et al., 1996), the block surfaces were left unsealed, to examine environmental effects coming from all atmospheric flows and their pollutants. The blocks were cured in a humidity chamber (RH ≈95%; T =23°C), following ASTM C31 for the preparation and curing of concrete specimens in the field.

Figure 1 a) Overview of exposed concrete block; b) electronic data (RH, T and TOW) data collection system. Source: Authors, 2013.



Exposure site

After curing, the concrete block was exposed to a rural-urban test-station (at CINVESTAV-IPN, Mérida) with a humid tropical climate located approximately 30 km from the Gulf of Mexico, on the Yucatan Peninsula. This distance was chosen because, from a corrosion point of view, chloride contamination is essentially absent (Corvo et al., 1997). Thus, TOW measurements would not be influenced by the presence of chlorides and their hygroscopicity. In a later project stage, blocks will be exposed in a marine environment. The tested concrete block was oriented towards the northeast to ensure that the thinnest wall surfaces (faces) would receive the first and last contact with sunlight (Figures 1 and 2).

The humid tropical environment, characterized by high annual average values of RH and T its highly aggressive for metals. This climate distinguishes itself by two distinct seasons: a dry season, which spans the winter months and a rainy season during the summer. In the winter the air salinity content as a consequence of the the predominant winds come from the north, crossing the Gulf of Mexico. During the rainy season in the summer, atmospheric pollution decreases and heavy rainfalls clean the concrete surfaces, preventing a salt accumulation.

Figure 2. Experimental concrete block diagram. Source: Authors, 2013

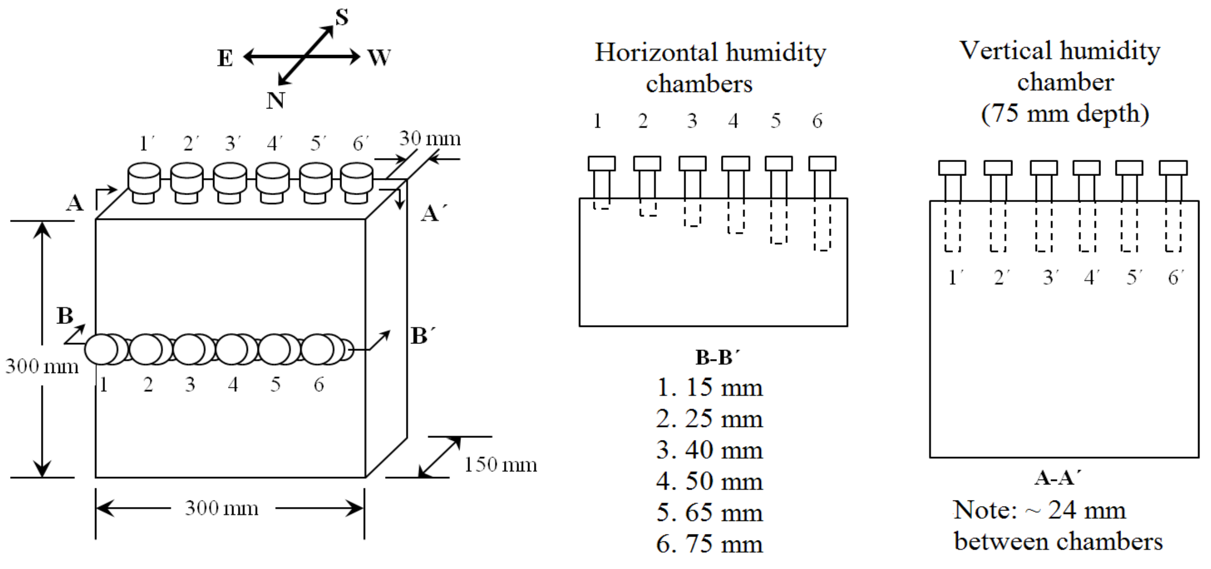
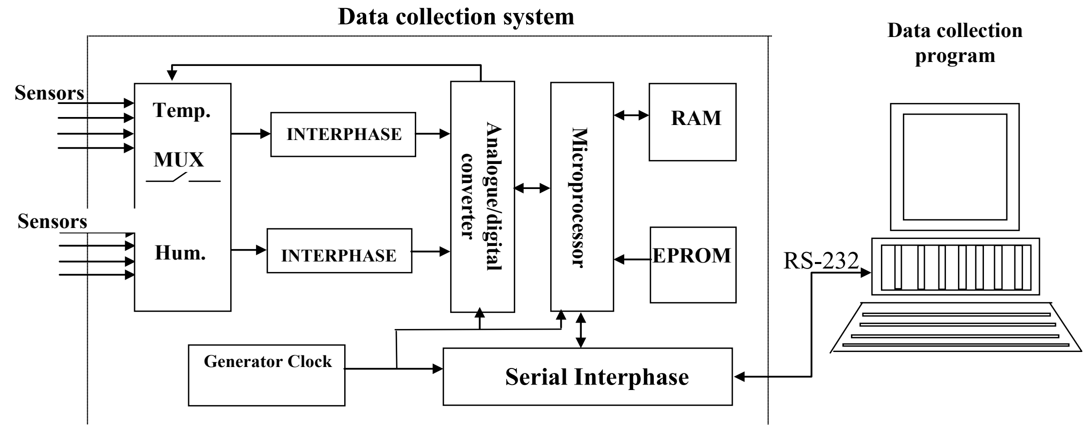


