Research Article

Durability Environmental Regionalization for Concrete Structures

Daming Luo,¹ Yan Wang,² and Ditao Niu¹

¹ School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China

² Material Science and Engineering Centers for Postdoctoral Studies, Xi'an University of Architecture and Technology, Xi'an 710055, China

Correspondence should be addressed to Ditao Niu; niuditao@163.com

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Environment is the external factor that affects the durability of concrete structures. Buildings in different regions with different climates will respond to durability deterioration in different ways. For macroenvironmental regionalization, the dominant factor analysis method of the climatic zonation was applied into the environmental regionalization in this paper. Based on the environmental characteristics in China and the effect of environmental factor on the durability of concrete structure, the proper regionalization indexes are chosen, and the environmental regionalization is made. For microenvironmental regionalization, fuzzy set and rough set theories were used in data mining on discrete measured data, and the weight determination of various factors affecting durability was transformed into evaluation of the significance of attributes among rough sets. The method of durability environmental regionalization is established by analyzing the degree of influence that various factors have on the durability of concrete structures. The result of durability environmental regionalization for concrete structures in Shenzhen city shows that the proposed approach is reasonable.

1. Introduction

The concrete structures are located in a changeable environment, different regional environment leads to different damage mechanism and different damage level, and the structural durability degradation form has its regional characteristics. It means a lot to insure the concrete construction durability and to extend the service life if a reasonable durability design method combining with the various environmental conditions can be found.

Durability environmental regionalization is to divide a region into different areas according to the environmental conditions which influence the durability of the concrete structure. The influence of the environment on the architecture is involved in many professional fields, from architectural planning, design, and construction to the building operation and management. The architects have long ago realized the influence of the climate on the architectural design. Early in 1949–1952, the American Institute of Architects (AIA) proposed the principle of the architectural design under the influence of different climates in the main areas of the USA

[1]. The research on the weather in China began in the 1950s, and “Standard of Climatic Regionalization for Architectural” was issued in 1993 [2], but these research achievements was aimed at the influence of climate condition on the function of the building. Jin and Lü [3] had made durability environmental regionalization on Zhejiang Province; however, the regionalization doesnot have uniform indexes; only cursory regionalization according to the influence of the environment on the durability of the concrete structure was proposed.

The durability environmental regionalization for concrete structures is a problem of complex multiparameter and multiindex evaluation, and the selection and determination of the regionalization index directly relate to the accuracy of the regionalization. In the macroenvironmental regionalization, this paper will introduce the combination of dominant factor and comprehensive analysis method of the climatic zonation into durability environmental regionalization and select property indexes according to the environmental characteristics in each area of China, while in the microenvironmental regionalization, instead of macroscopic regionalization

methods, a new way, which is based on the fuzzy sets and rough sets to determine the weight distribution, is proposed in this paper to make a quantitative calculation for durability regionalization indexes and improve the regionalization quality and precision. This method allowed the durability environment regionalization to be done in specific city or area, which can reflect the durability influencing factors in the microenvironment around the buildings.

2. Macroenvironmental Regionalization

2.1. Regionalization Method. According to the climate condition and erosion medium characteristics in China, the environment around engineering structure can be divided into atmospheric environment, water environment, and soil environment. Moreover, the atmospheric environment can be divided into general atmospheric environment (including rural area and urban area), marine atmospheric environment, and industrial atmospheric environment; the water environment can be divided into seawater environment, freshwater environment, and industrial water environment, and the soil environment can be divided into alkaline soil, acid soil, inland saline soil, and coastal saline soil.

The principle of climate regionalization generally includes principle of dominant factor, principle of comprehensive analysis and combination of the both. The dominant factor principle advocates using uniform indexes, while the principle of comprehensive analysis laid stress on the climate similarity among regions instead of uniform indexes. In the durability environmental regionalization, factors influencing concrete durability such as the atmospheric temperature and humidity, the distance from coastline, and the acid rain situation, should be considered. Therefore, it would be necessary to employ the combination of dominant factor and comprehensive analysis method of the climatic zonation to make the durability environmental regionalization. Due to the various distribution of spatial and temporal of the environment elements and the different influence of each environmental element on the durability environmental regionalization, this paper will use two-level regionalization approach to make durability environmental regionalization for concrete structures.

2.2. Regionalization Index. The environmental factors that affect concrete durability include (1) climate condition, such as atmospheric temperature, relative humidity, and precipitation, which are closely related to freeze-thaw damage, concrete carbonization, reinforcing steel corrosion, and chloride ion penetration; (2) Erosion medium, such as carbon dioxide, chloride, acid rain, and sulfate. The selection of environmental index is the key issue of durability environmental regionalization. Here we will choose the regionalization index for each grade of regionalization, respectively.

(1) Primary Regionalization Index. The primary regionalization is made mainly according to the environmental factor that affects the durability in the overall country. The atmospheric CO_2 concentration has little contrasts, and the

atmospheric Cl^- content shows large gradient only in the coastal area. Therefore, the density of CO_2 and the Cl^- content will not be used as the main index. The distribution of environmental temperature and relative humidity, which reflects the main difference of climate characteristic, has large difference throughout the country and has significant influence on the concrete carbonization, reinforcing steel corrosion and freeze-thaw damage of concrete [4–9]. Therefore, the temperature and relative humidity are selected as the primary regionalization index.

