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Research Article

Durability Assessment of Lightweight Cellular Concrete in Subgrade by the Method of Analytic Hierarchy Process Combined with Fuzzy Comprehensive Evaluation

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The durability of lightweight cellular concrete (LCC) and the corresponding assessment method are studied in this paper to improve the utilization of LCC in subgrade construction engineering. The durability assessment method is established by combining the analytic hierarchy process (AHP) with fuzzy comprehensive evaluation (FCE). The main assessment processes are as follows. Firstly, based on the physical and mechanical properties of LCC, the influencing factors are selected in terms of preliminary design, construction technology, and operation and management after completion of construction. The grading standard of influencing factors is established as well. Secondly, a multilevel assessment model with targets level, criteria level, and indexes level is established. AHP determines the effective weight of the lower level relative to the upper level. The consistency check of the judgment matrix is conducted to prove the rationality of the distribution of influencing factors' effect weight. Thirdly, the membership function which is suitable for each influencing factor is built to calculate the membership degree. Besides, the practicality and reliability of AHP combined with FCE are demonstrated through a practical engineering case, which is the third section of a highway in Guangdong Province, China.

1. Introduction

LCC is a very promising modern building material which has more and more applications in civil engineering because of its low density, adjustable strength, and self-reliance after curing [1]. It is mainly composed of cement, water, and preformed foam. There are numerous unpredictabilities of its mechanical properties, especially the durability problem. The durability is the ability to resist climate impacts, chemical erosion, physical action, and other damages. The structural damage caused by insufficient durability is common at home and abroad, which not only affects the regular use of the structure but also causes substantial economic losses. At present, some studies are being conducted on the durability of LCC. For example, Neramitkornburi et al. [2] studied the dry-wet cycle strength of LCC with clay and fly ash added, established an equation for the series and intensity of dry-wet cycles, and verified the applicability of the equation. Kang and Shin [3] investigated the compressive strength changes of LCC with different cement content under low outdoor temperature, below ground, and in a water immersion environment. At the same time, the density and compressive strength of the samples under the conditions of long-term water immersion, dry-wet cycle, and partial water immersion are compared. Park and Kim [4] used artificial neural networks to establish a model based on experimental data and predicted the unconfined compressive strength of LCC. Shen et al. [5] applied Dramix 3D steel fibers to strengthen the early age properties of HSC to increase the cracking resistance. Similarly, Kobayashi et al.

[6] and Furukawa and Fujimura [7] added chopped fibers to LCC to increase durability. Kikuchi et al. [8] conducted a series of LCC dry-wet cycle durability tests. Furthermore, the test results compared the LCC that had been in use for ten years in the engineering project. Chao-Lung and Tran [9] investigated the engineering and durability properties of self-consolidating concrete specimens incorporating various types of foamed lightweight aggregate. Jaini et al. [10, 11] studied rice husk ash as a substitute for sand in foam concrete, which can react with cement. Consequently, the strength and durability of LCC increased. Hilal et al. [12] investigated the bubble size distribution of foam (before adding to the mixture) and the LCC (after curing). Ahmad and Awang [13] studied the effects of fly ash inclusions on the mechanical properties and durability of LCC with steel fibers and alkali-resistant glass fibers. These studies only consider one or two influencing factors. However, in practical engineering, the durability problem of LCC is not caused by a single element, but by interacting multiple factors. It is challenging to express their relationship accurately by mathematical and mechanical functions. Therefore, this article uses the combined method of AHP with FCE to study LCC durability.

FCE is a multifactor decision-making method. It can evaluate things that have multiple factors which are interrelated and interact with each other. The theoretical basis of this method is fuzzy mathematics, where some fuzzy, difficult-to-quantify factors can be quantified by fuzzy synthesis. On the one hand, many factors are influencing the durability assessment of the LCC. On the other hand, the comments are usually ambiguous. For these reasons, an FCE method should be adopted. However, when the FCE is applied, the effect weights of the influencing factors are given by the experts' experience, with strong subjectivity. The AHP can quantify the qualitative factors and reduce the impact of personal speculation to a certain extent, making the assessment more scientific. At present, the FCE method based on AHP has gradually matured. In the literature [14–17], the method of AHP combined with FCE was applied for the practice of security risk assessment and some results were achieved. These engineering practices and results prove the feasibility of this method in the LCC durability assessment. As a new type of material, LCC is rarely studied on its durability, and there is no accurate assessment method. Therefore, it is of great engineering significance to research the LCC durability assessment based on the method of AHP combined with FCE.

In summary, the durability assessment process of LCC cannot simply perform with one single influencing factor. At the same time, the influencing factors should not be treated equally. Thus, based on the method of AHP combined with FCE, the authors select the corresponding influencing factors and give them reasonable effect weights. Simultaneously, combining the grade standard of the influencing factors, a reasonable membership function is established, and a specific method of FCE is given. On this basis, it is possible to make a comprehensive assessment of the LCC durability of an actual project.

