CORROSIVITY MAP FOR PENINSULAR MALAYSIA

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Abstract

JKR has recently embarked on a research study on concrete deterioration in the Malaysian environmental conditions. The long-term goal of the study is to produce an isograph map of Peninsular Malaysia indicating geographically the "corrosivity" of each locality. Corrosivity is defined as the likelihood of concrete deterioration. The map would give a general guide of relative degradation hazard in the Peninsula. As an initial effort, a pilot study is restricted to field works at 10 sites in the Peninsula. The procedure established could later be replicated to cover more sites in the country. The approach of the study involves identification of appropriate measures to indicate the risk of concrete deterioration, key contribution factors to concrete deterioration, development of a deterioration index, and establishing a relationship between the index and the observed concrete deterioration. This paper reports the approach and methodology of the study.

Keywords: Corrosivity map, concrete deterioration, deterioration index

1.0 INTRODUCTION

Concrete durability is now an important aspect of the design of concrete structures. The traditional approach to designing for concrete durability has been based on the recipe method by specifying concrete cover or concrete strength [1,2]. There is now a new approach that seeks to design for durability against environmental loads in structural design [3].

JKR had embarked on a study to produce an isograph map of Peninsular Malaysia; indicating geographically the "corrosivity" of each locality [4]. Corrosivity here refers to the likelihood of causing concrete deterioration. It is common knowledge that the general atmosphere or macroclimate around buildings has less influence on concrete durability than the microclimate (distance in mm or cm). Notwithstanding, knowledge of the generalized condition at a site would help the designer in specifying appropriate durable concrete discriminately depending on its locality for buildings to be replaced or newly constructed. This is in line with the new approach to durability design.

A logical strategy of obtaining the corrosivity map would be to determine the degree of deterioration in buildings around the country and plot the isographs accordingly. However, *degree of deterioration* is a "latent variable" whose value, like *intelligence*, is unobservable. We need to use a suitable proxy measure to represent it, much like the use of *IQ* as a proxy measure of intelligence.

Further, to produce such a map would require a large amount of data covering an extensive area. If a climatic index whose value depends on measurable climatological data can be obtained; and its relationship with the observable deterioration measure established then an isograph of the index is equivalent to that for the risk of deterioration. This will allow us take advantage of the well coverage of meteorological stations in the country and the availability of climatological data from these stations. This is the approach adopted for the JKR study.

Also, from previous studies and past experience it is known that the rate of concrete deterioration is influenced by many factors related to the exposure conditions, material properties of concrete, maintenance levels, and the usage of the structure; besides the climatological factors [5]. The influence of these factors must be removed or otherwise accounted for in our attempt to establish a relationship between concrete deterioration and the climatic index.

2.0 PROXY MEASURE FOR CONCRETE DETERIORATION

Of interest is the search of a proxy measure to indicate the degree of deterioration, rate of deterioration or risk of deterioration. From the literature review it is noted that *condition rating* is often used to indicate concrete deterioration [6,7,8]. We first considered the JKR condition rating for bridges (JKR rating). The rating consists of a numerical scale of 1 to 5 with 1 being the best (as new) condition and 5 the worst condition [8]. It was however observed that because condition rating involves subjective appraisal, its use would likely give rise to variability in the data collected. Another anticipated problem was the data collected would be devoid of ratings 1 or 5 because all buildings chosen for the study were at least 18 years (whose condition could not likely to be "as new"); and members in very poor condition (rating 5) could logically have been already repaired. Based on these observations, JKR condition rating was considered not so ideal as the measure for concrete deterioration to be used in this study. Nevertheless, the condition rating was useful as a "bench mark" in obtaining a new measure of concrete deterioration. This is discussed later.

The *depth of carbonation* was considered a good candidate as an indicator for the degree of deterioration in concrete subject to carbonation. Carbonation is the process where the protective passivating layer around steel reinforcement is broken down due to lowering of pH value in concrete by the presence of carbon dioxide. In permanently dry environment (RH < 60%) the corrosion risk is very low, even if the concrete is carbonated because the electrolytic process is impeded. On the other hand, in permanently water saturated content the corrosion risk is again very low due to the lack of oxygen, even if the concrete is highly contaminated. As such, carbonation rate is not synonymous to corrosion rate. Notwithstanding, carbonation and corrosion are interrelated processes. Properly defined, we could use carbonation depth as an indication of the degree of concrete corrosion.