The annual average temperature can comprehensively reflect the influence of the temperature on the durability of concrete structures; the average temperature in January reflects the coldest degree of the area and determines whether frost freeze-thaw cycle damage occurs in concrete. Therefore, the annual average temperature and average temperature in January are chosen as the primary index.

July has the highest relative humidity and temperature in the overall year in China, therefore leading to the fastest reinforcing steel corrosion. Hence, the average relative humidity in July is chosen as the humidity index.

(2) Secondary Regionalization Index. The secondary regionalization index was chosen according to the environmental characteristic of each primary area. For coastal environment, the distance from the costal line can well reflect the change of atmospheric Cl^- content. Besides, due to the different industrialization in each city, the emission of acid gases such as SO_2 , CO_2 , NO_2 , and H_2S is different, which leads to different pH levels of acid rain. Therefore, the distance from the costal line or the annual average pH of acid precipitation is chosen as the secondary regionalization index, depending on the area location.

2.3. Regionalization Standard. The primary regionalization indexes include annual average temperature (T), January average temperature (T_1), and July average relative humidity (RH_7). T_1 is related to whether frost freeze-thaw cycle damage occurs in the concrete. If T_1 is lower than -10°C , freeze-thaw damage is serious; if it is around 0°C , freeze-thaw damage may be occur; if T_1 is higher than 10°C , frost and freeze-thaw will not occur in the concrete structure [9]. Therefore, T_1 is divided into four parts: $T_1 \leq -10^\circ\text{C}$, $[-10^\circ\text{C} \sim 0^\circ\text{C}]$, $[0^\circ\text{C} \sim 10^\circ\text{C}]$, and $>10^\circ\text{C}$. Relative humidity has large effect on concrete carbonation and reinforcing steel corrosion process. The carbonation will have a highest speed when relative humidity is 50%. Besides, the relative humidity is a decisive factor for the degree of pore saturation which, in turn, will influence the transportation of oxygen and chloride ion [10, 11], so 50% is chosen as critical relative humidity.

The secondary regionalization indexes include the distance from coastline (S) and the annual average pH of acid precipitation (pH_w). Researches show that if S is more than 3 km, chlorine-ion erosion could be ignored [12], so the critical S can be selected as 3 km. Since rain that has equilibrated with atmospheric CO_2 has a pH_w value of about 5.6 and if pH_w value is less than 4.5, acid rain becomes a serious regional environmental problem [13]. Therefore, 5.6

TABLE 1: Regionalization standard.

Regions		Primary regionalization criteria	Secondary regionalization criteria
I	Ia	$T_1 \leq -10^\circ\text{C}$; T : $-4.8\sim 8^\circ\text{C}$; $\text{RH}_7 \geq 50\%$	$\text{pH}_w > 5.6$
	Ib		$4.5 < \text{pH}_w \leq 5.6$
II	IIa	T_1 : $-10\sim 0^\circ\text{C}$; T : $8\sim 14^\circ\text{C}$; $\text{RH}_7 \geq 50\%$	$\text{pH}_w > 5.6$ and $S > 3\text{ km}$
	IIb		$4.5 < \text{pH}_w \leq 5.6$ and $S > 3\text{ km}$
	IIc		$4.5 < \text{pH}_w \leq 5.6$ and $S \leq 3\text{ km}$
III	IIIa	T_1 : $0\sim 10^\circ\text{C}$; T : $14\sim 20^\circ\text{C}$; $\text{RH}_7 \geq 50\%$	$4.5 < \text{pH}_w \leq 5.6$ and $S > 3\text{ km}$
	IIIb		$\text{pH}_w \leq 4.5$ and $S > 3\text{ km}$
	IIIc		$\text{pH}_w \leq 4.5$ and $S \leq 3\text{ km}$
IV	IVa	$T_1 > 10^\circ\text{C}$; T : $20\sim 25^\circ\text{C}$; $\text{RH}_7 \approx 80\%$	$4.5 < \text{pH}_w \leq 5.6$ and $S \geq 3\text{ km}$
	IVb		$\text{pH}_w \leq 4.5$ and $S \geq 3\text{ km}$
	IVc		$4.5 < \text{pH}_w \leq 5.6$ and $S \leq 3\text{ km}$
V	V	$T_1 \leq -10^\circ\text{C}$; T : $2\sim 9^\circ\text{C}$; $\text{RH}_7 \leq 50\%$	$\text{pH}_w > 5.6$
VI	VI	T_1 : $-10\sim 0^\circ\text{C}$; T : $10\sim 14^\circ\text{C}$; $\text{RH}_7 \leq 50\%$	$\text{pH}_w > 5.6$

FIGURE 1: Regionalization map of durability environment for concrete structures in China.

and 4.5 are chosen as critical pH_w of acid rain. Detailed regionalization standard is shown in Table 1.