Figure 3. Flow diagram for collection, storage and transmission of RH-T and TOW data from the concrete block specimen. Source: Authors, 2013.



Annual TOW was calculated as 4840 h based on the ambient atmospheric RH-T complex (HR≥ 80% at 25°C ≥T≥ 0°C) according to ISO 9223 (Veleva et al., 1997) distributed in different ranges temperature. For example, the largest percentage of TOW (54-66%) occurs in the 20-25ºC Temperature range, which is characteristic of a humid tropical climate.

RH-T complex and TOW collection sensors and devices

An electronic device was designed and built with software to collect, store and transmit T and TOW data to a computer for up to eight independent channels (4 for T and 4 for TOW; Figure 3). It continuously stored data for a twenty-day period. Both T and TOW were measured using specific electronic components and a Cu/Au capacitive sensor appropriate for recording TOW data, following ASTM G84-89.

Data were recorded hourly and processed with commercial spreadsheets. Selection of the humidity chambers, into which the sensors were placed, was based on a previous study done with a portable RH-T measurer (Castro et al., 1997). These previous results indicated that the 15, 40, 65 and 75 mm depths were most representative for demonstrating environmental effects on internal T and TOW. However, measurements taken with the portable RH-T measurer made TOW calculation rather impractical (Castro et al., 1997).

Results

The present data represent one year of exposure in a rural-urban environment with a humid tropical environment. They are comparisons between concrete internal RH-T complexes and the external environment. The RH and T values shown below are for the winter months (October or January) when external RH values are high and therefore have a greater impact on concrete degradation and steel reinforcement corrosion.

Block internal RH values (October, surface B-B', north-south) showed that at about 0830 h, after external RH ≈100% in the early morning, zones nearer the surface (2.5 – 4 cm) had values near 100%, whereas deeper zones (6.5 mm) had slightly lower values (87%) closer to external RH at this time (Figure 4). As the sun heated the concrete, RH tended to reach equilibrium between the different depths, with a tendency to dry out, although concrete internal RH was always higher than external RH. For example, at 1230 h, concrete internal RH was 30% more humid than the external environment. Among other things, this could mean that any steel bar at these depths is exposed during the morning hours in damp concrete in which RH surpasses 80%, the point at which water condensation begins. This would promote development and continuation of the corrosion process. As mentioned above, the presence of water leads to dissolution of the chlorides deposited on the concrete surface and would facilitate their transport and propagation throughout the structure (Enevoldsen et al., 1994). The seriousness of this corrosion threat depends on the amount time the structure remains wet.

Temperature data for the same depths in the block and at the same times shows that at 0830 h the temperatures at shallow depths (2.5 – 4 cm) were very similar to external T, while at 6.5 cm T was much cooler than at the shallower depths (Figure 5). By mid-day (1230 h), T at shallower depths was approximately 7 °C higher than in the environment. These differences in internal T at different depths would be reflected in the steel reinforcement corrosion rate. Indeed, a 10 °C increase can change the corrosion rate an order of magnitude.

