Multi-factor Comprehensive Evaluation on Durability of Various Grouting Materials

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Abstract. In this paper, four grouting materials, namely new type grouting material, pure cement, cement-sodium silicate and glue sand, were tested by single factor for their water corrosion resistance, permeability resistance and volume stability. The durability of the four grouting materials under the environment of three factors was evaluated by the multi-factor fuzzy comprehensive evaluation method. The results show that the three kinds of new type grouting materials are better than the other three kinds of grouting materials in terms of anti-water corrosion and volume stability. In terms of impermeability, the performance of cement reached the best impermeability pressure of 0.8Mpa, but the impermeability pressure of new type grouting material with a water-cement ratio of 1.0 has also reached 0.6MPa, which can meet the impermeability requirement with a small gap with cement. As a scientific and effective evaluation method, the method will be helpful to the further study of the durability of grouting materials.

1. Introduction
The construction of underground engineering such as underground rail transit is increasing in our country. Shield tunneling method is widely used in tunnel construction. In shield construction, synchronous grouting at the shield tail becomes an indispensable link in shield construction when the lining ring of the pipe sheet is detached from the shield tail. Therefore, under the premise of satisfying the mechanical properties, the durability of grouting materials is also put forward with higher requirements. The biggest factors affecting the durability of grouting materials include volume instability, pressure water infiltration and groundwater erosion. Literature found that the strength loss rate of industrial waste residue series grouting material can be reduced from 76.5% to 10.4% after mixing with industrial waste residue and metakaolin under the condition of water erosion for 360d. Literature added polymer emulsion to fast hard sulphoaluminate cement to make polymer cement based grouting material. It was found that the filling effect of polymer particles can improve the compactness, strength and impermeability of the material and 10% was the optimal impermeable polymer cement ratio. In reference, high impermeable grouting material was prepared by adding alkali-free admixtures into ordinary cement slurry then the impermeable grade is greater than P8. In reference, Portland cement with different fineness was mixed with fly ash, and it was found that appropriate increase of specific surface area of fly ash was beneficial to improve the dry shrinkage resistance of fly ash-cement mortar.

However, in practical engineering, factors that affect the durability of grouting materials generally appear at the same time. It is limited to evaluate the durability of grouting materials only by a specific
influencing factor, so a more comprehensive method is needed to effectively evaluate the durability of grouting materials. The fuzzy evaluation method has been applied effectively in fire risk assessment of construction site\cite{9} and other aspects. In literature\cite{10}, the method was used to comprehensively evaluate the durability of grouting materials composed of ordinary cement, sulphoaluminate cement and ultra-fine cement.

The new type grouting material\cite{11} used in this paper is a new type of grouting material, which has the characteristics of rapid coagulation, early strength and easy pumping of single grout, and can control the setting and hardening time of mixed grout according to different proportions. Single factor experiment was conducted on the water corrosion resistance, impermeability and volume stability of four kinds of grouting materials, new type grouting materials (C1.0, C1.5, C2.0), pure cement slurry (C), cement-sodium silicate (C-S) and colloidal sand (JS). The durability of the grouting materials was evaluated by fuzzy comprehensive evaluation method based on the single factor experiment.

2. Materials

2.1. Materials

The new type grouting material used in this test consists of two parts: material A and material B. The main components of the material A are sulphoaluminate cement, suspending agent, retarder, dispersant, etc. The main components of the material B are gypsum, activator, early strength agent, suspending agent, dispersing agent, etc. Cement slurry (C) is a mixture of ordinary Portland cement and water. Cement-sodium silicate material (C-S) is composed of cement slurry and commercially available sodium silicate (Sodium-silicate). Colloidal sand material (JS) is composed of ordinary Portland cement, fly ash, bentonite, sand and water.

2.2. Preparation of slurry

New type grouting material: firstly, weigh the materials A and B according to the water cement ratio of 1.0, 1.5 and 2.0, and mix them evenly in the clean slurry mixing pot. Measure the required water with the measuring cylinder, then pour it into the net slurry mixer, stir and mix evenly to form liquid A and liquid B, then mix liquid A and liquid B rapidly, and at the same time, make the mixed slurry.