2.4. Regionalization Result. According to the primary and secondary regionalization criteria of durability environmental regionalization standard, China can be divided into six primary regions and thirteen secondary regions. The result is shown in Figure 1, and the environmental character and main reason of durability degradation of every regions are provided in Table 2.

3. Microenvironmental Regionalization

For Macroenvironmental regionalization, the method mentioned above can give a qualitative division for a large-scale environment. For microenvironmental regionalization of a small-scale environment, the following method will give a precise division based on quantitative indicators.

3.1. Fuzzy Cluster Analysis and the Rough Set

3.1.1. Fuzzy Cluster Analysis. Traditional cluster analysis is a hard regionalization method, which divided each object into a certain category, and it cannot satisfy the field requirement. With the intermediary in their properties, the type of objective things is often not very clear. However, fuzzy cluster analysis can effectively deal with these problems [14–16], Fuzzy clustering methods allow objects to belong to several clusters simultaneously with different degrees of membership. In many field situations, fuzzy clustering is more natural than hard clustering, as objects on the boundaries between several classes are not forced to fully belong to one of the classes.

For durability environmental regionalization, let $\mathbf{X} = \{x_1, x_2, \dots, x_n\}$ be all buildings to be tested; these buildings will be divided into different categories according to their durability degradation causes; each sample $\mathbf{x}_i = \{x_{i1}, x_{i2}, \dots, x_{im}\}$ consists of m measured testing value of the

TABLE 2: Environmental character and main reason of durability degradation of every regions.

Regions	Environmental character of primary regions	Environmental character of secondary regions	Main reason of durability degradation
I	Ia	No acid rain, far from coastline	Serious freeze-thaw damage, concrete carbonation, and reinforcing steel corrosion
	Ib	$4.5 < \text{pH}_w \leq 5.6$, far from coastline	Serious freeze-thaw damage, slightly acid rain corrosion, concrete carbonation, and reinforcing steel corrosion
II	IIa	No acid rain, far from coastline	Freeze-thaw damage, concrete carbonation, reinforcing steel corrosion
	IIb	$4.5 < \text{pH}_w \leq 5.6$, far from coastline	Freeze-thaw damage, concrete carbonation, and reinforcing steel corrosion, slightly acid rain corrosion
	IIc	$4.5 < \text{pH}_w \leq 5.6$, closer to the coast	Chloride ion corrosion, freeze-thaw damage, concrete carbonation, reinforcing steel corrosion, slightly acid rain corrosion
III	IIIa	$4.5 < \text{pH}_w \leq 5.6$, far from coastline	Slightly acid rain corrosion, concrete carbonation, reinforcing steel corrosion, and slightly freeze-thaw damage
	IIIb	$\text{pH}_w \leq 4.5$, far from coastline	Severe acid rain, concrete carbonation, reinforcing steel corrosion, and slightly freeze-thaw damage
	IIIC	$\text{pH}_w \leq 4.5$, closer to the coast	Chloride ion corrosion, severe acid rain, concrete carbonation, reinforcing steel corrosion
IV	IVa	$4.5 < \text{pH}_w \leq 5.6$, far from coastline	Concrete carbonation, slightly acid rain corrosion, and reinforcing steel corrosion
	IVb	$\text{pH}_w \leq 4.5$, far from coastline	Severe acid rain, concrete carbonation, and reinforcing steel corrosion
	IVc	$4.5 < \text{pH}_w \leq 5.6$, closer to the coast	Chloride ion corrosion, concrete carbonation, slightly acid rain corrosion, and reinforcing steel corrosion
V	V	No acid rain, far from coastline	Serious freeze-thaw damage, concrete carbonation,
VI	VI	No acid rain, far from coastline	Freeze-thaw damage and concrete carbonation

durability factor. Then, we can obtain the raw $n \times m$ data matrix.

Fuzzy clustering analysis as follows [16].

Step 1 (data standardization). In order to compare different testing values with different dimensions, the measured data should be standardized. A collection of numeric data is standardized by subtracting a measure of central location (such as the mean or median) and dividing it by some measure of spread (such as the standard deviation or range). The commonly methods of standardization are Translation-Standard

Deviation Transformation and Translation-Range Transformation,

$$x'_{ij} = \frac{x_{ij} - \mu_j}{s_j}, \quad (1)$$

$$x'_{ij} = \frac{x_{ij} - \min\{x_{ij}\}}{\max_{1 \leq i \leq n}\{x_{ij}\} - \min_{1 \leq i \leq n}\{x_{ij}\}},$$

where μ_j and s_j are the mean value and standard deviation of x_{ij} , respectively; and $i = 1, 2, \dots, n$, $j = 1, 2, \dots, m$.

Step 2. Establish the fuzzy similar matrix $\mathbf{R}$. The correlation coefficient $r_{ij} = \mathbf{R}(x_i, x_j)$ between x_i and x_j can be calculated using standardized data and build the fuzzy similar matrix.

Step 3. Establish the fuzzy equivalent matrix $\mathbf{R}^*$. Fuzzy similar matrix $\mathbf{R}$ is a fuzzy matrix and may not be transferable. In order to cluster these objects, the square method can be used in finding the equivalent matrix $\mathbf{R}^*$. Stepwise compute $\mathbf{R}^2, \mathbf{R}^4, \dots$, until $\mathbf{R}^k = \mathbf{R}^{2k} = \mathbf{R}^2$.