In the vertical chambers, all at 7.5 cm depth and spaced 2.4 cm apart along the block's A-A' surface, RH values were similar to external RH at 0830 h but decreased over time (Figure 6). Even so, by 1230 h concrete RH values remained 15-20% higher than external RH. Small differences in RH between sensors was due to differential sun exposure from east to west along the block's eastern edge.

Figure 4. Average RH values at different depths in the concrete block (surface B-B', north-south) compared to late morning external RH values in October (Winter) Source: Authors, 2013.

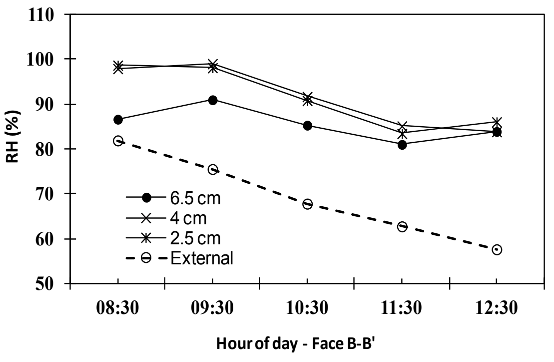


Figure 5. Average T values at different depths in the concrete block (surface B-B', north-south) compared to late morning external T values in October (Winter) Source: Authors, 2013.

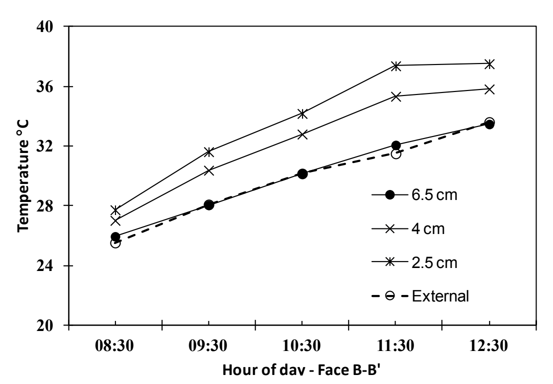


Figure 6. Average RH values at the same depth (7.5 cm) and at equal distances on the block's A-A' surface (east-west) compared to external RH in late morning hours of October (winter). Source: Authors, 2013.

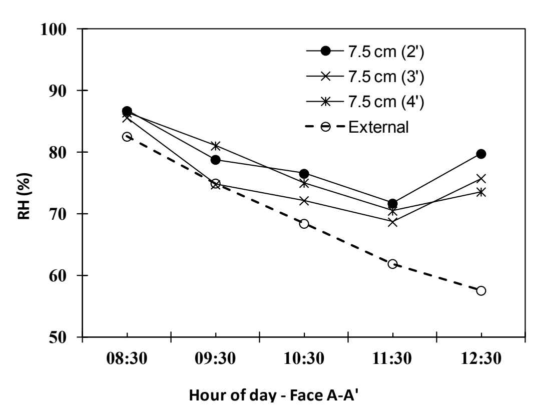
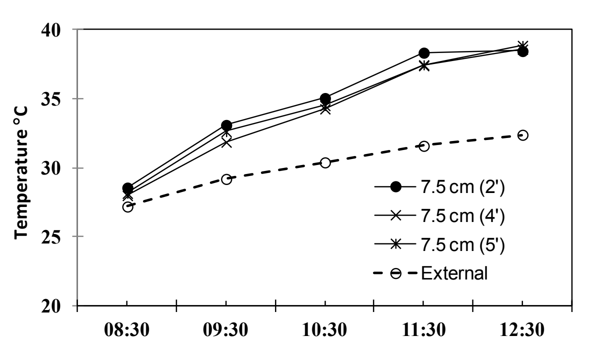


Figure 7. Average T values at the same depth (7.5 cm) and at equal distances on the block's A-A' surface (east-west) compared to external T in late morning hours of October (winter). Source: Authors, 2013.