The presence of chloride ion in concrete at the steel position is another way the protective barrier around steel reinforcements can be broken down. While carbonation occurs in a relatively dry concrete paste, chloride attack prevails in concrete saturated with water and was thus treated separately from carbonation. When the Cl^- ion reaches a concentration of around 0.4% by weight of cement, corrosion would take place. As such, chloride content by weight of cement is also a candidate for measuring the risk of deterioration.

Sulfate content present in the concrete paste was considered yet another candidate as a measure of concrete deterioration. When the content exceeds 4% by weight of cement, spalling of concrete is very likely to occur due to internal expansion.

The coexistence of carbonation, chloride and sulfate would compound the problem [9]. In the light of the above discussion, a new measure of corrosion risk and its definition were proposed by modifying the definition given by [9]. The measure called “corrosion risk rating” or CRR is based on a numerical scale from 1 to 5. The choice of this scale was meant to resemble JKR condition rating so that comparisons with the JKR rating could be carried out. The depth at which the chloride content is to be considered was arbitrarily fixed at 20mm, which is the minimum nominal cover specified in Table 3.3 of BS 8110 [1]. The limits for each category of chloride content were arbitrarily lowered from the values given in [9] to represent the situation prevalent in the study structures where chloride was from an external source.

Table 1 Proposed measure of deterioration (corrosion risk rating)

Sulfate content	Chloride by wt. Of cement at 20mm depth	Mean Carbonation depth	Corrosion risk rating (CRR)
Equal or Less than 4.0%	Equal or Less than 0.2%	1. More than 55mm	5
		2. 40mm - 55mm	4
		3. 25mm - 40mm	3
		4. 10mm - 25mm	2
		5. Equal or Less than 10mm	1
	0.2% - 0.8%	1. More than 40mm	5
		2. 10mm - 40mm	4
		3. Equal or Less than 10mm	3
	More than 0.8%	All cases	5
More than 4.0%	Equal or Less than 0.1%	4. More than 40mm	5
		5. 10mm - 40mm	4
		6. Equal or Less than 10mm	3
	More than 0.1%	All cases	5

Further, in the proposed scheme, mean carbonation depths were used. The ranges of mean carbonation depths for each rating were arbitrarily specified based on Table 3.3 of BS 8110: Part 1: 1997 and assuming grade 40 concrete with a w/c ratio of 0.55. Adjustments to these ranges were made in order to bring the CRR close to the corresponding JKR rating observed at sites.

It is important to mention the availability of an indirect measure of concrete deterioration by *electrolytic resistivity* measurement, either independently or in conjunction with *half-cell potential* measurement [10]. Resistivity measurements actually measure the ability of corrosion currents to flow through the concrete while half-cell potential measurements involve measuring the potential of embedded reinforcing steel relative to a reference half-cell. Both techniques measure the *condition or quality of the concrete medium* to promote passage of corrosion current. They were considered not appropriate to measure concrete deterioration in this study.

3.0 KEY CONTRIBUTING FACTORS TO CONCRETE DETERIORATION

Many factors can affect the rate of concrete deterioration. They include environment (which include exposure condition) and concrete material properties. [5]. In addition, human intervention like workmanship, maintenance and usage of the structure can have a significant bearing on the deterioration.

Environmental condition refers to the condition in which the structure is located. The parameters include: proximity to the coastlines, climate (temperature and relative humidity), and reduced levels of ground where the building is situated.

Exposure condition refers to how protected the structure is from “rain and shine”. For the purpose of this research two condition states were considered: sheltered and exposed conditions.

Material properties of concrete considered important in affecting concrete durability are the age of the concrete structure; the strength of in-situ concrete; cement content, cement type, concrete cover, sorptivity and water-cement ratio. The values were obtained from laboratory test on cored samples extracted from hardened concrete using petrography.

The *level of maintenance* can be indicated by the frequency and type of maintenance operations done on the structures under study. For this research, three levels of maintenance were assigned: good, moderate or poor. Good maintenance refers to regular and effective maintenance. Poor maintenance refers to ineffective maintenance or lack of maintenance. In terms of usage of the structure, heavy usage refers to frequent and rough use of the facility. Light usage is just the contrary.