Step 4. Cluster analysis. According to different confidence level $\lambda \in [0, 1]$, the ranks of the fuzzy equivalent matrix $\mathbf{R}^*$ obtained in Step 3 can be gradually merged into different clustering results. when $r_{ij} \geq \lambda$, the correlation between the samples is strong enough, and the samples can be classified as the same class. For durability environmental regionalization, factors influencing durability of concrete can be treated as similar. The greater the value of λ is, the higher the stability of sample element is, and more details can be distinguished. However, the smaller the value of λ is, the less accurate the classification results is. Therefore, the variance of λ causes different classification results and forms a dynamic cluster result. In order to determine the optimal threshold λ , F-statistics method is used in this paper. In the process of cluster analysis, first obtain the center vector through raw data matrix:

$$\begin{aligned} \bar{x} &= (\bar{x}_1, \bar{x}_2, \dots, \bar{x}_k, \dots, \bar{x}_m), \\ \bar{x}_k &= \frac{1}{n} \sum_{i=1}^n x_{ik}, \quad k = 1, 2, \dots, m, \end{aligned} \quad (2)$$

where $\bar{x}$ is the center vector of the sample space.

Assume that there are r kinds of classes for certain λ , and samples size of the j th class is n_j . The samples in the j th class are recorded as $x_1^{(j)}, x_2^{(j)}, \dots, x_{n_j}^{(j)}$ and the center vector of the j th class is $\bar{x}^{(j)} = (\bar{x}_1^{(j)}, \bar{x}_2^{(j)}, \dots, \bar{x}_k^{(j)}, \dots, \bar{x}_m^{(j)})$, where $\bar{x}^{(j)}$ is the mean value of k th feature. Consider

$$\bar{x}_k^{(j)} = \frac{1}{n_j} \sum_{i=1}^{n_j} x_{ij}^{(j)}, \quad k = 1, 2, \dots, m. \quad (3)$$

The random variable

$$F = \frac{\sum_{j=1}^r n_j \|\bar{x}^{(j)} - \bar{x}\|^2 / (r-1)}{\sum_{j=1}^r \sum_{i=1}^{n_j} \|x_i^{(j)} - \bar{x}^{(j)}\|^2 / (n-r)} \quad (4)$$

is a F-distribution with $(n-1, n-r)$ degrees of freedom. Here $\|\bar{x}^{(j)} - \bar{x}\| = \sqrt{\sum_{k=1}^m (\bar{x}_k^{(j)} - \bar{x}_k)^2}$ is the distance between $\bar{x}^{(j)}$ and $\bar{x}$, and $\|x_i^{(j)} - \bar{x}^{(j)}\|$ is the distance between sample $x_i^{(j)}$ and center vector $\bar{x}^{(j)}$ in j th class. Numerator of F-distribution suggests the distances between different classes, and denominator of F-distribution suggests the distances between samples in the same class. Hence the larger F , the longer the distances between different classes, and the better the cluster result.

3.1.2. The Theory of the Rough Set. The theory of rough set, which is proposed by the mathematician Pawlak some 30 years ago, is a new approach to decision making in the presence of uncertainty and vagueness. The main idea of this theory is to make determination or regionalization by knowledge reduction on the basis of maintain resolving ability. Due to the feature that it does not make any presumptions or require a priori knowledge about the data, rough set has been widely used in the fields of data mining, pattern recognition, machine learning, and intelligent control successfully [17–21].

With the development of testing methods [22, 23], we can easily get the durability environmental data of concrete structures; however, due to the randomness of the practical project, statistical analysis for the factors affecting structural durability cannot be proposed. To solve this problem, the rough set theory is introduced to obtain the significance of various environmental factors affecting the durability of concrete structures.

Definition 1. Knowledge representation system is as follows:

$$S = (U, A, V, f), \quad (5)$$

where U is the sample set; $A = C \cup D$ is the attribute set, in which C and D are the condition attributes and the decision attributes of the samples, respectively; $V = \cup_{a \in A} V_a$ is the set of attribute values; and $f : U \times (C \cup D) \rightarrow V$ is an information functions which specifies the property value for each sample of U . Each subset of attributes $R \subseteq A$ determines an indistinguishable binary relation $\text{IND}(R)$:

$$\text{IND}(R) = \{(x, y) \in U \times U \mid \forall a \in R, f(x, a) = f(y, a)\}. \quad (6)$$

Definition 2. Given knowledge representation system $S = (U, A, V, f)$, for each subset $X \subset U$ and an indistinguishable relation $R \subset A$, the upper approximation set and lower approximation set of X can be defined as follows:

$$\begin{aligned} R^-(X) &= \bigcup \left\{ Y \subset \frac{U}{\text{IND}(R)} \mid Y \cap X \neq \emptyset \right\}, \\ R_+(X) &= \bigcup \left\{ Y \subset \frac{U}{\text{IND}(R)} \mid Y \subset X \right\}. \end{aligned} \quad (7)$$

Definition 3. The dependence between the two attribute sets C and D can be defined as follows:

$$\gamma(C, D) = \frac{|\text{POS}_C(D)|}{|U|}, \quad (8)$$

where $\text{POS}_C(D) = C_+(D)$, and $|U|$ is the number of the set element.

