Discussion about models for estimation of relative humidity - case study of the brazilian coast versus influence in concrete durability

Discusión acerca de modelos para la estimación de la humedad relativa - estudio de caso de la costa brasileña frente la influencia en la durabilidad del hormigón

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Abstract

Relative humidity is very important for different applications in engineering, including the durability of concrete structures. However, it has been noted that in several cities there are no weather stations with complete time series data. The aim of this paper is to discuss models available in literature to estimate the relative humidity and check its behavior for marine environments. The methodology consisted in comparative analyzes of relative humidity predicted by models and values measured by weather stations for a period of 30 years of data. Two models for 16 different cities of the Brazilian coast were analyzed. For analysis and comparison of these data, the statistical performance of results was evaluated. Among the results, it has been observed through statistical analyzes that one of the models showed better conditions to estimate the relative humidity for marine environments than the other one. However, the need for developing a more appropriate model for this kind of environment has been identified.

Keywords: Humidity, concrete structures, models, statistics, coastal environment

Resumen

En la ingeniería, la humedad relativa es muy importante para diferentes aplicaciones, entre ellas la durabilidad de las estructuras en hormigón. Sin embargo, se ha observado que en algunas ciudades no existen estaciones meteorológicas que reúnan datos completos de las series de tiempo. El objetivo de este trabajo es discutir los modelos disponibles en la literatura para estimar la humedad relativa y comprobar su comportamiento para entornos marinos. La metodología utilizada consiste en el análisis comparativo de la humedad relativa predicha por los modelos y de los valores medidos por las estaciones meteorológicas durante un período de treinta años. Se analizaron dos modelos en dieciséis ciudades de la costa brasileña. Para el análisis y la comparación de los datos, se evaluó el comportamiento estadístico de los resultados. En los resultados de los análisis estadísticos practicados, se observa que uno de los modelos ha demostrado ser mejor para estimar la humedad relativa de los medio ambientes marinos. De igual forma, se identificó la necesidad de desarrollar un modelo más apropiado para este tipo de ambiente.

Palabras claves: Humedad, estructuras de hormigón, modelos, estadística, medio ambiente costero

1. Introduction

The lack of continuous data from weather stations is a persistent problem that affects studies related to monitoring and analyzing events in nature. Especially when it comes to countries with large territories, such as Brazil, the scarcity of such data reduces the possibility of further studies involving climate variables. The estimation of such data is a commonly used alternative for filling incomplete series (Koehn and Brown, 1985; McVicar and Jupp, 1999; Tardivo and Berti, 2012).

Among these climatic variables, relative humidity is extremely important for engineering and agricultural applications (Castro et al., 2000; Goodrum et al., 2009; Yang et al., 2013; Chai et al., 2014), and it is also related with effect on human discomfort (Schoen, 2005).

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Relative humidity is an essential environmental variable for the built environment (especially in marine environment), as in the case of reinforcement corrosion. For example, the chloride ion diffusion is a damp process, which can occur only if water is present in the pores of concrete (Page et al., 1981; Saetta et al., 1993; Bastidas-Arteaga et al., 2010). Some predicting models of chloride penetration into concrete require data on relative humidity in their formulations (Saetta et al., 1993; Bob, 1996; Andrade, 2001).

Two models to estimate the service life of reinforced concrete structures can be discussed to illustrate what has been mentioned in the previous paragraph. Saetta et al. (1993) applied a numerical procedure based on the finite element method to formulate the chloride penetration in concrete. In their analysis, they proposed the model of Equation 1.

$$D_{c2} = D_{c1} \cdot f_1(T) \cdot f_2(t_e) \cdot f_3(RH) \quad (1)$$

Where D_{c1} and D_{c2} (cm^2/s) are the reference and corrected chloride diffusion coefficient, respectively; $f_1(T)$ is the factor that represents the influence of temperature; $f_2(t_e)$ is the factor that represents the influence of the equivalent maturation time; and $f_3(RH)$ is the factor that represents the influence of relative humidity. According to this model, relative humidity impacts the chloride diffusion coefficient according to Equation 2.

$$f_3(RH) = \left[1 + \frac{(1 - RH)^4}{(1 - RH_c)^4} \right]^{-1} \quad (2)$$

In Equation 2, RH_c is the humidity at which D_{c2} drops halfway between its maximum and minimum values, equal to 75 %, according Saetta et al. (1993); and RH is the currently considered relative humidity (%). Figure 1 shows the $f_3(RH)$ variation for different values of relative humidity. It has been observed that relative humidity plays an important role in chloride penetration in concrete mainly in the range 60-90%.