2. Influencing Factors and Their Grade Standards

2.1. Selection of Influencing Factors for LCC Durability. There are not only a large number of factors that affect LCC durability, but also many test items that affect the assessment result of LCC. According to the relevant requirements [18] and the basic physical and mechanical properties of LCC, the factors affecting the LCC durability are considered in terms of three aspects, including preliminary design, construction technology, and operation and management.

(a) *Preliminary Design*. Engineering construction requires a scientific and rational design scheme. In the design period, the material ratio and structural safety and stability should be considered. If there is a problem with the design, there will be a safety risk in the construction of the project. Therefore, the durability of LCC is affected by the preliminary design. From the design perspective, six influencing factors are selected: wet density, compressive strength, filling aspect ratio, safety factor, slope rate of connecting surface, and steel wire mesh setting.

(b) *Construction Technology*. LCC has strict requirements for construction technology, and different technologies have different effects on the LCC durability. In this paper, seven influencing factors are selected from the perspective of construction technology: production equipment, agitation sufficient degree, flow value, single layer pouring thickness, single layer pouring time, interlayer pouring interval time, and construction environment.

(c) *Operation and Management*. The influence of later-period management of LCC on durability is crucial. Severe overload will inevitably lead to the cracking of LCC and shorten its life. In the meantime, long-term immersion in water can also cause a decrease in strength. Also, there are temperature change, chemical corrosion, and other factors. Therefore, five influencing factors are selected from the perspective of operation and management: curing time, vehicle load, drainage condition, chemical corrosion, and temperature change.

2.2. Durability Influencing Factors Rating Standard for LCC. The determination of the value of each influencing factor varies from the project classification, characteristics, and assessment purposes. In the FCE method, it is called the determination of the set of comments. Comments are descriptions of the evaluation results of the evaluated objects after considering various factors, and the comment set is a collection of these comments. In view of the embankment filling of LCC, descriptions or influencing factors such as wet density and compressive strength should be considered. The general evaluation level is divided into 3~7, and this paper selects 4 levels. The appropriate numerical value is beneficial to grade division in the process of evaluation. According to the existing literature [9, 19–22] and the research progress of this group [23–27], the grades of influencing factors are divided as follows:

(a) *Wet Density*. The wet density range of LCC is 500~1200 kg/m^3, and the density range of full-filled subgrade is 1900~2000 kg/m^3. The wet density can be divided into four levels: [5, 10), [10, 15), [15, 20), and [20, ∞), comparing the above two ranges.

(b) *Compressive Strength*. As per the principle of density adjustment, the strength can be adjusted within the range of 0.3~5 MPa by changing the ratio of various components in LCC. In this paper, compressive strength can be divided into the following four levels: [3.5, ∞), [2, 3.5), [0.5, 2), and (0, 0.5).

(c) *Filling Aspect Ratio*. From the perspective of stability, the aspect ratio cannot be too large, and the anchorage measures are required when the aspect ratio is greater than two as stipulated in [18]. This paper chooses to divide the filling aspect ratio of LCC into the following four grades when there is no anchorage treatment: (0, 1), [1, 1.5), [1.5, 2), and [2, ∞).

(d) *Safety Factor*. As a whole, the LCC embankment is needed to be checked for its stability. This paper selects the safety factor of the anti-overturning checking including the foundation as the assessment index and divides the safety factor into the following four levels: [1.5, ∞), [1.3, 1.5), [1.2, 1.3), and (0, 1.2).

(e) *Slope Rate of Connecting Surface*. The uprightness of the LCC is good; however, if the slope rate is too large, it will cause cracking or even instability. The specification also limits the slope of the connecting surface of the LCC not to exceed 1 : 1. This paper uses the angle between the connecting surface and the horizontal plane to classify it. When the included angle is <90°, the LCC is above the subgrade soil. Conversely, when the included angle is >90°, the LCC is under the subgrade soil. According to the engineering application, it can be divided into the following four levels: (0°, 45°], (45°, 90°], (90°, 135°], and (135°, 180°].

(f) *Steel Wire Mesh Setting*. The steel wire mesh setting should conform to the general regulations. When the LCC filling height is less than 5 m, one layer of steel wire mesh should be placed within 50 cm of the filling body bottom and 50 cm of the top. Furthermore, when the height of the LCC is 5~12 m, a two-layer steel wire mesh should be placed within 100 cm of the filling body bottom and 100 cm of the top. The classification of the steel wire mesh setting depends mainly on whether it is set as above.

(g) *Production Equipment*. The assessment of the production equipment mainly depends on the foaming equipment. The foaming equipment should preferably form foam by mixing compressed air with an aqueous solution of a blowing agent, and it is not suggested to generate bubbles by stirring. The foaming equipment should have a stable foaming ratio, large gas production, and high gas pressure.

(h) *Agitation Sufficient Degree*. Producing different amounts of LCC requires different mixing time. Generally, it should be 5~10 min, and the mixing time should not be too long or too short. It is necessary to control different mixing speeds when mixing cement slurry or LCC.