Definition 4. Attribute $a \in C$, the significance to D of attribute a can be defined as follows:

$$\text{SGF}(a, C, D) = \gamma(C, D) - \gamma(C - \{a\}, D), \quad (9)$$

where $\gamma(C - \{a\}, D)$ is the dependence degree of the condition attribute on the decision attribute when remove attribute a from C .

3.2. Method of Index Weight Allocation for the Durability Environmental Regionalization. When doing regionalization, the weight of indexes should be allocated due to the durability of concrete structures affected by various factors. Using rough set theory to determine the weight of the various regionalization indexes is that using attributes reduction of the rough set to determine the significance of each index under the premise of maintaining the ability of classification. Specific steps are as follows.

Step 1. Taking all samples tested as objects set $C = \{c_1, c_2, \dots, c_n\}$, the durability environmental regionalization index $(c_{i1}, c_{i2}, \dots, c_{im})$ as condition attributes, the component durability damage level $(d_1, d_2, \dots, d_m)$ as decision attributes, we can obtain the raw data matrix as follows:

$$A = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1m} & d_1 \\ c_{21} & c_{22} & \cdots & c_{2m} & d_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nm} & d_m \end{bmatrix}, \quad (10)$$

and then, make classification according to the traditional fuzzy clustering analysis.

Step 2. Determine the threshold value λ of the best confidence level by F-statistic, then make equivalence partitioning of the detected buildings according to the durability environmental regionalization index and the durability damage level, and then obtain the best classification,

$$Y = \{Y_1, Y_2, \dots, Y_s\}, \quad (11)$$

where Y_i represents a compressible set, which can be regard as a set of equivalence relations that corresponds to a durability damage level.

Step 3. In order to find out the significance of index c_i ($i = 1, 2, \dots, m$), we can first remove the index and then take fuzzy cluster analysis to the data matrix using the Step 2 method; then we can get the category set after removing the index c_i in turn:

$$E = \{E_1, E_2, \dots, E_m\}, \quad (12)$$

where $E_i = \{Y_1^{(i)}, Y_2^{(i)}, \dots, Y_k^{(i)}\}$ is the classification equivalence set after removing the i th regionalization index, and for different i , k is different. And $Y_l^{(i)}$ ($1 \leq l \leq k$) is the i th classification equivalence set.

Step 4. Using rough set theory to solve the significance of each index. First solve the union lower of approximate set of each equivalence set of each durability damage level respectively. Consider

$$\text{POS}_{C-\{c_i\}}(D) = \{C - \{c_i\}\} - (D) = \bigcup \{\{C - \{c_i\}\} - Y_l\}. \quad (13)$$

For each regionalization index c_i , the dependence degree of durability damage level D on the regionalization index set C and the regionalization index set $C - c_i$ were solved, respectively, by Definition 3 of rough set. Consider

$$\gamma(C, D) = \frac{|\text{POS}_C(D)|}{|U|}, \quad (14)$$

$$\gamma(C - \{c_i\}, D) = \frac{|\text{POS}_{C-\{c_i\}}(D)|}{|U|}.$$

Then solve the significance SGF (c_i, C, D) of the regionalization index set c_i according to Definition 4 of rough set.

Step 5. According to the significance of each regionalization index, allocate weight using the normalization method and get more intuitive results:

$$W_i = \frac{\text{SGF}(c_i, C, D)}{\sum_{k=1}^m \text{SGF}(c_k, C, D)}. \quad (15)$$

The knowledge system was established through the establishment of relational data model and the characterization of attribute value; then calculate the factor weight through the support degree and significance analysis of evaluation object under the data driven. This is an objective allocation method of the index weights of durability regionalization proposed in this paper.

3.3. Durability Environmental Regionalization for Concrete Structures in Shenzhen City. The influence factors detection and damage level assessment of durability was taken for 515 in-service concrete structures in Shenzhen city. Considering the operability of field detection, the concrete carbonation depth, chloride ion content of the concrete surface, ambient temperature, and relative humidity are taken as the index of durability environmental regionalization. In order to express the weights allocation process, the detect results of the outdoor trestle of Yantian fishing port, the teaching building of ShenZhen Donghe primary school, and the Bio entertainment center of sea world are taken for examples. Select 20 detected samples as the sample space $U = \{1, 2, \dots, 20\}$, and the condition attribute set $C = \{c_1, c_2, c_3, c_4\}$ are four durability environmental regionalization indexes, which are the concrete carbonation depth, surface chloride concentration, ambient temperature, and ambient relative humidity, respectively. The decision attribute set $D = \{d\}$ is the durability damage level of the concrete components, which can be calculated according to "standard for durability assessment of concrete structures CECS 220:2007" [24]. Where (1) represents that components almost have no durability damage; (2) represents that components have mechanical damage or slight durability damage; (3) represents that components have some relatively serious durability damage; and (4) represents that components have serious durability damage. The detecting data are show in Table 3.