4.0 CLIMATIC INDEX

For the purpose of producing a “corrosivity map” a number of meteorological indexes were considered. The first index was the Corrosivity index, or more appropriately, *atmospheric corrosion index* [11]. Atmospheric corrosion is an electrochemical process, requiring the presence of an electrolyte. The severity of the corrosion and the rate at which corrosion will take place are dependent primarily upon properties of the surface formed electrolytes, which in turn are dependent upon factors such as the humidity and pollution levels in the atmosphere. Indeed, it involves corrosion of metal surfaces due to atmospheric condition and in particular, the air quality. Since the focus of this study relates more to concrete deterioration in marine environment we considered this index not suitable for our purpose.

The second index considered was known as Scheffer’s Climatic Risk Index (SCRI) [12]. This index combines the effect of rain and temperature. The formula for the determination of SCRI is

$$SCRI = \frac{\sum_{Jan.}^{Dec.} (T-2)(D-3)}{16.7} \qquad (1)$$

where T is the mean monthly temperature (°C), and D is the mean number of days in the month with 0.25 mm or more rainfall. The temperature and rainfall factors relate to the condition conducive for decay fungal growth. The sum of products is arbitrarily divided by 16.7 to make the index fall largely within the range of 0 to 100. The formula was meant for estimating potential for decay in wood structures.

The third index considered was known as Driving Rain Index (DRI). The index was based on the total amount of annual rainfall and maximum wind velocity. According to Norzan, who produced a corrosivity map for Peninsular Malaysia using DRI [13], the index was originally meant for assessing the risk of rain penetration through a wall, to calculate thermal transmittance of rain wetted building fabric and for assessing the long term weathering, staining or washing of building facades.

To study the suitability of these indexes for our study requires that we look further into the mechanism of concrete deterioration due to external agents. We must acknowledge that concrete deterioration is a rather complex process. To be simplistic but without losing its essential point, we note that three elements must be present for corrosion of steel in concrete to take place:

i. presence of moisture
ii. presence of chemical substance
iii. presence of oxygen

The CEB Guidelines [14] noted that the presence of water or moisture is the one, single most important factor controlling the various types of deterioration. This is because corrosion is an electrolytic process, which needs moisture in the concrete to provide a sufficiently conductive electrolyte [14]. However, it is not any amount of moisture. Diffusion of CO_2 is only possible in air filled pores, and for this reason, totally water-saturated concrete will not carbonate. The increasing humidity of the air will cause the larger pores to be filled with water thus reducing the pore space available for the diffusion of the gas. Also, the pores would be totally deprived of oxygen needed for corrosion.

In the case of chloride, surfaces subjected to constant rain lashing may loose the alkalinity through leaching while chloride at the surface may be washed away by rain [15]. The effect of rain on chloride-induced concrete deterioration is thus uncertain and need further investigation. For this study, total rainfall or number of rain days used in DRI and SCI respectively is thus not used. A more relevant indicator of moisture, that is, the Relative Humidity (RH) was considered.

Like many processes that depend on chemical reactions, corrosion is accelerated as the temperature increases [14]. The rate increase effect of increasing temperature is mainly the effect on the rate of transport (higher temperature results in higher mobility of ions and molecules). A simple rule-of-thumb is: an increase in temperature of 10°C causes a doubling of the rate of reaction [14].

Based on the above discussions, we concluded that all three indexes considered were not suitable for our purpose. We sought out to define our own climatic index. By adopting Scheffer's approach [12], we considered the following requirements of the intended index:

i. The index must correlate satisfactorily with measures of concrete corrosion.
ii. Climatological data to be used for the determination of the value of the index must be readily available.
iii. As few elements of climate as possible be used for easy application of the formula.
iv. The index should be in a range from 0 to 100 for rapid recognition of the relative magnitude of corrosion potential.

An additional requirement is that the index must be a function of temperature and RH.

We first considered contribution of RH in determining the value of the proposed index. Moisture is required for carbonation reaction, which takes place not as a gas reacting with a solid but as a gas dissolved in the moisture reacting with alkali in solution. Carbonation is most active in an RH of between 45% and 85%. Below 45% a moisture film does not tend to form on the surface of the pores. Above 75%, the pores tend to become blocked by water, slowing the rate of penetration of more CO_2 to replace that used up [16]. As was mentioned above, corrosion rate may differ slightly with carbonation rate. The relationships between corrosion rate and Relative Humidity, and between carbonation rate and Relative Humidity are given in Table A-3.1 of the CEB Guide [14]. This table is reproduced in Table 2.