Temperature in the vertical chambers confirmed the effect of sun exposure on the sensors from east to west (Figure 7). At 0830 h, internal block T was 2 to 3 °C higher than external T, but by 1230 h internal T was 7 to 8 °C higher than external T. Using 24-hour cycles during the month of January, post mid-day changes are easily observed and provide data for a longer time period than in Figures 4-7. RH values in this period showed a tendency for concrete humidification beginning after sunset with internal RH at different depths being higher than external RH (Figure 8). After midnight and during the early morning, internal RH remained almost constant and was only slightly (5 to 8%) drier than external RH.

During the same cycles and time period, block internal T tended to remain from 2 to 3 °C higher than external T at the studied depths (Figure 9). The data for the A-A' surface (vertical humidity chambers) for the same cycle and during the same period coincide with the previous observations. During the night, internal values were near external values while during the day they were less humid and hotter. Differences between sensors were greatest for the chambers in the final positions (7 and 8), which were the last to receive morning sunlight. Overall, however, sun exposure throughout the day caused T to be depth-dependent. Time of wetness (TOW) data collected with the Cu/Au capacitive sensor constitutes vital real time information on corrosion process development in steel reinforcement. In Figure 10, hourly data for T and TOW at different depths compared to external data are shown for one rainy day in July (summer). The rain fell between 1500 and 1820 h.

Changes in internal T responded to changes in external T, although internal T was out of phase during the period of greatest sun exposure. A small but clear difference in T values at different depths is apparent during this period. Concrete internal T at all depths was 2 to 3 °C higher than external T from midnight to 0700 h (dawn) and from sunset (1800 h) to midnight (i.e. 1800 – 0700h). This pattern was repeated every day that data were collected, demonstrating that concrete internal T exhibits a clear logical response to the external environment.

This can also be said of TOW since no TOW was recorded at the 40 and 65 mm depths, but was detected at the 15 mm (TOW = 6 h) and 75 mm (TOW = 20 h) depths. Although this was a rainy day, the wind pushed the rainfall onto the southern surface of the block, resulting in these discrepancies in TOW values. External environment TOWcalc (HR≥ 80% to 25°C ≥T≥ 0°C) was 16 h. The depth at which a steel reinforcing bar is placed is clearly not the only factor affecting TOW (real time corrosion process development) since structural element orientation, concrete thickness and rainfall direction on a given day can also affect this parameter.

On a dry day in July (summer), external environment TOWcalc (HR≥ 80% to 25°C ≥T≥ 0°C) was approximately 12 h (Figure 11). Again, concrete internal T at different depths followed changes in external T with shallower depths being hotter overall (43 to 44 °C). Block orientation also affected internal T behavior. The block's east face remained hotter throughout the day, causing the sensors at 15 and 40 mm to have higher T, while the west face accumulated less heat, resulting in lower T in the 65 and 75 mm sensors. The exterior layers of the block (the 15 mm and 75 mm sensors) were those which cooled more rapidly once the sun had set, leading to humidification. It was these same sensors that detected TOW (Figure 11).

Discussion

The RH-T complex values showed concrete block internal T to be near external environment T at 0830 h, but to exceed external T by 1230 h due to sun exposure. Relative humidity is closely related to environmental T. The concrete internal RH values reported here are sufficiently high for the corrosion process to develop in steel reinforcement. A critical RH (RHcrit) does exist below which corrosion will not occur on a metal structure (Enevoldsen et al., 1994), but this value refers to metal surfaces free of corrosion products (Weiss, 1935). A second (lower value) RHcrit is therefore used when porous corrosion products have formed and/or hygroscopic salts (e.g. chlorides) have been deposited on the metal surface.

Figure 8. Average internal RH values for concrete block at different depths (B-B' surface, north-south) compared to external RH in 24 h cycles during January (winter). Source: Authors, 2013.