In order to eliminate the impact of dimension, the standard derivation method is used to obtain standardized sample matrix R ; and the Euclidean distance method is

TABLE 3: Detecting data of concrete structures (extract).

Sample number	Durability environmental regionalization index				
	Concrete carbonation depth (mm)	Surface chloride concentration (%)	Ambient temperature (°C)	Ambient relative humidity (%)	Durability damage level
1	17	1.39	23.91	80	3
2	27	0.80	23.25	72	1
3	18	2.18	23.5	79	3
4	16	1.59	23.94	83	4
5	9	1.98	23.31	85	4
6	22	0.80	23.25	75	2
7	20	2.18	23.67	80	3
8	28	0.01	22.46	74	2
9	26	0.20	22.59	72	1
10	17	2.78	23.28	79	3
11	25	0.39	22.32	74	2
12	7	2.18	23.17	86	4
13	12	2.97	23.88	84	4
14	16	1.19	22.66	84	4
15	21	0.60	23.12	78	3
16	26	0.99	22.47	73	2
17	21	2.58	22.9	80	3
18	10	2.18	23.55	85	4
19	22	0.99	22.41	80	3
20	10	2.38	22.74	86	4
$\bar{x}_k$	18.50	1.52	23.12	79.45	2.95
$\bar{s}_k$	6.26	0.88	0.51	4.76	0.97

used to establish fuzzy similar matrix $\mathbf{R}$. Through the square

method, we get the transitive closure of $\mathbf{R}$ and then obtain fuzzy equivalent matrix $\mathbf{R}^*$

1	0.783	0.859	0.91	0.817	0.783	0.859	0.783	0.783	0.859	0.783	0.817	0.817	0.783	0.783	0.783	0.859	0.817	0.783	0.817
0.783	1	0.783	0.783	0.783	0.87	0.783	0.818	0.818	0.783	0.818	0.783	0.783	0.818	0.87	0.818	0.783	0.783	0.818	0.783
0.859	0.783	1	0.859	0.817	0.783	0.937	0.783	0.783	0.898	0.783	0.817	0.817	0.783	0.783	0.783	0.874	0.817	0.783	0.817
0.91	0.783	0.859	1	0.817	0.783	0.859	0.783	0.783	0.859	0.783	0.817	0.817	0.783	0.783	0.783	0.859	0.817	0.783	0.817
0.817	0.783	0.817	0.817	1	0.783	0.817	0.783	0.783	0.817	0.783	0.936	0.854	0.783	0.783	0.783	0.817	0.931	0.783	0.875
0.783	0.87	0.783	0.783	0.783	1	0.783	0.818	0.818	0.783	0.818	0.783	0.783	0.818	0.896	0.818	0.783	0.783	0.818	0.783
0.859	0.783	0.937	0.859	0.817	0.783	1	0.783	0.783	0.898	0.783	0.817	0.817	0.783	0.783	0.783	0.874	0.817	0.783	0.817
0.783	0.818	0.783	0.783	0.783	0.818	0.783	1	0.921	0.783	0.911	0.783	0.783	0.821	0.818	0.899	0.783	0.783	0.823	0.783
0.783	0.818	0.783	0.783	0.783	0.818	0.783	0.921	1	0.783	0.911	0.783	0.783	0.821	0.818	0.899	0.783	0.783	0.823	0.783
0.859	0.783	0.898	0.859	0.817	0.783	0.898	0.783	0.783	1	0.783	0.817	0.817	0.783	0.783	0.783	0.874	0.817	0.783	0.817
0.783	0.818	0.783	0.783	0.783	0.818	0.783	0.911	0.911	0.783	1	0.783	0.783	0.821	0.818	0.899	0.783	0.783	0.823	0.783
0.817	0.783	0.817	0.817	0.936	0.783	0.817	0.783	0.783	0.817	0.783	1	0.854	0.783	0.783	0.783	0.817	0.931	0.783	0.875
0.817	0.783	0.817	0.817	0.854	0.783	0.817	0.783	0.783	0.817	0.783	0.854	1	0.783	0.783	0.783	0.817	0.854	0.783	0.854
0.783	0.818	0.783	0.783	0.783	0.818	0.783	0.821	0.821	0.783	0.821	0.783	0.783	1	0.818	0.821	0.783	0.783	0.821	0.783
0.783	0.87	0.783	0.783	0.783	0.896	0.783	0.818	0.818	0.783	0.818	0.783	0.783	0.818	1	0.818	0.783	0.783	0.818	0.783
0.783	0.818	0.783	0.783	0.783	0.818	0.783	0.899	0.899	0.783	0.899	0.783	0.783	0.821	0.818	1	0.783	0.783	0.823	0.783
0.859	0.783	0.874	0.859	0.817	0.783	0.874	0.783	0.783	0.874	0.783	0.817	0.817	0.783	0.783	0.783	1	0.817	0.783	0.817
0.817	0.783	0.817	0.817	0.931	0.783	0.817	0.783	0.783	0.817	0.783	0.931	0.854	0.783	0.783	0.783	0.817	1	0.783	0.875
0.783	0.818	0.783	0.783	0.783	0.818	0.783	0.823	0.823	0.783	0.823	0.783	0.783	0.821	0.818	0.823	0.783	0.783	1	0.783
0.817	0.783	0.817	0.817	0.875	0.783	0.817	0.783	0.783	0.817	0.783	0.875	0.854	0.783	0.783	0.783	0.817	0.875	0.783	1