(i) *Flow Value*. According to the requirements of the specification, the flow value should be controlled at about 180 mm. This paper divides the flow value into the following four levels: [170, 180], (180, 200], [160, 170), and (0, 160).

(j) *Single Layer Pouring Thickness*. LCC should be poured in a layered and block manner to reduce the heat of hydration. In addition to void filling and pipeline backfilling, the thickness of a single layer should be controlled between 0.3~0.8 m.

(k) *Single Layer Pouring Time*. If the cement material is the same, the single layer pouring time should be controlled within the initial setting time of the cement.

(l) *Interlayer Pouring Interval Time*. The upper layer should be poured after the final set of the lower layer. Generally, the time from pouring to the final set of LCC is 6~7 hours, so the interval pouring time between layers is at least 7 hours.

(m) *Construction Environment*. Factors affecting the construction environment include rainfall, high temperature in summer, low temperature in winter, and so on. According to the weather conditions recorded during the construction period, it is possible to judge the quality of the construction environment.

(n) *Curing Time*. When the filling body of LCC completed, the surface of the filling body should be covered with plastic film or geotextile for moisturizing and curing. Moreover, the curing time should not be less than seven days.

(o) *Vehicle Load*. The greater the vehicle load is, the greater the impact on the life of LCC will be. The overload frequency directly affects the durability of the LCC.

(p) *Drainage Condition*. According to whether the drainage is smooth and whether there is frequent water accumulation, it is possible to judge the quality of drainage condition.

(q) *Chemical Corrosion*. Since the foaming agent is alkaline, the LCC is an alkaline material, and the resistance to acidic substances is weak. The stronger the acidity is, the more acid the light soil will be. Nevertheless, the degree of corrosion should be less than 10%.

(r) *Temperature Change*. Tan et al. [28] conducted a freeze-thaw cycle test on LCC. The results show that as the number of freeze-thaw cycle increases, the compressive strength of the sample decreases, and the compressive strength decreases exponentially with the number of freeze-thaw cycles increasing.

The durability of the LCC is divided into four assessment grades: excellent, good, general, and poor. Based on the classification mentioned above, the grading standard of the influencing factors is established as shown in Tables 1–3.

3. Comprehensive Assessment Model of LCC Durability

The FCE method uses the fuzzy transformation, the basic principle of fuzzy mathematics to comprehensively evaluate the uncertain things from various aspects, quantitatively transforming the fuzzy qualitative factors with unclear boundary conditions. In the process of evaluation, it is suggested that the fuzzy linear principle and membership degree be used to describe the object with fuzzy boundary. The results of FCE combine qualitative and quantitative analysis, making the results more persuasive.

3.1. Establishment of Factor Sets and Comment Sets. Factors are those attributes that can describe the characteristics of the evaluated object, and they are also interrelated and affect each other, usually represented by $U = \{u_1, u_2, \ldots, u_n\}$. Each element $u_i\,(i = 1, 2, \ldots, n)$ is not only the factor of the evaluated object but also the indexes used in the evaluation.

Comments are the evaluation results of the evaluated objects after taking all factors into consideration, usually represented by $V = \{v_1, v_2, \ldots, v_m\}$. Each element $v_i\,(i = 1, 2, \ldots, m)$ is the comment of the evaluated object.

Combined with the main influencing factors of the LCC durability, a comprehensive assessment model for the durability of LCC shown in Table 4 was constructed. The durability assessment model of LCC is divided into three levels based on the AHP method. The targets level is the LCC durability, and the criteria level is the preliminary design, construction technology, and operation and management. The third level is the specific factors that affect the durability of LCC. The assessment model comprehensively considers the characteristics of LCC, the construction technology, and operation and management and involves the implementation and use phase of the construction project. Also, the assessment model can comprehensively reflect the influencing factors of the LCC durability. At the same time, it is in line with the comprehensive, scientific, and feasible assessment principles.

Let $U_i\,(i = 1, 2, \ldots, n)$ be the ith influencing factor of the criteria level, and n be the influencing factors' number of the criteria level. $u_{ik}\,(k = 1, 2, \ldots, l)$ is the kth influencing factor corresponding to the ith influencing factor of the criteria level. l is the influencing factors' number of the ith influencing factor of the criteria level, and $l = 6$ when $i = 1$; $l = 7$ when $i = 2$; and $l = 5$ when $i = 3$. $\{U\}$ is the influencing factors set of the criteria level, and $\{U_i\}$ is the subfactors set of the ith influencing factor of the criteria level. According to the LCC$'$ durability assessment model, the following factor sets are established:

$$\{U\} = \{U_1, U_2, U_3\} = \{\text{Preliminary Design, Construction Process, Operation Management}\}. \tag{1}$$