Figura 1. Variación del $f_3(RH)$ como función de la humedad relativa
Figure 1. $f_3(RH)$ variation as a function of relative humidity

Andrade (2001) proposed another model (Equation 3) for estimating the depth penetration of chlorides in concrete.

$$x = 7.35 \cdot \frac{UR^{0.7} \cdot T^{0.1} \cdot Cl^{0.7}}{k_1 \cdot f_{ck} \cdot k_2 \cdot (1 + Ad)^{0.2}} \cdot \sqrt{t} \quad (3)$$

Where: x = depth of chloride penetration (equivalent to a chloride content of 0.4% by mass of cement); UR = average relative humidity (%); T = average temperature ($^{\circ}\text{C}$); Cl = surface chloride concentration (% by mass of cement); k_1 = factor dependent on the type of cement (tabulated); f_{ck} = characteristic compressive strength of concrete (MPa); k_2 = factor dependent on the type of mineral admixture (tabulated); Ad = amount of mineral admixture in concrete (% by mass of cement).

According to Andrade's (2001) model, the chloride depth varies with relative humidity by an exponential relationship ($y = a^b$; where $b = 0.7$). In addition to the models discussed, it is noteworthy that other models (Bob, 1996) also use the relative humidity as input parameter in equations to estimate concrete service life. However, the lack of such data may inhibit the implementation of these models.

This is just one example about the importance of relative humidity in durability of concrete structures. Several other cases can be discussed, such as carbonation evolution and leaching process in concrete, among others, but they were not the subject of this paper.

2. How to estimate relative humidity

As a way to overcome data gaps, the relative humidity can be obtained, among other ways, using psychrometric tables (Stull, 2011), by spatially interpolated climate data on grids (Hijmans et al., 2005), or by models having the capacity of estimating this variable as a function of other environmental parameters as in Castellví et al. (1996), Laurence et al. (2002) and Silva (2006) models.

Castellví et al. (1996) suggest the application of Equation 4 for calculating relative humidity.

$$RH = 100 \frac{e_s(T_n)}{e_s(T_m)} \quad (4)$$

Where $e_s(T_n)$ is the saturation vapor pressure (hPa), determined from the dewpoint temperature ($^{\circ}\text{C}$), and it may be replaced by the minimum temperature (T_n), according to experiments of Castellví et al. (1996) and Mcvicar and Jupp (1999); and $e_s(T_m)$ is the saturation vapor pressure (hPa), calculated from the hourly average temperature ($^{\circ}\text{C}$).

One way to calculate the saturation vapor pressure (e_s in Pa) is through the classic Equation 5 proposed by Tetens (1930), where temperature (T) is given in Celsius degrees ($^{\circ}\text{C}$).

$$e_s = 610.8 \cdot e^{\left(\frac{17.3T}{237.3+T}\right)} \quad (5)$$

Another way to determine e_s is by Equation 6 given by Kuo and Raymond (1980), and which was applied by Raymond (2000) to study moisture advection using relative humidity. T is given in Kelvin (K).

$$e_s = 6.11 \cdot \exp \left[25.22 \left(1 - \frac{273.16}{T} \right) \right] \cdot \left(\frac{273.16}{T} \right)^{5.31} \quad (6)$$

Vuille et al. (2003) found consistency in applying the method proposed by Castellví et al. (1996) to estimate the relative humidity. They applied such model to study the Global Climate Change in the Tropical Andes during the period from 1950 to 1998.

