Evaluation of Concrete Durability Based on Cloud Model and D-S Evidence Theory

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Abstract. The environment in alpine region is complex and harsh, and the durability of concrete is seriously affected by freeze-thaw and salt invasion. In this paper, the relative dynamic modulus of elasticity, chloride permeability coefficient, mass loss rate and carbonation depth are selected as the evaluation indexes of concrete durability in Northeast China. Based on prior knowledge and expert group decision-making, the durability grade is divided and the evaluation standard is established; The evaluation model of concrete durability based on cloud model and D-S evidence theory is established. According to the engineering experimental data, the membership degree of concrete durability evaluation index in different grades is obtained through the correlation measurement of cloud model. The normalized evidence is formed and fused by D-S evidence theory. The results show that the durability grade of concrete is grade I, which is consistent with the actual project. It shows that using cloud model and evidence theory evaluation model to evaluate the durability of concrete is a new and effective method.

Keywords. Concrete; Freeze thaw cycle test; Evaluation criteria; Cloud model; D-S evidence theory; Durability evaluation.

1. Introduction
As an excellent building material, concrete has been widely used in civil engineering industry, and its durability has a direct impact on the safe use of engineering structure [1]. In practical engineering, because of the durability of concrete, a lot of structural deterioration and huge economic losses are caused. Therefore, how to evaluate the durability of concrete reasonably and improve the durability of concrete has become an urgent need for engineering construction and concrete development [2]. At present, many scholars have carried out a series of researches on the durability of concrete. Aït-Mokhtar et al.[3] conducted an experimental study on the change of concrete durability. Wang et al.[4] studied the influence and coupling effect of carbonation, dry wet cycle and freeze-thaw cycle on the durability of three kinds of recycled polymer concrete. Zhu et al.[5] evaluated the durability of recycled polymer concrete in complex environment based on freeze-thaw cycles and chloride coupling experiments. Choi et al.[6] Put forward a method to determine the early frost damage of concrete by measuring the permeability change of concrete, and studied the influence of early frost damage on the durability of concrete. Alireza Habibi et al. [7] evaluated the mechanical properties and durability of recycled polymer concrete via RSM method. Considering the current research, most of the research is...
mainly based on experimental and theoretical analysis methods. For concrete durability evaluation, a set of practical, reasonable and complete evaluation methods has not been established yet. How to effectively mine the collected information, so as to carry out scientific risk identification, early warning and prevention and control of concrete durability has become an urgent problem.

Cloud model can transform qualitative concepts and quantitative values, and deal with fuzzy and random problems effectively [8, 9]. D-S evidence theory is a multi information fusion method which can deal with uncertain decision and reasoning. It is widely accepted and applied in the field of information fusion [10, 11]. In this paper, a concrete durability evaluation method based on cloud model and D-S evidence theory is proposed. Through the cloud model, the index evidence of concrete durability is constructed, and the improved D-S evidence theory is used to fuse the index evidence for many times to realize the evaluation of concrete durability, which provides the basis for the prevention and control management decision of concrete durability.

2. Preliminaries

2.1. Cloud Model
Cloud model is a kind of uncertainty transformation model between qualitative concept and accurate value, which can deal with both fuzzy and random events. Let $U = \{x\}$ be a quantitative universe and $C$ be a qualitative concept over $U$. Element $x$ is a random implementation of qualitative concept $C$. The membership degree $\mu(x)$ is a random number with a value of $0 \sim 1$. Cloud is actually a mapping from the universe $U$ to interval $[0, 1]$, that is

$$\mu: U \rightarrow [0, 1] \quad \forall x \in U \quad x \rightarrow \mu(x)$$ (1)

Then, $(x, \mu)$ is cloud drop. The generation process of cloud droplets realizes the mapping between qualitative concept and quantitative value. Expectation $E_x$, Entropy $En$ and Hyper entropy $He$ are the three characteristic values of cloud model.