Subfactor sets:

$$\begin{aligned}
\{U_1\} &= \{u_{11}, u_{12}, u_{13}, u_{14}, u_{15}, u_{16}\}\\
&= \{\text{Wet Density, Compressive Strength, Filling Aspect Ratio, Safety Factor,}\\
&\quad \text{Slope Rate of Connecting Surface, Steel Wire Mesh Setting}\},\\
\{U_2\} &= \{u_{21}, u_{22}, u_{23}, u_{24}, u_{25}, u_{26}, u_{27}\}\\
&= \{\text{Production Equipment, Agitation Sufficient Degree, Flow Value,}\\
&\quad \text{Single Layer Pouring Thickness, Single layer Pouring Time,}\\
&\quad \text{Interlayer Pouring Interval Time, Construction Environment}\},\\
\{U_3\} &= \{u_{31}, u_{32}, u_{33}, u_{34}, u_{35}\}\\
&= \{\text{Curing Time, Vehicle Load,}\\
&\quad \text{Drainage Condition, ? Chemical Corrosion, Temperature Change}\}.
\end{aligned} \tag{2}$$

Let $V_j\,(j = 1, 2, \ldots, m)$ be the jth assessment level in the comment sets, m be the number of assessment levels, and the comprehensive comment set is $\{V\}$. Then there is

$$\{V\} = \{V_1, V_2, V_3, V_4\} = \{\text{Excellent, Good, General, Poor}\}. \tag{3}$$

3.2. Determining Effect Weights by Analytic Hierarchy Process. In order to determine the importance of each factor, which is often different between factors, it is necessary to assign a weight to each factor. Weight set is usually represented by $A = \{a_1, a_2, \ldots, a_n\}$, which $a_i\,(i = 1, 2, \ldots, n)$ represents the degree of influence of this factor on the things to be evaluated. In general, $0 \le a \le 1$, $\sum_{i=1}^{n} a_i = 1$.

Table 1: Grade classification of influencing factors of preliminary design.

Assessment grade	Wet density (kg·m^{-3})	Compressive strength (MPa)	Filling aspect ratio	Safety factor	Slope rate of connecting surface (°)	Steel wire mesh setting
Excellent	[500, 1000)	[3.5, ∞)	(0, 1)	[1.5, ∞)	(0, 45]	Excellent
Good	[1000, 1500)	[2, 3.5)	[1, 1.5)	[1.3, 1.5)	(45, 90]	Good
General	[1500, 2000)	[0.5, 2)	[1.5, 2)	[1.2, 1.3)	(90, 135]	General
Poor	[2000, ∞)	[0, 0.5)	[2, ∞)	(0, 1.2)	(135, 180]	Poor

Table 2: Grade classification of influencing factors of construction technology.

Assessment grade	Production equipment	Agitation sufficient degree	Flow value (mm)	Single layer pouring thickness (m)	Single layer pouring time (min)	Interlayer pouring interval (time/hour)	Construction environment
Excellent	Excellent	Excellent	[170, 180]	[0.3, 0.5]	10 min before initial setting	[8, ∞)	Excellent
Good	Good	Good	(180, 200]	(0.5, 0.7]	5 min before initial setting	[7, 8)	Good
General	General	General	[160, 170)	(0.7, 0.8]	Initial setting time	[6, 7)	General
Poor	Poor	Poor	(0, 160)	(0.8, ∞)	Greater than the initial setting time	[0, 6)	Poor

Table 3: Grade classification of influencing factors of operation and management.

Assessment grade	Curing time (day)	Vehicle load	Drainage condition	Chemical corrosion (%)	Temperature change
Excellent	[10, ∞)	No overload	Excellent	[0, 1)	Minimal
Good	[8, 10)	Very little overload	Good	[1, 3)	Quite small
General	[7, 8)	A small amount of overload	General	[3, 10)	Large
Poor	(0, 7)	A lot of overloads	Poor	[10, ∞)	Quite large

Table 4: An assessment model of LCC durability.

Preliminary design	Construction technology	Operation and management
Wet density	Production equipment	Curing time
Compressive strength	Agitation sufficient degree	Vehicle load
Filling aspect ratio	Flow value	Drainage condition
Safety factor	Singer layer pouring thickness	Chemical corrosion
Slope rate of connecting surface	Singer layer pouring time	Temperature change
Steel wire meshing setting	Interlayer pouring interval time	
	Construction environment	

Since there are numerous data involved and the weight determination is cumbersome, the criteria level is taken as an example to determine the weight of the preliminary design, construction technology, and operation and management. By comparing the two influencing factors of the criteria level, the importance of them is quoted by the numbers 1–9 and their reciprocal as the scale assignment. Specifically, scale 1 indicates that the two factors are of equal importance. Scale 3 indicates that when two factors compared, one factor is slightly more important than the other. Scale 5 indicates that when two factors compared, one factor is significantly more important than the other. Scale 7 indicates that when two factors compared, one factor is strongly more important than the other. Scale 9 indicates that when two factors compared, one factor is significant than the other. Meanwhile, scales 2, 4, 6, and 8 are indicated as the median of the above two adjacent judgments. If one factor is compared with another to get a value, the latter's comparison with the former is the reciprocal of the value.