Silva (2006) statistically evaluated monthly values of several meteorological variables in order to obtain an equation to compensate the lack of data about relative humidity for the Brazilian states of Alagoas, Bahia and Sergipe.

The independent variables evaluated and proposed by Silva (2006) to elaborate the model were: the effective moisture index (I_m); the rainfall; the minimum (T_n), medium (T_m) and maximum (T_x) temperature; the minimum and maximum saturation vapor pressure; the saturation vapor pressure deficit; the thermal amplitude; and geographical variables such as longitude (λ), latitude (θ) and elevation (z).

Thus, Silva (2006) selected the most important environmental and geographical independent variables from multiple regressions and proposed the model represented by Equation 7.

$$UR = a \exp \left\{ - \exp \left[\frac{-(I_m - b)}{c} \right] \right\} \cdot [d + e(T_m \lambda)] \quad (7)$$

Where parameters a , b , c , d and e were regionally adjusted by Silva (2006). These parameters are shown in Table 1.

Tabla 1. Parámetros propuestos por Silva (2006)
Table 1. Parameters proposed by Silva (2006)

Parámetros/Parameters	Valor ($\pm$ desviación estándar)/Value ($\pm$ standard deviation)
a	83.04 ($\pm$ 1.34)
b	- 139.20 ($\pm$ 5.49)
c	56.01 ($\pm$ 6.29)
d	1.496 ($\pm$ 0.043)
e	5.04×10^{-4} ($\pm$ 0.439×10^{-4})

The correlation coefficient (r) and the index of agreement (d) determined by Silva (2006) to validate the proposed model (Equation 7) were 0.86 and 0.92, respectively. According to Silva (2006), the values showed an acceptable accuracy for estimating the relative humidity for a specific location, and a good performance when the interest is to estimate average values. The model is also recommended to prepare climatic zoning maps.

Laurence et al. (2002) compared the relative humidity calculated from weather radar measurements to the relative humidity observed at weather stations. However, the applicability of such study is more suitable in microclimatic scale, making it difficult to extrapolate for larger areas.

Generally, it has been observed that the estimation models of relative humidity are an interesting tool for sites that have few climatologically data. However, it should be noted that different types of external environment may require more accurate data of relative humidity, such as the marine environment.

The marine environment can be characterized as a region which is influenced by the ocean, and its area depends on the local climatic variables. The intense urbanization of this environment is responsible for the large movement of people and resources, especially in developing countries. As stated before, relative humidity is one of the most significant parameters regarding the durability of concrete structures in such environment (Andrade and Castillo, 2003; Nielsen and Geiker, 2003; Rincón and Duracon Collaboration, 2006).

The presence of the ocean near the marine environment provides, to the coastal climate, peculiarities in composition and action of different climate variables. Studies point to the presence of large amounts of chloride (Cl^-) in the composition of aerosol and cloud water in this environment (Menon et al., 2000; Rincón et al., 2004; Hossain et al., 2009). Besides, the winds, the raindrop size, and precipitation lines may also have different characteristics in the marine environment (Pestaina-Haynes and Austin, 1976; Goroch et al., 1982; Haque et al., 2007; Wilson et al., 2011).

Therefore, this paper aims to verify the efficiency of some models to estimate the relative humidity, observing their behavior for marine environment by studying the Brazilian coast. Thus, it has been sought to validate an alternative for complementing incomplete data for this variable, as well as to identify the need for improvement or for development of new models for this purpose.

3. Material and methods

The materials used in this study were the relative humidity data recorded and collected in weather stations arranged along the Brazilian coast. The set of uninterrupted data available to be used in this study covered the period from 1961 to 1990, totaling 30 years of data. It has not been possible to get a series of continuous data for a longer or later period than the one mentioned from the weather stations.