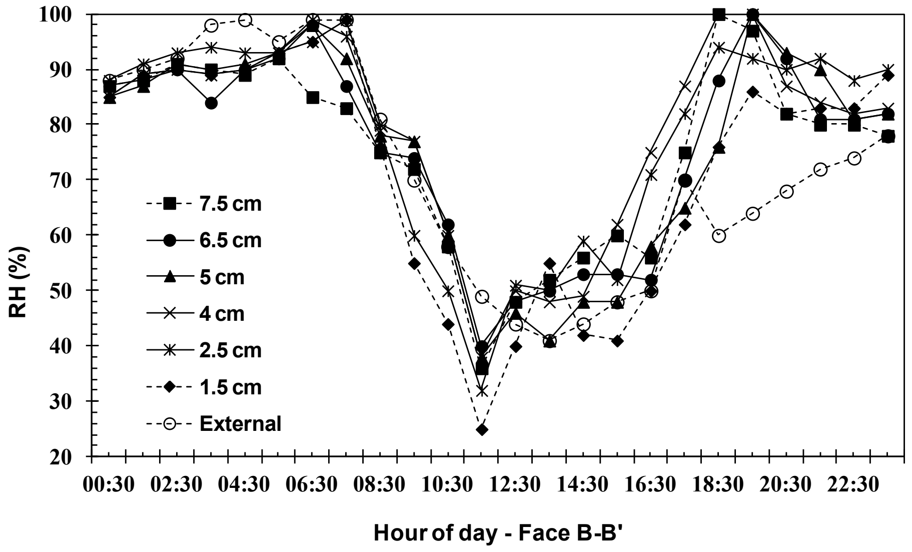
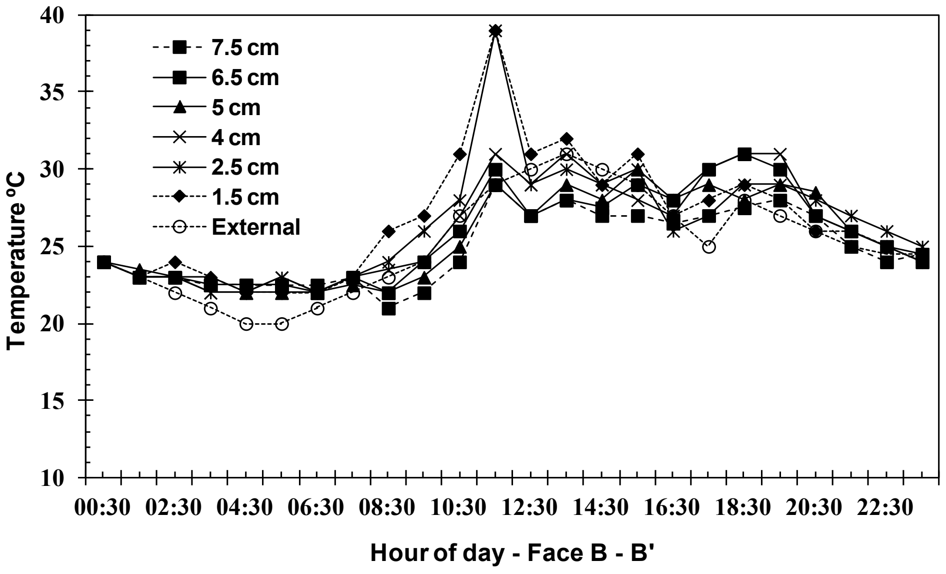


Figure 9. Average internal T values for concrete block at different depths (B-B' surface, north-south) compared to external T in 24 h cycles during January (winter). Source: Authors, 2013.



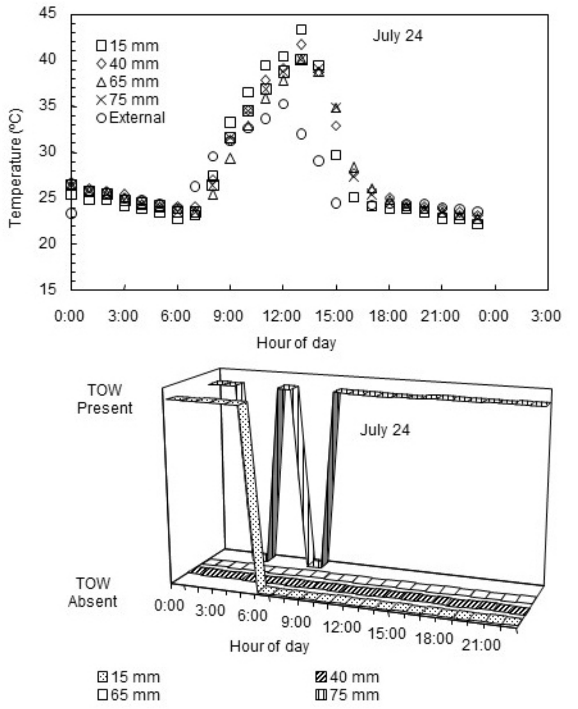
When metal exposed in a marine-coastal environment begins to corrode, even slowly, a RHcrit value of 60% has been reported (Schikorr, 1964). However, when environmental RH reaches 75-80%, a thin layer of capillary humidification forms on the metal surface, accelerating the corrosion process (Weiss, 1935; Schikorr, 1964). At 95% RH, the corrosion rate is still higher as a thicker humidity layer forms, known as dew. In other words, the RHcrit value is common for all metals free of corrosion products and in chloride-free environments, but secondary and tertiary RHcrit values will be condition-dependent.