We noted that the numerical rating is of an *interval scale* and replacement of the ratings 0, 1, 2 and 3 with ratings of 1, 2, 3 and 4 respectively should not matter. The motivation of this change is merely to avoid having a product of zero value when the rating 0 is multiplied with another factor. The revised values for the corrosion process in carbonated concrete are plotted in Fig. 1.

Table 2 Influence of Moisture state on Durability Processes

Effective R.H.	Carbonation	Corrosion of steel in concrete which is	
		Carbonated	Chloride contaminated
V. Low (<45%)	1	0	0
Low (45-65%)	3	1	1
Medium (65-85%)	2	3	3
High (85-98%)	1	2	3
Saturated (>98%)	0	1	1

Risk: 0 = not significant
1 = slight
2 = medium
3 = high

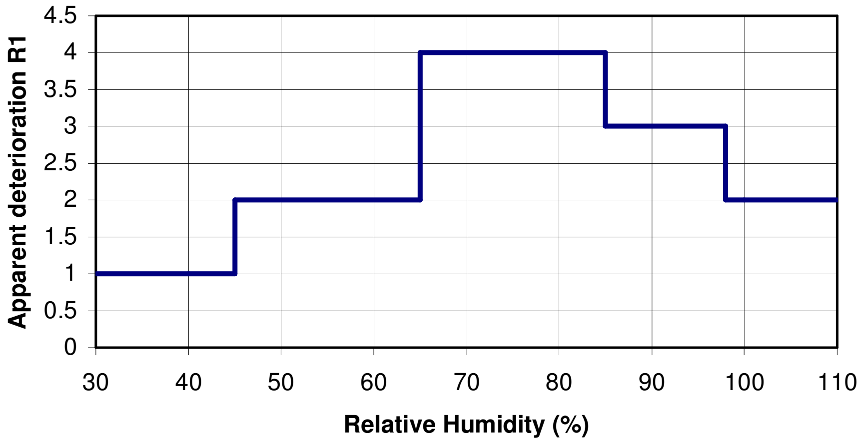

Fig. 1 Influence of RH on concrete deterioration [14]

To consider the effect of temperature in the formula requires much consideration. Two criteria were used:

i. A simple rule-of-thumb, which states that an increase in temperature of 10°C causes a doubling of the rate of reaction [14].
ii. The total index value is fixed at around 100.

We propose a formula following the format of Scheffer's index:

$$CCI = \frac{\sum_{Jan.}^{Dec.}(R1)(R2)}{12} \quad (2)$$

In Eq. (2), the *Concrete Climatic Index* (CCI) is formulated as the annual average of monthly CCI defined as the product of R1 and R2. In order that the maximum monthly CCI be 100 and consider that the maximum value for R1 has been set as 4, the maximum value for R2 would have to be 25. This should take place for temperature at 40°C or higher. The lowest value for R2 is arbitrarily fixed at 3 for temperature lower than 10°C. We thus obtained the curve as given in Fig. 2.

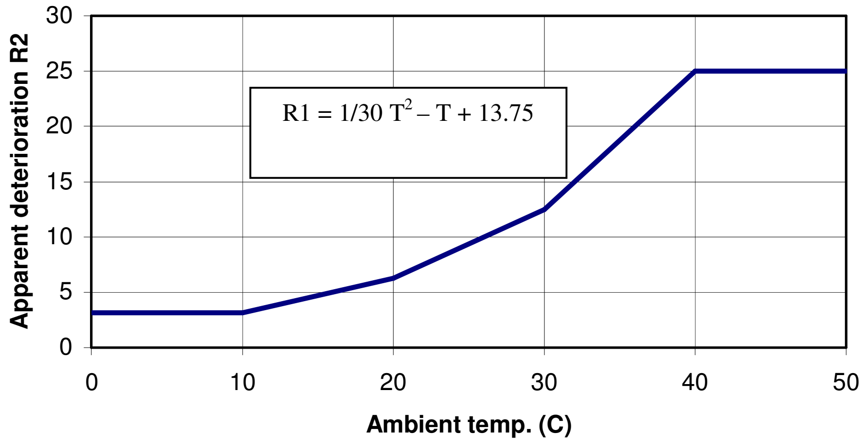

Fig. 2 Influence of temperature on concrete deterioration

5.0 RELATIONSHIP OF DETERIORATION MEASURE AND CLIMATIC INDEX

The methodology of study comprises collection and analysis of data from existing structures and meteorological stations. Data collection in the field includes material tests on concrete and condition surveys. Interviews with building owners and their maintenance personnel were also carried out during the field surveys to determine the extent of human intervention on the structures.