Having the data on relative humidity, the performance of Castellví et al. (1996) and Silva (2006) models to estimate the relative humidity was evaluated for different cities in Brazil, located in the marine environment. The criteria for the selection of cities on the Brazilian coast that served for the models analysis were:

(1) Cities located in an environment that suffers direct influence of the sea (i.e. coastal cities);

(2) Cities with validated records by the Brazilian National Institute of Meteorology (INMET, 1992) of all input data (i.e. T_n , T_m , I_m , λ) for the models analyzed in the period from 1961 to 1990;

(3) Cities with relative humidity data recorded by weather stations in the period from 1961 to 1990 (INMET, 1992) for comparison with relative humidity values estimated by the models.

It is important to highlight that cities located in marine environment, which belong to the Northern region of Brazil, were excluded from analyzes due to the significant influence of the rivers around them, making these cities with characteristics very different from the proposed objective of this paper.

According to the criteria, 16 cities have been selected, presented in Table 2 and located on the map of Figure 2.

Once cities that meet the criteria used in this paper have been established, comparative analyzes were performed between the model results and the relative humidity effectively recorded by INMET (1992) weather stations. Therefore, the statistical performance of each selected model was evaluated.

Tabla 2. Ciudades brasileñas seleccionadas para verificar los modelos necesarios para estimar la humedad relativa
Table 2. Brazilian cities selected for verification of models to estimate the relative humidity

Referencia/Reference	Ciudad/City	Estado/State
1	Macau	Rio Grande do Norte (RN)
2	Natal	Rio Grande do Norte (RN)
3	Joao Pessoa	Paraíba (PB)
4	Recife	Pernambuco (PE)
5	Maceio	Alagoas (AL)
6	Aracaju	Sergipe (SE)
7	Salvador	Bahia (BA)
8	Caravelas	Bahia (BA)
9	Vitoria	Espirito Santo (ES)
10	Cabo Frio	Rio de Janeiro (RJ)
11	Rio de Janeiro	Rio de Janeiro (RJ)
12	Ilha Guaiba	Rio de Janeiro (RJ)
13	Angra dos Reis	Rio de Janeiro (RJ)
14	Santos	Sao Paulo (SP)
15	Florianopolis	Santa Catarina (SC)
16	Rio Grande	Rio Grande do Sul (RS)

Figura 2. Ubicación de las ciudades seleccionadas para el análisis de los modelos para estimar la humedad relativa
Figure 2. Location of the cities selected for analysis of models to estimate relative humidity

For statistical tests of models, the following statistical indices recommended and described by Willmott et al. (1985) and Jacovides and Kontoyiannis (1995) have been adopted: (1) the correlation coefficient (r); (2) the index of agreement (d); (3) the mean bias error (MBE); and (4) the root mean square error (RMSE), as shown in Equations 8, 9, 10 and 11, respectively.

$$r = \frac{\left[\sum_{i=1}^n P_i (O_i - \bar{O}_i) \right]}{\left[\sum_{i=1}^n (O_i - \bar{O}_i)^2 \cdot \sum_{i=1}^n (P_i - \bar{P}_i)^2 \right]^{0.5}} \quad (8)$$

$$d = 1 - \left[\frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P_i - \bar{O}_i| + |O_i - \bar{O}_i|)^2} \right] \quad (9)$$

$$MBE = \frac{1}{n} \sum_{i=1}^n (P_i - O_i) \quad (10)$$

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2 \right]^{0.5} \quad (11)$$

Where: P_i = value predicted by the model; O_i = value observed; $\bar{P}_i$ = mean of predicted values; $\bar{O}_i$ = mean of observed values; and n = number of data pairs.

The r coefficient is an indicative of a model accuracy and reveals the adequacy of independent variables in explaining the variability of relative humidity. The correlation between the values is higher as r nears 1 (Willmott et al., 1985).

Index d suggests the degree of exactness between the observed and predicted values for models, and as r , the accuracy of the prediction model is higher as d nears 1 (Willmott et al., 1985).

Regarding the statistical errors, the mean bias error (MBE) evaluates the performance of a long-term model, unlike the root mean square error (RMSE), which provides short-term assessments (Jacovides and Kontoyiannis, 1995). For both MBE and RMSE, lower values determined by Eqs. (10) and (11) indicate better performance of the estimation models.