2.2. Dempster-Shafer Evidence Theory
D-S evidence theory can solve some important problems such as "uncertainty" and "prophet". Through uncertainty reasoning, the fusion idea is adopted to synthesize the information represented by multi-source data as the basis of evaluation, so as to obtain the most likely result from imprecise and incomplete information, and then get more reliable and effective conclusions. It is a simple method of information fusion and decision-making.

Suppose $\Theta$ is an identification framework, for $\forall A \subseteq \Theta$, $m_i (i = 1, 2, \ldots, n)$ is the basic probability assignment (BPA) of $A_i (i = 1, 2, \ldots, n)$, thus, the combination rule of multiple evidences is as follows:

$$m(A) = \frac{\sum_{A \subseteq A_1 \cap \ldots \cap A_n = A} m_1(A_1) \cdot m_2(A_2) \cdots m_n(A_n)}{1 - k}$$ (2)

$$k = \sum_{A \subseteq A_1 \cap \ldots \cap A_n = \emptyset} m_1(A_1) \cdot m_2(A_2) \cdots m_n(A_n)$$ (3)

$k$ is the conflict coefficient between $n$ evidences.

3. Modeling

3.1. Evaluation Framework of Concrete Durability
In this paper, the relative dynamic modulus of elasticity, chloride ion permeability coefficient, mass loss rate and carbonation depth are selected as the indexes to evaluate the durability of concrete under freeze-
thaw cycle test in northeast cold region, which can well reflect the change of internal microstructure and damage degree of concrete after freeze-thaw cycle test [12]. The durability of concrete is divided into three grades, I (very good), II (good) and III (fairly good), which respectively indicate that the effective service life of concrete can reach 200-250 years, 150-200 years and 100-150 years. On this basis, the prior knowledge and expert group decision are used to identify and divide the attribute interval of concrete durability index and determine the evaluation standard.

Based on the obtained experimental data rules, assuming that n experts participate in decision-making, the i-th expert believes that \([c_i(L), c_i(R)]\) \(i = 1,2, ..., n\) is the interval of an evaluation index belonging to a certain level. The reverse cloud algorithm is used to estimate the judgment of N experts as a whole. In order to promote the convergence of decision-making results, n experts are arranged for multiple rounds of inquiry. Each expert needs to carry out the next round of feedback on the basis of the previous round of inquiry cloud, so as to gradually eliminate the differences of expert opinions and obtain more reasonable attribute interval division results.

To determine the comprehensive durability grade of concrete specimens to be tested, the variable weight theory is used to determine the comprehensive weight of each index. Based on the above steps, the results of durability evaluation grade standard grade and index weight are obtained as shown in Table 1.

**Table 1. Evaluation index grade and criterion of concrete durability under freeze-thaw cycles.**

| Evaluating index | Weight | Classification Criterion |
|------------------|--------|-------------------------|
|                  |        | I                       | II                      | III                     |
| Relative dynamic modulus of elasticity \( l(\%) \) | 0.35   | \([95,100]\)            | \([90,95]\)             | \([85,90]\)             |
| Chloride ion permeability coefficient \( / (10^{-12}m^2/s) \) | 0.35   | \([0,1]\)               | 200-250                 | 150-200                 | 100-150                 |
| Mass loss rate \( l(\%) \) | 0.2    | \([0,2]\)               | \([2,4]\)               | \([4,5]\)               |
| Carbonation depth \( / (mm) \) | 0.1    | \([0,10]\)              | \([10,20]\)             | \([20,30]\)             |

3.2. Evidence Generation Via Cloud Model

In the process of concrete durability evaluation, the important premise to determine the basic probability assignment is to get the three digital features of cloud model. The parameters of cloud model \( (Ex_y, En_y, He_y) \) of evaluation index \( X \) in response interval \([C_y(min), C_y(max)]\) of concrete durability grade \( T_j (j = I, II, III) \) are obtained by formula (4).

\[
\begin{align*}
Ex_y &= \left( C_y(min) + C_y(max) \right)/2 \\
En_y &= \left( C_y(max) - C_y(min) \right)/2 \\
He &= s
\end{align*}
\]

\( s \) is a constant, which is determined by engineering experience and the fuzzy threshold of the index, indicating the uncertainty of the membership degree. In this paper, \( s = 0.002 \).