Many experts have been consulted, and a large number of data have been analyzed. The following is specific information about relevant research subjects that our research group has been responsible for:

(a) *Section C of Guang-Fo-Zhao Expressway in Guangdong*. There are four sections, and the specific location is K80 + 679.679~K80 + 760.116

(b) *Fengzihe Road in Nanjing*. There are two sections, and the specific location is K3 + 300~K13 + 253.226.

(c) *Guang-Ming Expressway Toll Plaza in Guangdong*. There are two sections, and the specific location is K30 + 893.745~K31 + 303.926

(d) *The Second Phase of an East Extension Line of Kuiqi Road in Foshan, Guangdong*. There are two sections, and the specific location is K2 + 483~K5 + 630

For the above ten sections, there is one project manager, one deputy manager, one general engineer, one deputy chief engineer, one engineering minister, two on-site surveying personnel, and two construction personnel, respectively. Table 5 shows the corresponding survey data. Therefore, according to the expert conclusions, the corresponding data collation is conducted.

The relative importance between the preliminary design, construction technology, and operation and management is comprehensively and objectively compared, and then the judgment matrix is obtained. The calculation of the maximum eigenvalue of the judgment matrix and the corresponding eigenvector is as follows:

$$A = \begin{bmatrix} 1 & 0.5 & 0.5 \\ 2 & 1 & 2 \\ 2 & 0.5 & 1 \end{bmatrix}$$

$$\xrightarrow{\text{column vector normalization}} \begin{bmatrix} 0.2 & 0.25 & 0.143 \\ 0.4 & 0.5 & 0.571 \\ 0.4 & 0.25 & 0.286 \end{bmatrix} \quad (4)$$

$$\xrightarrow{\text{sum by line}} \begin{bmatrix} 0.593 & 1.471 & 0.396 \end{bmatrix}^{T}$$

$$\xrightarrow{\text{normalized to get } \alpha} [0.198\ 0.490\ 0.312]^{T}.$$

Based on this, the maximum eigenvalue $\lambda_{\max}$ and the weight $\mathbf{W}$ of the matrix are judged. $\lambda_{\max} = 1/n\sum_{i=1}^{n}(\mathbf{A\alpha})_i/\alpha_i = 3.05, \mathbf{W} = (0.198, 0.4\,90, 0.312)$. In the formula, $\boldsymbol{\alpha}$ is the eigenvector corresponding to the largest eigenvalue and α_i is the element of the eigenvector.

It is necessary to check the consistency of the judgment matrix to verify whether the distribution of weights is reasonable. The formula is

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}. \quad (5)$$

where CR is the consistency ratio, when its value is less than 0.1, the consistency check is considered to be passed; CI is the consistency indicator, $\mathrm{CI} = \lambda_{\max} - n/(n-1)$, n is the order of the judgment matrix; and RI is the average consistency indicator, the RI corresponding to $n = 1{\sim}9$ is 0.00, 0.00, 0.58, 0.90, 1.12, 1.24, 1.32, 1.41, and 1.45. When RI is equal to 0, CR defaults to 0, which means it passes the consistency check.

Substituting the relevant data into the formula (5) yields $\mathrm{CR} = 0.043 < 0.10$, so the judgment matrix has satisfactory consistency, which proves that the weight distribution is reasonable.

The method and steps for determining the weight of the indexes level relative to the criteria level are the same as above, and the judgment matrix A_i $(i = 1, 2, 3)$ is

$$\mathbf{A}_1 = \begin{bmatrix} 1 & \frac{1}{4} & \frac{1}{3} & \frac{1}{5} & 3 & 4 \\ 4 & 1 & 4 & \frac{1}{2} & 8 & 7 \\ 3 & \frac{1}{4} & 1 & \frac{1}{4} & 3 & 4 \\ 5 & 1 & 4 & 1 & 8 & 8 \\ \frac{1}{3} & \frac{1}{8} & \frac{1}{3} & \frac{1}{8} & 1 & 2 \\ \frac{1}{4} & \frac{1}{7} & \frac{1}{4} & \frac{1}{8} & \frac{1}{2} & 1 \end{bmatrix},$$

$$\mathbf{A}_2 = \begin{bmatrix} 1 & 3 & 6 & 4 & 5 & 5 & 4 \\ \frac{1}{3} & 1 & 5 & 3 & 5 & 5 & 4 \\ \frac{1}{6} & \frac{1}{5} & 1 & \frac{1}{5} & \frac{1}{3} & 2 & \frac{1}{4} \\ \frac{1}{4} & \frac{1}{3} & 5 & 1 & 4 & 5 & 2 \\ \frac{1}{5} & \frac{1}{5} & 3 & \frac{1}{4} & 1 & 3 & \frac{1}{5} \\ \frac{1}{5} & \frac{1}{5} & \frac{1}{2} & \frac{1}{5} & \frac{1}{3} & 1 & \frac{1}{5} \\ \frac{1}{4} & \frac{1}{4} & 4 & \frac{1}{2} & 5 & 5 & 1 \end{bmatrix}, \quad (6)$$

$$\mathbf{A}_3 = \begin{bmatrix} 1 & 2 & 4 & 3 & 4 \\ \frac{1}{2} & 1 & 4 & 2 & 4 \\ \frac{1}{4} & \frac{1}{4} & 1 & \frac{1}{2} & 1 \\ \frac{1}{3} & \frac{1}{2} & 2 & 1 & 4 \\ \frac{1}{4} & \frac{1}{4} & 1 & \frac{1}{4} & 1 \end{bmatrix}.$$