4. Results and discussion

Estimation of the relative humidity - statistical tests results

Figure 3 shows the values of the mean relative humidity observed by weather stations and estimated by the models analyzed for the period of 30 years (i.e. from 1961 to 1990) for the Brazilian coast cities studied in this paper (Table 2 previously presented).

Figura 3. Valores de la humedad relativa promedio observados por las estaciones meteorológicas y calculados por los modelos
Figure 3. Mean relative humidity values observed by weather stations and calculated by models

Observing Figure 3, it is possible to see that the greatest difference between the observed and estimated relative humidity for Castellví's et al. (1996) model was found for the city of Vitória (Reference 9 in Figure 3), with a percentage variation of 9.33 % between values. As for Silva's (2006) model, this actually happened to the city of Natal (reference 2 in Figure 3), with percentage range of 10.67 %.

Another fact observed in Figure 3 is that Castellví's et al. (1996) model overestimated the relative humidity for all cities studied, unlike Silva's (2006) model, in which there was overestimation and underestimation, depending on the studied locality. The statistical performance of each model studied has been evaluated and the results are shown in Figure 4 and 5, and in Table 3.

Figura 4. Relación entre los valores observados y los predichos para la humedad relativa – modelo de Castellví et al. (1996)
Figure 4. Relationship between observed and predicted values of relative humidity – Castellví's et al. (1996) model

Figura 5. Relación entre los valores observados y los predichos para la humedad relativa – modelo de Silva (2006)

Figure 5. Relationship between observed and predicted values of relative humidity – Silva's (2006) model

Tabla 3. Índices estadísticos

Table 3. Statistical index

Modelo/Model	<i>r</i>	<i>d</i>	MBE (%)	RMSE (%)
De Castellví et al./Castellví's et al. (1996)	0.71	0.62	3.40	3.89
De Silva/Silva's (2006)	0.27	0.56	3.40	4.17

According to Figure 4 and 5, the correlation coefficient determined for Castellví's et al. (1996) model was closer to 1 ($r = 0.71$) than the same coefficient found for Silva's (2006) model ($r = 0.27$). Analyzing Table 3, it has been observed that Castellví's et al. (1996) model also had *d* value closer to 1, as compared to Silva's (2006) model. Thus, Castellví's et al. (1996) model showed a better estimation of average values of relative humidity than Silva's (2006) model.

According to Table 3, both models analyzed had the same value of MBE. However, when analyzing RMSE values, it has been proven that once again Castellví's et al. (1996) model showed a better performance for the selected cities, expressed by the lower RMSE found.

Silva et al. (2007) found values for *r* around 0.86 to estimate the relative humidity by Silva's (2006) model in the states of Alagoas, Bahia and Sergipe. The MBE and RMSE values determined by Silva et al. (2007) were 0.63 % and 2.03 %, respectively. However, it should be noted that Silva's (2006) model was proposed exactly for these 3 states in Brazil.

Delgado et al. (2009) applied Silva's (2006) model for the state of Minas Gerais, Brazil, and found values of *d* varying in the range 0.68 to 0.96. These authors found values ranging from 5.33 to 17.95 % for the RMSE. However, it is important to note that the area studied by Delgado et al. (2009) is not located on the coast but within continental Brazil.

According to the statistical verifications performed, it has been observed that Castellví's et al. (1996) model showed a better estimation for relative humidity for the marine environment. It must be emphasized again that the initial proposal of Silva (2006) is the estimate of relative humidity in the states of Alagoas, Bahia and Sergipe, since the model parameters were adjusted to these states. Therefore, it must be emphasized that Silva's (2006) model appears to be more suitable for the continental climate than to the coastal one, which probably influenced the efficiency of the model in estimating values of relative humidity for the region of interest in this paper.