The membership degree of the observation value \( x_j \) to the j-th durability grade is obtained by
formulas (5) and (6). Considering the uncertainty of concrete durability evaluation caused by measurement error and external interference, the membership degree of global uncertainty $\varphi_i$ is calculated by equation (7).

$$\mu(T_i) = \exp\left(-\frac{(x_i - Ex_i)^2}{2(En_i)^2}\right)$$  \hspace{1cm} (5)

$$En_i \sim N(En_i, He)$$  \hspace{1cm} (6)

$$\varphi = 1 - \max\left(\mu(T_i)\right), j = I, II, III$$  \hspace{1cm} (7)

The membership degree is normalized to be transformed into the basic credibility allocation function in D-S evidence theory to receive the evidence $\{m_1(T_1), m_2(T_{in}), m_3(T_{in}), m_4(\Theta)\}$.

3.3. Information Fusion Via D-S Theory

The conflict coefficient $k$ between multiple evidences is calculated by formula (3). When $k \leq T_i$, it’s regarded as credible evidence and kept the original evidence information unchanged; when $k \geq T_i$, it’s considered as high conflict evidence, which needs to be revised and reused. Based on many experiments and literature review, the threshold $T_1 = 0.85$ was preliminarily determined.

For the evidence with high conflict, firstly calculate the distance $d$ and similarity $Sim$ between each pair of evidences. Then by summing the similarity between one piece of evidence and other evidences, the support degree $Sup(m_i)$ of the evidence $m_i$ is obtained. All $Sup(m_i)$ are normalized to get the weight $W(m_i)$ of the evidence $m_i$. The weighted evidence is used to replace the conflict evidence, and the conflict detection is carried out again. If there is no conflict, the evidence fusion is carried out. If there is conflict, the evidence replacement is continued until there is no conflict.

After dealing with high conflict evidence, Dempster rule by formula (2) is used to realize multiple evidences fusion. The fusion results of a certain durability index evidence is separately acquired, then the weighted fusion of the above four index evidence is realized using the weights of the evaluation indexes in Table 2 to perceive the durability grade status of the batch of concrete specimens.

4. Case Study

4.1. Data Collection

The data samples obtained in this study are from seven sections of a highway project in the northeast cold region.25 groups of prismatic concrete specimens with dimensions of 100mm×100mm×400mm were randomly selected for freeze-thaw cycle test. The durability evaluation index was measured in the same cycle. The test results are shown in table 2.

| Evaluation index | Specimen number | Relative dynamic modulus of elasticity / (%) | Chloride ion permeability coefficient /($10^{12}$m²/s) | Mass loss rate / (%) | Carbonation depth / (mm) |
|-----------------|-----------------|---------------------------------------------|-----------------------------------------------|-----------------|------------------|
| Specimen number | 1               | 97.2                                        | 1.3                                          | 1.5             | 6.7              |
| 2               | 93.4            | 96.2                                        | 1.8                                          | 3.2             | 16.7             |
| 3               | 96.2            | 0.9                                         | 3.2                                          | 1.7             | 8.9              |
| ...             | ...             | ...                                         | ...                                          | ...             | ...              |
| 24              | 88.2            | 3.8                                         | 4.6                                          | 24.3            |
| 25              | 93.8            | 2.1                                         | 3.1                                          | 15.3            |
4.2. Results Analysis
A normal cloud model is constructed for each durability grade interval of the evaluation index, and the characteristic diagram of the grade cloud model of the four indexes is shown in Figure 1.