(16)

F-statistics method is used to determine the optimum threshold value $\lambda = 0.91$, and the classification results for 20 detected samples according to condition attributes C (four durability environmental regionalization indexes) and decision attributes D (the durability damage level of the concrete components) are

$$\begin{aligned}\frac{U}{\text{IND}(C)} &= \{\{1, 4\}, \{2\}, \{3, 7\}, \{5, 12, 18\}, \{6\}, \{8, 9, 11\}, \\ &\quad \{10\}, \{13\}, \{14\}, \{15\}, \{16\}, \{17\}, \{19\}, \{20\}\}; \\ \frac{U}{\text{IND}(D)} &= \{\{2, 9\}, \{6, 8, 11, 16\}, \{1, 3, 7, 10, 15, 17, 19\}, \\ &\quad \{4, 5, 12, 13, 14, 18, 20\}\}.\end{aligned}\quad (17)$$

Similarly, after removing the condition attribute c_i , classify the condition attribute set C by the fuzzy clustering methods, and all the best classifications were as follows:

$$\begin{aligned}\frac{U}{\text{IND}(C - \{c_1\})} &= \{\{1, 4\}, \{2, 6, 15\}, \{3, 7, 10, 17\}, \\ &\quad \{5, 12, 18\}, \{8, 9, 11, 16\}, \\ &\quad \{13\}, \{14\}, \{19\}, \{20\}\}; \\ \frac{U}{\text{IND}(C - \{c_2\})} &= \{\{1, 3, 4, 7, 10, 13, 15, 17\}, \{2\}, \\ &\quad \{5, 12, 18\}, \{6\}, \\ &\quad \{8, 9, 11, 16\}, \{14\}, \{19\}, \{20\}\}; \\ \frac{U}{\text{IND}(C - \{c_3\})} &= \{\{1\}, \{2, 16\}, \{3, 7, 17\}, \{4, 14\}, \\ &\quad \{5, 12, 18, 20\}, \\ &\quad \{6, 8, 9, 11\}, \{10\}, \{13\}, \{15, 19\}\}; \\ \frac{U}{\text{IND}(C - \{c_4\})} &= \{\{1, 4\}, \{2, 6, 15\}, \{3, 7\}, \{5, 12, 18\}, \\ &\quad \{8, 9, 11, 16, 19\}, \{10\}, \\ &\quad \{13\}, \{14\}, \{17\}, \{20\}\}.\end{aligned}\quad (18)$$

Then solve the union lower of approximate set of each equivalence set of each durability damage level, respectively. Consider

$$\begin{aligned}\text{POS}_C(D) &= \{2, 3, 5, 6, 7, 10, 12, 13, 14, 15, 16, 17, 18, 19, 20\}, \\ \text{POS}_{C-\{c_1\}}(D) &= \{3, 5, 7, 10, 12, 13, 14, 17, 18, 19, 20\}, \\ \text{POS}_{C-\{c_2\}}(D) &= \{2, 5, 6, 12, 14, 18, 19, 20\},\end{aligned}$$

$$\text{POS}_{C-\{c_3\}}(D) = \{1, 3, 4, 5, 7, 10, 12, 13, 14, 15, 17, 18, 19, 20\},$$

$$\text{POS}_{C-\{c_4\}}(D) = \{3, 5, 7, 10, 12, 13, 14, 17, 18, 20\}.\quad (19)$$

Then calculate the significance $\text{SGF}(c_i, C, D)$ of each regionalization index c_i through the dependence degree of durability damage level D on the regionalization index set C and the regionalization index set $C - c_i$. Consider

$$\begin{aligned}\text{SGF}(c_1, C, D) &= \gamma_C(D) - \gamma_{C-\{c_1\}}(D) \\ &= \frac{|\text{POS}_C(D)|}{|U|} - \frac{|\text{POS}_{C-\{c_1\}}(D)|}{U} \\ &= \frac{15}{20} - \frac{11}{20} - \frac{4}{20}, \\ \text{SGF}(c_2, C, D) &= \gamma_C(D) - \gamma_{C-\{c_2\}}(D) \\ &= \frac{|\text{POS}_C(D)|}{|U|} - \frac{|\text{POS}_{C-\{c_2\}}(D)|}{U} \\ &= \frac{15}{20} - \frac{8}{20} - \frac{7}{20}, \\ \text{SGF}(c_3, C, D) &= \gamma_C(D) - \gamma_{C-\{c_3\}}(D) \\ &= \frac{|\text{POS}_C(D)|}{|U|} - \frac{|\text{POS}_{C-\{c_3\}}(D)|}{U} \\ &= \frac{15}{20} - \frac{14}{20} - \frac{1}{20}, \\ \text{SGF}(c_4, C, D) &= \gamma_C(D) - \gamma_{C-\{c_4\}}(D) \\ &= \frac{|\text{POS}_C(D)|}{|U|} - \frac{|\text{POS}_{C-\{c_4\}}(D)|}{U} \\ &= \frac{15}{20} - \frac{10}{20} - \frac{5}{20}.\end{aligned}\quad (20)$$