5. Example of application

As discussed before, the largest variation between the observed and estimated values of relative humidity for Castellví's et al. (1996) model was found for the city of Vitória (Reference 9 in Figure 3). According to the results of this paper, the relative humidity observed for this city was 76.7% and the value estimated by Castellví et al. (1996) was 83.9%. Thus, the Saetta et al. (1993) model was used to check how this variation impacts the chloride diffusion coefficient, according to Equation 1 and 2. Depth of chloride penetration (equivalent to a chloride content of 0.4% by mass of cement) was also calculated to both values of relative humidity through Andrade's (2001) model.

These two models were also applied in the results of Silva's (2006) model, however, results of relative humidity for the city of Natal (Reference 2 in Figure 3) were used. This city showed the largest relative humidity variation between observed and estimated. For this city, the relative humidity observed by weather stations was 77.3% and the value estimated by Silva's (2006) model was 85.5%.

For both cases, the conditions and parameters defined in Table 4 were assumed. Table 5 shows the results.

Tabla 4. Valores para el cálculo
Table 4. Values for the calculation

D_{cl} (cm ² /s)	5.0×10^{-8}
$f_j(T)$	1.0
$f_2(t_e)$	1.0
RH_c (%)	75
T (°C)	23
Cl (%)	2.0
k_1	1.0
f_{ck} (MPa)	30
k_2	1.0
Ad (%)	0.0
t (years)	20

Tabla 5. Ejemplos de las variaciones del coeficiente de difusión y profundidad de penetración de los cloruros debido a las diferencias entre la humedad relativa observada y a la estimada por los modelos

Table 5. Examples of variations in diffusion coefficient and penetration depth of chlorides due to differences between the relative humidity observed and the one estimated by models

Ciudad/City	UR (%)		D_{c2} (cm ² /s)	x (mm)
Vitoria	76.7	Valor observado/Value observed	2.85×10^{-8}	50.8
Vitoria	83.9	Estimado por el modelo de Castellví (1996)/Estimated by Castellví's (1996) model	4.26×10^{-8}	54.1
Natal	77.3	Valor observado/Value observed	2.98×10^{-8}	51.1
Natal	85.5	Estimado por el modelo de Silva (2006)/Estimated by Silva's (2006) model	4.50×10^{-8}	54.8

According to Table 5, the percentage variation of 9.3% between the relative humidity observed and estimated by Castellví's et al. (1996) model for Vitoria city resulted in an increase of 49.5% in the chloride diffusion coefficient and of 6.4% in the depth of chloride penetration. Regarding the city of Natal, an increase of 51.1% in the chloride diffusion coefficient and 7.4% in the depth of chloride penetration was found due to a percentage variation of 10.7% between the relative humidity observed and estimated by Silva's (2006) model.

This application example shows that although Castellví's et al. (1996) model presents better results for estimating the relative humidity to the marine environment than Silva's (2006) model, it has been identified a need to develop a more suitable model for this type of environment for studies that require better precision in estimating point values of relative humidity.

One must consider that the applied example used cities that showed the largest variations of relative humidity between observed and estimated values in order to analyze the most critical cases of variation. However, it has also been observed that the models showed similar values between the observed and estimated relative humidity to some other cities, such as Recife and Caravelas (References 4 and 8 in Figure 3), for instance, which would certainly reduce the percentage changes found in chloride diffusion coefficients and in depth of chlorides penetration calculated in this exercise.

6. Conclusions

Relative humidity is a variable of great importance for different applications, including the case of marine environment. Through statistical analyzes, represented by the correlation coefficient (r), the agreement index (d), the statistical errors: mean bias error (MBE) and root mean square error (RMSE), the model proposed by Castellví's et al. (1996) showed better results to estimate the relative humidity for marine environments than the model presented by Silva's (2006), proving to be a useful tool for filling datasets.

However, it should be noted that its enforceability may be compromised for studies requiring greater accuracy in estimating this variable for the marine environment. For applications in models of durability of concrete, for example, the correlation coefficient and the agreement index found in this paper may not be adequate for the degree of accuracy required, as has been shown in the application example.

It has been found that the model of Castellví et al. (1996) tends to overestimate the relative humidity, while the model of Silva (2006) sometimes results in overestimated values and sometimes in underestimated values.

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