![Figure 1. Cloud chart of durability index grade.](image)

Engineering data cannot effectively characterize the concrete durability grade status. Combining the actual values in Table 2 and the fuzzy set constructed in Figure 1, it is transformed into the degree of membership of the index $X_i$ to the durability grade $T_j$ by formulas (4)-(6). The membership degree is normalized to construct BPAS. Taking the relative dynamic modulus of elasticity as an example, the basic reliability distribution is shown in Table 3.

| Grade Number | I    | II   | III  | $\Theta$ |
|--------------|------|------|------|----------|
| 1            | 0.9373 | 0.0000 | 0.0000 | 0.0627   |
| 2            | 0.0000 | 0.5579 | 0.0000 | 0.4421   |
| 3            | 0.2961 | 0.0000 | 0.0000 | 0.7039   |
| ...          | ...  | ...  | ...  | ...      |
| 24           | 0.0000 | 0.0000 | 0.7026 | 0.2974   |
| 25           | 0.0000 | 0.2972 | 0.0000 | 0.7028   |

Conflict detection is performed on the 25 pieces of evidence in Table 3, and the $k$ between these evidences is calculated to be $0.927>0.85$. It is considered that this group of evidence is high conflict evidence and should be corrected and reused.

For high conflict evidence, the Euclidean distance of pairwise evidence is calculated to get the distance matrix, and further the evidence support degree is calculated and normalized to obtain the weight of each evidence. The support degree and weight of 25 evidences are shown in Figure 2; Finally, the conflict evidence is weighted.
Conflict detection is performed on the revised evidence again. At this time, the conflict coefficient of the 25 pieces of evidence is $0.429 < 0.85$, therefore, there is no conflict between the modified evidences. The modified evidences are fused according to the combination rule of equation (2). For the remaining three indexes like chloride ion permeability coefficient, mass loss rate and carbonation depth, the corresponding evidences of 25 groups of concrete specimens are obtained and fused with reference to the above steps to obtain the evaluation results of each index of concrete durability. The evaluation results of the four indexes are weighted and fused again to obtain the durability grade state of the batch of concrete specimens, as shown in figure 3.

Figure 3 shows that the durability of this batch of concrete specimens is good. The evaluation results of relative dynamic elastic modulus, chloride ion permeability coefficient, mass loss rate and carbonization depth index all have the largest reliability distribution at level I, which are 0.8209, 0.7865, 0.8065 and 0.8494 respectively. According to the principle of maximum membership degree, the final evaluation result of concrete durability is determined by the level of the maximum reliability distribution value. It can be seen from figure 3 that the final fusion result of the concrete specimens under the freeze-thaw cycle experiment has the largest reliability distribution at level I, which is 0.9991. Therefore, the durability level of the concrete in the service life of the project is considered to be level I. The results
are consistent with the actual inspection results of the project and the expected service life is 200-250 years. It indicates that the model selected in this study has a good effect on the evaluation of concrete durability.

5. Conclusion

1. In this paper, the relative dynamic elastic modulus, chloride ion permeability coefficient, mass loss rate and carbonization depth are selected as the concrete durability evaluation indicators in the severe cold area of Northeast China. The inverse cloud model is used to realize the exchange and integration of the knowledge decision of the expert group. The durability level is divided as level I (very good), II (good), and III (fairly good), and the evaluation criteria and the corresponding concrete effective service life is given.

2. This paper constructs a concrete durability evaluation model based on cloud model and D-S evidence theory. The cloud model is established one by one for the durability grade interval in response to each evaluation index and the membership degree of the measured data to each grade cloud is obtained. Conflict detection and conflict evidence replacement are carried out, and information fusion is realized by D-S evidence theory.

3. The concrete specimens of Song-Tong expressway project are selected for durability evaluation. The results show that the reliability distribution of each index in grade I is the largest under the freeze-thaw cycle test, which indicates that the concrete durability is excellent. The evaluation results are consistent with the actual test results, and the expected service life is 200-250 years. This proves the rationality and accuracy of the model proposed in this paper for concrete durability evaluation.

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