The same phenomenon can occur in steel-reinforced concrete. In a study of concrete internal RH during one year exposure (Andrade et al., 1996), internal RH values ranged from 55 to 90% and reinforcement corrosion rates varied from insignificant corrosion current values (0.06 μA/cm2) to significant values two orders of magnitude greater (0.7 μA/cm2). Under laboratory trial conditions using mortar specimens contaminated with 2% chloride, a critical RH value of 80% was determined, although this still requires field testing (Enevoldsen et al., 1994).

The correspondence of different RHcrit values to different degrees of environmental pollution and metal surface conditions makes it difficult to correlate RH and corrosion rate. More precise parameters are therefore needed. Time of wetness (TOW) includes the time during which an electrolyte layer (humidification) remains on the metal surface and is therefore considered a real time measurement of corrosion process development (Shereir et al., 1994).

Susceptibility to corrosion initiation and corrosion process propagation varies widely depending on circumstances and needs to be studied according to the conditions in specific

Figure 10. T and TOW values at different depths in a concrete block exposed to a humid tropical climate during one rainy day in July (summer), compared to values for the external environment. Source: Authors, 2013.



TOW (15 mm) = 6 h (00 to 05 h)
TOW (40 mm) = 0 h
TOW (65 mm) = 0 h
TOW (75 mm) = 20 h (00 h to 02 h, 05 to 06 h, 09 to 00 h)
TOWcalc = 16 h (01 to 07 h, de 15 to 00 h)

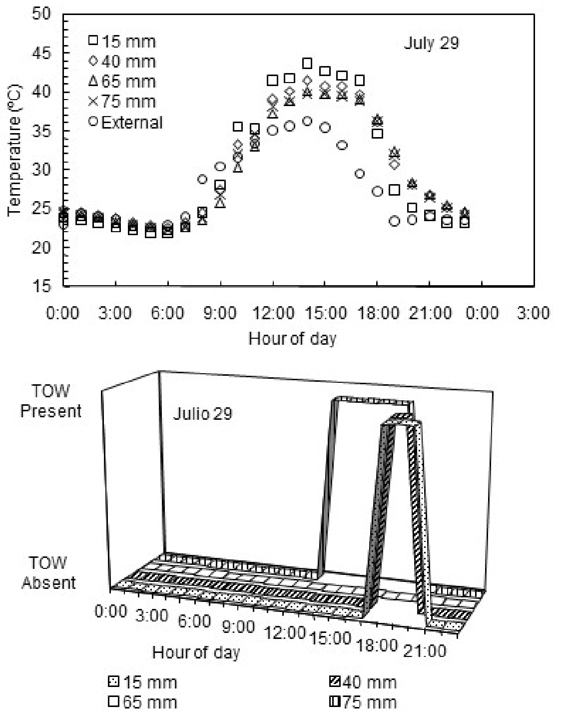
environments. Recording of concrete block internal RH-T complex and TOW data in the present study allowed quantification of how environmental parameters in a humid tropical climate and block orientation affected values on different block faces and at different concrete depths. These data are vital to structure designers.

The present results indicate that, under the tested exposure conditions, structure concrete cover needs to be thicker on surfaces with higher TOW values (the west face in this case) than on those with lower TOW values (east face). Higher TOW values obviously facilitate the beginning and progression of steel reinforcement corrosion, but may also increase the possibility of reaction with gasses such as CO2 that can lead to concrete carbonation. More detailed future research will need to use steel reinforcement in concrete blocks to generate more data on the possible correlations between TOW, the general steel corrosion process at different depths and block surface proximity-orientation.