Finally, normalize the significance of each regionalization index c_i and we can obtain the weight of the durability influencing factors:

$$(\omega_{c_1}, \omega_{c_2}, \omega_{c_3}, \omega_{c_4}) = (0.2353, 0.4118, 0.0588, 0.2941).\quad (21)$$

From Formula (21) we can see that, among the factors influencing concrete durability in Yantian district, the surface chloride concentration has the most influential effect, followed by the ambient relative humidity and concrete carbonation depth, while the ambient temperature had the least influence. After assessing the durability damage level of the 515 in-service concrete structures in Shenzhen city, the weight of each affecting factors for building's durability is obtained.

Considering the administrative division of Shenzhen city and roads regionalization of Longda Express highway, Guangshen Express highway, Jihe Express highway, Huishen

TABLE 4: Result of durability environmental regionalization for concrete structures in Shenzhen city.

Regions	Weight of durability environmental regionalization indexes				Geographical area
	Surface chloride concentration	Concrete carbonation depth	Ambient temperature	Ambient relative humidity	
I	0.3154~0.4250	0.1803~0.2560	0.0154~0.1737	0.0213~0.3125	A narrow distribution along the coastline, mainly in the south of Guangzhou-Shenzhen highway
II	0.2758~0.3239	0.2445~0.3460	0.0758~0.1239	0.0250~0.2375	Central of Bao'an district, northern of nanshan and Futian District, most parts of the Luohu and Yantian district, southern of Longgang district
III	0.1762~0.2618	0.3219~0.4795	0.0758~0.1998	0.0219~0.1843	Mainly in the north of Longda expressway, huiyan Highway, and Shenzhen-Shantou expressway

FIGURE 2: Regionalization map of durability environment for concrete structures in Shenzhen City.

Express highway, Huiyan Express highway, and so forth, the durability environmental regionalization can be made based on the weight of each influencing factor and deterioration characteristics of detected structures. The Shenzhen city is divided into three areas: Chloride Erosion area (I); Adjacent Sea Air area, which makes chloride erosion as main action and carbonization supplementary (II); and Common Air area, which makes carbonization as main action (III) (Table 4). According to the regionalization results, the durability regionalization map of concrete structures in Shenzhen city can be plotted as Figure 2.

Table 2 and Figure 1 show that, among the factors affecting the durability of concrete structures from Chloride Erosion area (I) to Common Air area (III), the effect of chloride erosion is gradually weakened, while the effect of carbonization gradually become the dominant.

In the Chloride Erosion area (I), the relative humidity and atmospheric Cl^- content are relatively high, steel reinforcement in concrete has severely deteriorated, and concrete cover exhibits a large number of cracks along the longitude rebar or even a large area of spalling. More attention should be paid on chloride erosion when doing structural durability design, and appropriate durability protective measures should be taken in this region.

Adjacent Sea Air area (II) covers most areas of the Shenzhen special economic zone. With the distance from costal line increasing, atmospheric Cl^- content decreases rapidly. This is because the maritime air is forced to uplift due to the block of Lotus mountains, and the salt spray carried by the air is absorbed by most of the rocks and trees; besides, the air flow is blocked by the tall buildings in south of Shenzhen city, and most salt particles in the air were settled. The effect of

chloride ion penetration and concrete carbonation should be considered during structural durability design in this region.

After salt particle settlement in Region I and Region II, the chloride concentration of the components surface decreased. Reinforced concrete structures in Common Air area (III) has mild rust occasionally, the concrete protective layer of reinforcement has a small amount longitude cracks due to insufficient thickness. concrete carbonation is the major factor that influences the durability of concrete in this area.

4. Conclusion

- (1) The combination of dominant factor and comprehensive analysis method of the climatic zonation can be used in the macroenvironmental regionalization. Taking China for example, after comprehensive analysis of climate condition and erosion medium characteristics of China, property regionalization indexes can be selected, and China can be divided into six primary regions and thirteen secondary regions.
- (2) A new way based on the fuzzy sets and rough sets to determine the weight distribution can be used in the microenvironmental regionalization. Based on discretization of the measured data, the significance of attributes among rough sets can be estimated instead of weight determination, and a relational data model about the durability effecting factors of concrete structures can be established. A knowledge system can be built through making attribute value into eigenvalue. After that, the method of durability environmental division for microenvironment can be established by analyzing the degree of influence various factors have on the durability of concrete structures.
- (3) After researching on durability environmental regionalization for concrete structures in China and Shenzhen city, the proposed approach improved the accuracy and efficiency of comprehensive evaluation of the subjectivity of traditional environmental regionalization method, and the regionalization result, which will agree with the field situation of concrete durability degradation, is proved much more to be scientific and practical. Moreover, the recommended method provides a scientific basis to durability design and maintenance of reinforced concrete structures.

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