Field data collection

It was noted earlier that to produce an isograph of corrosivity requires extensive data covering many sites in the Peninsula. The time and cost needed to collect the data around the country would be high. In view of limited allocated funding for the study it makes sense to limit the sites to only 10 locations, consisting of major towns near the coasts. Two "interior" towns were included in the study as controls. A building from each of 10 different locations in the Peninsula was selected for the purpose of this study. They are as shown in Table 3.

Table 3 Study buildings

No.	City	Study Buildings	Date of field work
1.	Pulau Pinang	Bangunan gudang, Penang Port Commision	11-09-02
2.	Lumut	Pejabat Pos Malaysia, Lumut	12-09-02
3.	Johor Bharu (JB)	Wisma Persekutuan, J.B.	13-09-02
4.	Pelabuhan Kelang	Flat Polis Jln. Pelabuhan Selatan, Pelabuhan Kelang	14-09-02
5.	K. Terengganu	Pasar Besar, K.T.	15-09-02
6.	Port Dickson (PD)	Perhentian Bas PD	16-09-02
7.	Melaka	Bangunan Jabatan Laut	17-09-02
8.	Mentakab	Flat Polis Mentakab	23-09-02
9.	Temerloh	Kompleks Pejabat Kerajaan	23-09-02
10.	Kuantan	Wisma Sri Pahang	25-09-02

Concrete cored samples from buildings were used to determine its quality. The depth of carbonation was determined immediately after extraction by spraying on the cores with a solution of the indicator phenolphthalein. Noncarbonated concrete shows a colouration of pinkish while carbonated concrete remains colourless. The depth of carbonation was measured with a scale from the concrete surface.

Determination of density of hardened concrete is covered in BS 1881: Part 114 [17]. The microstructure of concrete, its porosity and its permeability are the most important factors controlling the durability of concrete where deterioration is due to external agencies, as in the case of Carbonation and chloride attack. For this research, *sorptivity test* using Taywood Method was adopted. In addition, petrographic examination of concrete was also carried out to determine the in-situ concrete quality, cement type and cement replacement materials, w/c ratio, and degree of compaction.

Data Analysis

Data analysis comprises mainly statistical analysis of the data. It includes “cleaning up” the raw data of outliers, determination of correlation between variables and establishing some relationships between the degree of deterioration and the above-mentioned parameters. For the regression model, the dependent variable is the proposed climatic index CCI and the independent variables are concrete properties and the climatic index derived from the R.H. and temperature measured at sites.

4.0 FINDINGS

4.1 General Description of Data

A crucial point to ponder in the data analysis is: What constitutes a data point? We noted earlier that due to budget constraint only 10 sites were studied. If each site is treated as one data point then the amount of data is too scarce. To overcome this problem, the mean values of data collected from the same members were treated as one data point and used in the data analysis.

The buildings selected for the study have their ages between 18 years and 50 years (see Table 4). Except for JB, all data were collected at the ground floor or first floor. At the building in JB, data were collected at Levels 4, 5, 8 and 9. This permitted investigation of the significance of different floors on concrete deterioration.

Table 4 Sites under study

No.	Town	Building utility	Age (years)	RH (%)	Temp. °C
1	Johor Bharu (JB)	Office	24	75	33
2	Kelang (KG)	Residence	34	62	33
3	Kuantan (KN)	Office	20	67	31

4	K. Terengganu (KT)	Wet market	18	73	30
5	Lumut (LM)	Office/ residence	69	60	32
6	Melaka (MA)	Office	37	67	32
7	Mentakab (MB)	Residence	21	86	27
8	Port Dickson (PD)	Residence	22	42	37
9	Penang (PG)	Go-down	65	46	35
10	Temerloh (TH)	Office	39	64	32

The average values of the concrete properties are determined and summarized in Table 5. As a summary, the cube strengths vary between 7.5N/mm^2 and 50.5 N/mm^2 with a mean value of 25.3 N/mm^2.