By calculating the weight value of the indexes level, $\mathbf{W}_i\,(i = 1, 2, \ldots, n)$ is as follows: $\mathbf{W}_1 = (0.091, 0.300, 0.131, 0.401, 0.045, 0.033)$, $\mathbf{W}_2 = (0.351, 0.340, 0.041, 0.148, 0.065, 0.034, 0.127)$, and $\mathbf{W}_3 = (0.398, 0.276, 0.08, 0.174, 0.072)$. The CR is 0.054, 0.08, and 0.031. Both of which are less than 0.1, indicating that the weight distribution is reasonable.

3.3. Determination of Membership Function. The quantitative factors (such as wet density and safety Factor) for the set of the LCC durability subfactors are described by the membership function method. The form of the membership

Table 5: Statistical table of the surveyed experts.

The expert level	Key personnel	Total number of experts	Convert coefficient	Converted number of experts
First	Project manager, deputy manager, general engineer, deputy chief engineer	40	2	80
Second	Engineering minister	10	1.6	16
Third	On-site surveying personnel	20	1.2	24
Fourth	Construction personnel	20	1	20

function is not unique. By the related literature [29, 30], the author determines the membership function according to the actual situation of the research object. It can be seen from Tables 1~3 that the variation law of the quantitative factors is not completely consistent. To reasonably express the inconsistent change law in a unified calculation formula, the values of each influencing factor are arranged from small to large. Also, their range of values is divided into four intervals, using I, II, III, and IV said. Each interval is not equally divided, and the interval and the assessment level are not a one-to-one correspondence but correspond to the level standard. Let the membership degree of the critical values d_2, d_3, and d_4 of the two adjacent intervals be 0.5, and the membership degree of the midpoint values d_1', d_2', d_3' of the interval be 1. I and IV are the two extreme intervals, thus giving them a higher degree of membership. For example, the wet density ranges from 500 to 2000 kg/m^3, and the smaller the wet density, the better. When the wet density is very close to the lower limit of the range of value, it can be considered that the degree of belonging to the excellent grade is 1. Conversely, when the wet density is outside the upper limit of the range of values, it is quite unfavorable, and it belongs to the poor grade. The membership function can completely cover the range of values of each influencing factor. By using the value of the relevant influencing factors to check the membership function, the obtained membership degree is reasonable. Therefore, the membership function is considered to be in line with the objective reality of each influencing factor.

Language variables are established for qualitative factors (such as production equipment and agitation sufficient degree), and each assessment grade is scored (1 point, 2 points, 3 points, and 4 points). The membership degrees corresponding to the scores of the four assessment grades are shown in Table 6.

3.4. Comprehensive Fuzzy Evaluation. Let r_{ikj} be the kth influencing factor, which belongs to the ith influencing factor of the criteria level, and corresponds to the membership degree of the jth assessment grade in the comment set. Then the fuzzy evaluation vector of a single influencing factor can be expressed as $\mathbf{R}_{\mathrm{ik}} = (r_{ik1}, \ldots, r_{ikm})$. By combining the fuzzy evaluation vectors of all the individual influencing factors, the fuzzy evaluation matrix of the subfactor sets can be obtained:

$$\mathbf{R}_i = \begin{bmatrix} \mathbf{R}_{i1} \\ \mathbf{R}_{i2} \\ \vdots \\ \mathbf{R}_{il} \end{bmatrix} = \begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1m} \\ r_{i21} & r_{i22} & \cdots & r_{i2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{il1} & r_{il2} & \cdots & r_{ilm} \end{bmatrix}. \tag{7}$$

According to the weight, $\mathbf{W}_i$ corresponding to the subfactor set, a first-level comprehensive assessment of the influencing factors of the ith influencing factor of the criteria level can be obtained:

$$\mathbf{B}_i = \mathbf{W}_i * \mathbf{R}_i = (b_{i1}, b_{i2}, \ldots, b_{im}). \tag{8}$$

where $*$ is the generalized fuzzy synthesis operation and b_{ij} is the membership degree of the ith influencing factor of the criteria level on the jth assessment grade.