Conclusions

In humid tropical climates, external environmental parameters have a well-defined influence on the distribution of internal RH-T complex and TOW values in concrete. These would directly affect the corrosion process in embedded steel reinforcement. Concrete block surface orientation and its depth clearly affected RH-T and TOW values. Overall, during daylight hours the concrete heated up, leading to internal T higher than external environmental T values. During these hours, HR values also remained higher than external values, which would facilitate the steel corrosion process.

Figure 11. T and TOW values at different depths in a concrete block exposed to a humid tropical climate during one dry day in July (summer) compared to values for the external environment. Source: Authors, 2013.



TOW (15 mm) = 3 h (18 to 20 h)
TOW (40 mm) = 2 h (18 to 19 h)
TOW (65 mm) = 0 h
TOW (75 mm) = 6 h (13 to 18 h)
TOWcalc = 12 h (01 to 07 h, 19 to 00 h)

The data reported here for a concrete block are important for structure designers when defining concrete wall thickness. For concrete structures exposed to the tested humid tropical climate, the most exposed surface has longer TOW values and therefore needs to be thicker than other surfaces. Prolonged TOW may lead to concrete carbonation via greater reaction with gases such as CO2, as well as more rapid initiation and progression of corrosion of embedded steel reinforcement.

Acknowledgments

The research reported here was partially financed by the CONACyT (projects 2667 PA and 2186 PA) and the CINVESTAV-IPN Unidad Mérida. The authors thank Dr. Neal S. Berke of the G-01 ASTM Committee for his comments. The opinions expressed here are those of the authors and not necessarily of the financing institutions. The authors also thank M. Balancán, F. Kantún and J. Bante for their technical assistance.

References

Andrade, C. (1989) Manual for inspecting corrosion damaged structures (in spanish), Madrid: Editorial ICCET/CSIC.

Andrade, C., Sarria, J. & Alonso, C. (1996) Statistical study on simultaneous monitoring of rebar corrosion rate and internal relative humidity in concrete structures exposed to the atmosphere. In: 4th International Symposium on Corrosion of Reinforcement in Concrete Construction, C L. Page, P. Bamfoth and J. W. Figg (Eds.), Cambridge, 233-242

Castro, P., Veleva, L. & García J. (1997). Distribution of relative humidity and temperature in concrete exposed to a rural-urban atmosphere. In XII National Congress of the Mexican Society of Electrochemistry (in spanish), Merida, 42-50.

Corvo, F., Haces, C., Betancourt, N., Maldonado, L., Veleva, L., Echeverría, M., Rincón, O. & Rincón, A. (1997). Atmospheric corrosivity in the Caribbean area. Corrosion Science, 39 (5) 823-833.

Enevoldsen, J. N., Hansson, C. M. & Hope, B. B. (1994). The influence of internal relative humidity on the rate of corrosion of steel embedded in concrete and mortar. Cement and Concrete Research, 24 (7), 1373-1382.

Nilsson, L. O. (1996). Moisture in marine concrete structures, In 7th International Conference on Durability of Building Materials and Components, L. Tang and L. O. Nilsson (Eds.), Stockholm, pp. 23-45.

Parrott, L. J. (1988). Moisture profiles in drying concrete. Advances in Cement Research, 1(3), 164-170.

Parrott, L. J. (1991). Factors influencing relative humidity in concrete. Magazine of Concrete Research, 43(154) 45-52.

Schikorr, G. (1964). Die Bedeutung des Schwefeldioxyds für die atmosphärische Korrosion der Metalle. Werkstoffe und Korrosion- Materials and. Corrosion, (15) 457-463.

Veleva, L., Pérez, G. and Acosta, M., (1997). Statistical analysis of the temperature-humidity complex and time of wetness of a tropical climate in the Yucatan Peninsula. Atmospheric Environment, 31 (5), 773-776

Weiss, J., (1935). Investigations on the radical HO2 in solution. Transactions of the Faraday Society, 31, 668-681