Table 5 Properties of concrete under study

	Cement content (%, m/m)	Est. in-situ cube strength (N/mm^2)	Density (kg/m^3)	Sorptivity (mm/min$^{1/2}$)	Xcess voidage	Apparent W/C	Compaction pore
Average	14.0	25.3	2244.5	0.2	1.2	0.6	3.1
Std. Dev.	6.20	9.70	92.91	0.19	0.79	0.08	2.33
Max. Value	48.5	50.5	2510.0	0.9	3.0	0.7	8.3
Min. Value	8.1	7.5	1970.0	0.0	0.5	0.5	0.0

The cement content, estimated in-situ cube strength, density and sorptivity of the concrete were determined in the laboratory from the cored samples. Excess voidage, apparent w/c ratio and compaction pore were determined by petrographic analysis of cored samples [18].

4.2 Correlation Analysis

Correlation analysis between CRR and CCI was the initial step to establish a regression model. First, the values of CRR and CCI were calculated using the formulas established earlier. Next, correlation analysis was carried out using SPSS. The result of the correlation analysis showed that CRR was negatively correlated with CCI. This relationship is not sensible. The likely source of the anomaly was in the use of instantaneous values of RH and temperature. Rightly, and in accordance to Eq. (2), 24hour mean values of RH and temperature should be used. Also, the data might not be large enough. Since this was a pilot study, we would ignore this anomaly and proceed with the next step of the study; which involved investigating the linear correlation between CRR with independent variables.

Variables that have coefficient of correlation of higher than 0.4% were considered as candidates for the regression model. They are:

i. Work quality
ii. Maintenance level
iii. Total cover thickness
iv. Cement content

v. Estimated in-situ concrete strength
vi. Density of concrete

Items i and ii relate to human intervention; item iii relates to the specified thickness of cover. The remaining items relate to concrete properties.

4.3 Regression model

A stepwise regression analysis was first performed using SPSS statistical package (Model I). A stepwise method considers the entry or removal of a variable into a regression model based on a certain predetermined criterion. This had allowed entry of variables work quality, maintenance level and concrete density into the model.

For the purpose of comparison, another model (Model II) was tried out with all the variables included in the regression model. There was a slight improvement in the adjusted R^2 compared with Model I. However, as the improvement was not large we would not accept this model.

The final model was the inclusion CCI in Model I. We thus obtained a regression model of this formula:

$$CRR = 15.16 - 0.0142CCI + 0.48A - 1.035B - 0.0046C \quad (3)$$

where CRR = Corrosive Risk Rating
CCI = Climatic corrosive index
A = Work quality
B = Maintenance level
C = Density of concrete

We recall from earlier discussion that we have to "remove" influence of other variables so that the regression equation constitutes a link between CRR and CCI only. In order to remove the variables from the regression equation we back substituted values of A = 1, B = 1 and C = 2240 kg/mm^3 into the equation. These values represent "normal" condition that conforms to JKR specification: A of 1 means good work quality, B of 1 means good maintenance. We thus have a new regression formula of:

$$CRR = 4.3 - 0.0142CCI \quad (4)$$

4.4 Isographs of corrosivity

The Climatic Corrosivity Index (CCI) is an index based on two climatological data, namely, RH and temperature. Values of these parameters were collected by Jabatan Khidmat Kajicuaca Malaysia. For the purpose of preparing the isographs of concrete corrosivity, the values of RH and temperature corresponding to the year 2001 were used. CCI was calculated using the formula in Eq. (4).

5.0 CONCLUSIONS

The authors had established a procedure for producing a “corrosivity” map of Peninsular Malaysia. The procedure involves first defining a measure for corrosion risk and a climatic index and establishing a relationship between them.

The measure of concrete corrosion risk known as Corrosive Risk Rating (CRR) was defined as a numerical scale ranging from 1 to 5. It is a dimensionless parameter whose value depends on sulfate content, chloride content at 20mm depth and carbonation depth on a concrete building. This rating compares quite well with JKR Condition rating.

A climatic index called Climatic Corrosive Index (CCI) based on monthly mean Relative Humidity (RH) and monthly mean temperature was also defined. Its value is determined by a formula, which calculates the annual mean of the product of two terms R1 and R2. R1 and R2 are indexes related to monthly mean RH and monthly mean temperature respectively.

In order to determine the value of CCI corresponding to concrete corrosion potential represented by CRR, a link between the two parameters was established using a regression model. Other factors affecting concrete deterioration, for example, density of concrete, were included in the regression analysis but were “removed” from the model by back substitution of assumed values of these factors in the regression equation. CCI and CRR for major towns (those which have climatological data) are plotted in the map of Peninsular Malaysia.

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