Using the weighted average type operator $M(\cdot, \oplus)$ to perform operations, there is $b_{ij} = \sum_{k=1}^{l} (w_{ik} \cdot r_{ikj}) = \sum_{k=1}^{l} w_{ik} r_{ikj}$, $(i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, m)$. Repeat the above steps for the second-level comprehensive assessment so that the fuzzy evaluation matrix of the factor set is $\mathbf{R} = (\mathbf{B}_1, \mathbf{B}_2, \ldots, \mathbf{B}_n)^{\mathrm{T}}$. And by calculating the weight $\mathbf{W}$ of the factor set $\{U\}$, the final result of the second-level fuzzy comprehensive assessment of the LCC durability is determined by the weighted average method:

$$\mathbf{B} = \mathbf{W} \cdot \mathbf{R} = (b_1, b_2, \ldots, b_m). \tag{9}$$

Finally, according to the principle of maximum membership degree, the largest assessment index b_j in the comprehensive assessment result $\mathbf{B}$ is selected as the final assessment result of the LCC durability. That is, the LCC durability is generally subordinate to the jth grade.

4. Practical Engineering Case

The LCC subgrade is in the toll area of the third section of a highway in Guangdong, the mileage pile number of which is K31 + 103.627~K31 + 302.878. The length is 199.251 meters, the narrowest parts at the starting and end are 95.07 m and 47.0 m, respectively, the maximum width in the middle is 114.4 m, and it has a thickness of 5.2 m. The façade design takes into account the factors of block pouring and lateral slope, for which steps are required that generally have a height of 20 cm. The raw data of each influencing factor are shown as follows: (a) Preliminary design factors: wet density is 7200 kg/m^3, compressive strength is 0.8 MPa, filling aspect

Table 6: The linguistic variables scoring membership of qualitative factors.

Assessment grade	Score			
	1	2	3	4
Excellent	0	0	0.33	0.67
Good	0	0.25	0.50	0.25
General	0.25	0.50	0.25	0
Poor	0.67	0.33	0	0

ratio is 0.06, safety factor is 1.93, slope rate of connecting surface is 90°, and the steel wire mesh setting is excellent. (b) Construction process factors: the production equipment is excellent, the agitation sufficient degree is good, the flow value is 180 mm, the single layer pouring thickness is 50 cm, the single layer pouring time is the initial setting time, the interlayer pouring interval time is 8 hours, and the construction environment is good. (c) Operation and management factors: the curing time is 15 days, the vehicle load is a small amount of overload, the drainage condition is general, there is no chemical corrosion, and the temperature change is minimal.

According to the fuzzy evaluation model of LCC durability, the fuzzy evaluation matrix of each subfactor set obtained is as follows:

$$\mathbf{R}_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0.7 & 0.33 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0 \\ 0.67 & 0.33 & 0 & 0 \end{bmatrix}, \quad \mathbf{R}_2 = \begin{bmatrix} 0.67 & 0.33 & 0 & 0 \\ 0.25 & 0.5 & 0.25 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0.25 & 0.5 & 0.25 \\ 0.5 & 0.5 & 0 & 0 \\ 0.25 & 0.5 & 0.25 & 0 \end{bmatrix}, \quad \mathbf{R}_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0.25 & 0.25 & 0.25 \\ 0 & 0.25 & 0.25 & 0.25 \\ 1 & 0 & 0 & 0 \\ 0.67 & 0.33 & 0 & 0 \end{bmatrix}. \quad (10)$$

The results of the first-level comprehensive fuzzy evaluation are as follows:

$$\begin{aligned} \mathbf{B}_1 &= \mathbf{W}_1 \cdot \mathbf{R}_1 = \left(0.645 \;\; 0.033 \;\; 0.233 \;\; 0.09 \right), \\ \mathbf{B}_2 &= \mathbf{W}_2 \cdot \mathbf{R}_2 = \left(0.436 \;\; 0.424 \;\; 0.123 \;\; 0.016 \right), \\ \mathbf{B}_3 &= \mathbf{W}_3 \cdot \mathbf{R}_3 = \left(0.620 \;\; 0.113 \;\; 0.178 \;\; 0.089 \right). \end{aligned} \quad (11)$$

Let the factor set fuzzy evaluation matrix be $\mathbf{R} = \left(\mathbf{B}_1 \;\; \mathbf{B}_2 \;\; \mathbf{B}_3 \right)^{\mathrm{T}}$; then, the second-level fuzzy comprehensive assessment results are as follows:

$$\mathbf{B} = \mathbf{W} \cdot \mathbf{R} = \left(0.535 \;\; 0.250 \;\; 0.162 \;\; 0.053 \right). \quad (12)$$

According to the principle of maximum membership degree, the largest assessment index $b_1 = 0.535$ in the comprehensive assessment result **B** is selected as the final assessment result of the LCC durability. That is, the LCC′ durability assessment result of this engineering is excellent.

Compared with the current specific operation of the engineering, the fuzzy comprehensive assessment results of the LCC durability made in this paper are consistent with the actual situation. The fuzzy comprehensive assessment model of the LCC established in this paper is reasonable and accurate, which proves the practicability and reliability of the combined method of AHP with FCE.

5. Conclusions

(a) In this paper, the durability assessment method of LCC is established by combining AHP with FCE. Based on the physical and mechanical properties of LCC, the influencing factors are selected in terms of preliminary design, construction technology, and operation and management after completion of construction. The grading standard of influencing factors is established as well.

(b) A multilevel assessment model for the LCC durability based on the targets level, criteria level, and indexes level is established. AHP determines the weight of the lower level relative to the upper level. The consistency check of the judgment matrix is conducted to prove the rationality of the distribution of influencing factors' weight.

(c) The membership function applicable to each influencing factor is constructed, the corresponding membership degree is calculated, and the specific method of FCE is given.

(d) The practicality and reliability of the technique combining AHP with FCE are demonstrated through a practical engineering case, which is S03 section of a highway in Guangdong Province, China.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

X. L. and B. H. formulated overarching research goals and aims. X. L. and K. S. created mathematical models. C. N. and L. Z. carried out data calculation. C. N., L. Z., and K. S. analyzed and validated the research data. K. S. wrote the original draft. C. N. reviewed and edited the article. B. H. provided study materials, computing resources, and other analysis tools. All authors read and approved the final manuscript.

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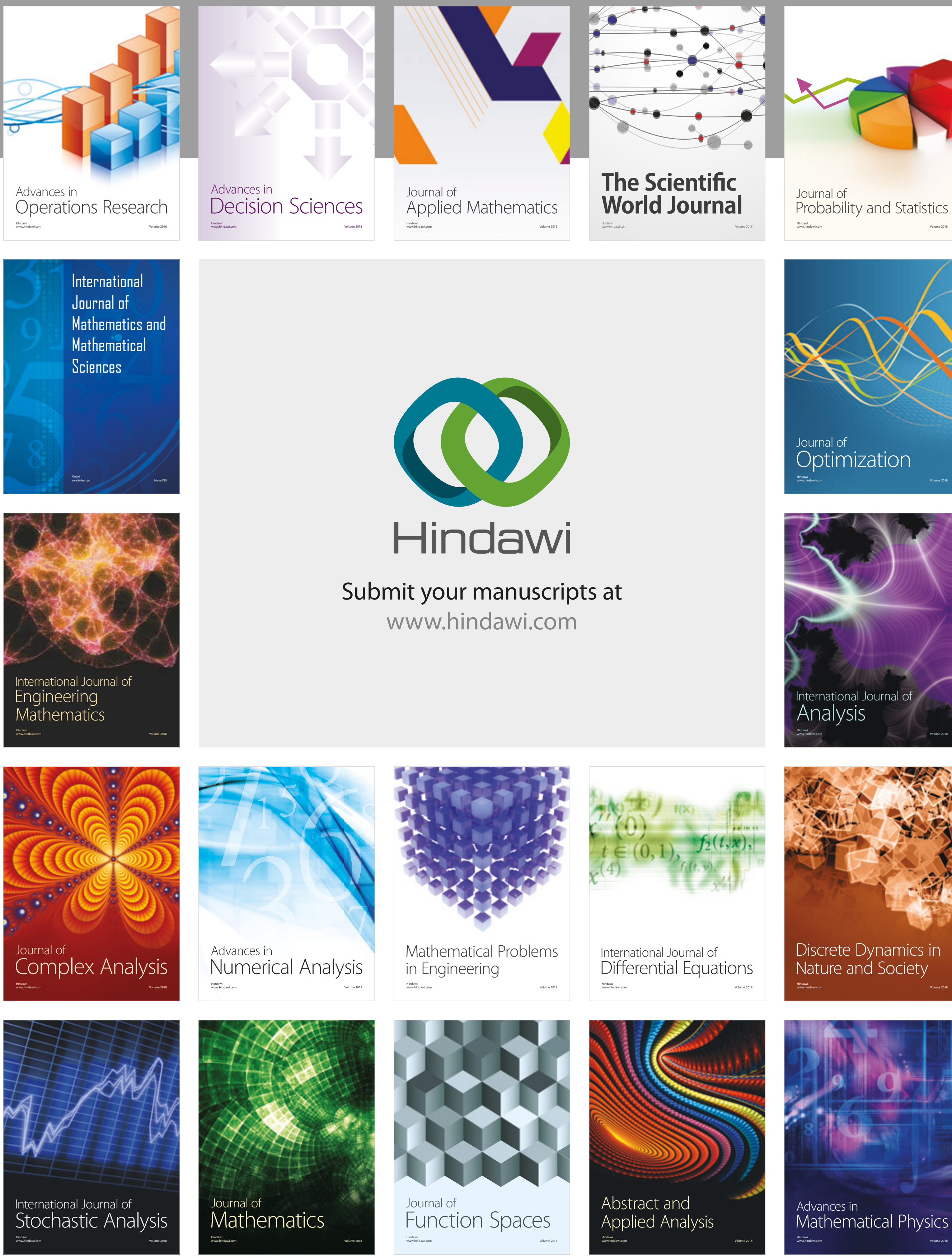
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