Pure cement grout (C): ordinary Portland cement P.O.42.5R and water-cement ratio 1:1 are used to prepare pure cement grout.

Cement-sodium silicate (c-s): firstly, prepare pure cement slurry by the mass ratio of 1:1, and mix it with sodium silicate solution by the volume ratio of 1:1 to prepare cement-sodium silicate slurry.

Cement mortar (JS): according to the proportion of cement: fly ash: bentonite: sand: water = 120:381:54:7:79:465, the mass of each component was weighed, and then each component was added into a clean slurry mixing pot to mix evenly.

3. Methodology

3.1. Water corrosion resistance

The new type grouting material, pure cement slurry, cement-sodium silicate and mortar are made into test blocks of 40 mm * 40 mm * 160 mm, and the test blocks are maintained under dynamic water conditions (water flow rate is 0.10 ~ 0.15 m/s) and standard conditions. The 28d compressive strength of the test block under two curing conditions was measured, and the water-corrosion resistance coefficient (the ratio of dynamic water curing to standard curing 28d compressive strength) was further obtained.

3.2. Impermeability

In this paper, impermeability pressure is used to characterize the impermeability of the grouting material. The pressure is measured using the standard test method specified in the mortar impervious instrument reference specification.
3.3. Volume stability

Volume change parameter, (dry shrinkage property) was used to characterize the volume stability of the grouting material. The test was conducted according to jct603-2004 dry shrinkage test method of cement mortar.

The results are shown in table 1, since the experimental results of all the influencing factors are within the range of 0-1, the comparison of the durability of each grouting material can be seen more intuitively in figure 1.

### Table 1. Test results of grouting materials

| Material type | C | C-S | JS | C1.0 | C1.5 | C2.0 |
|---------------|---|-----|----|------|------|------|
| water-corrosion resistance coefficient | 0.928 | 0.843 | 0.725 | 0.985 | 0.956 | 0.935 |
| impermeability pressure (MPa) | 0.8 | 0.7 | 0.5 | 0.6 | 0.7 | 0.3 |
| Volume change parameter (%) | 0.727 | 0.622 | 0.809 | 0.990 | 0.988 | 0.987 |

![Figure 1. Test results of the factors affecting the durability of grouting material](image)

4. Comprehensive evaluation of durability

4.1. Determination of factor sets

This paper adopts the following factors and applies the fuzzy comprehensive evaluation method to objectively evaluate the durability of various grouting materials. Factor concentration T represents the volume stability of the stone body; S is the permeability of the grouting stone body to the pressure water; R represents the water corrosion resistance of the grouting stone body.

\[ U = \{T, S, R\} = \{\text{Volume stability, Impermeability, Water corrosion resistance}\} \]

4.2. Decision set determination

Decision set is a set composed of comprehensive evaluation results. Its main function is to grade the performance of the evaluation object. In this paper, the durability evaluation of grouting materials is divided into five grades: excellent, good, general, poor and very poor. That is:

\[ V = \{V_1, V_2, V_3, V_4, V_5\} = \{\text{excellent, good, general, poor, very poor}\}. \]

4.3. Determination of weight set

Considering the complex environment that grouting materials will face in practical use in engineering, among the factors influencing the durability of grouting materials, volume stability is the most important, followed by impermeability, that is, volume stability > impermeability > anti-water corrosion resistance (\(T > S > R\)).

The degree of influence of each factor on the overall durability is different, so the weight values are given to each factor according to the service environment faced by the grouting stone body in practical application, and these weight values constitute the weight set A. The weight set \(A = (a_1, a_2, a_3)\), \(a_1, a_2\) and \(a_3\) represent the weight of volume stability, impermeability and water corrosion resistance respectively. According to the mutual comparison results of the importance of the above factors, the comparison matrix \(C\) can be established by using the nine-degree table method. Further construct
The preliminary calculation is \( A = w^T = (0.588, 0.322, 0.090) \), and the consistency test is carried out. The test results show that the judgment matrix is consistent, and the weight of each evaluation index is:

\[
A = (0.588, 0.322, 0.090).
\]

### 4.4 Evaluation structure

(1) Determine the degree of membership of each factor

The membership degree is determined by calculating the fuzzy grade of each factor and comparing and ordering.

| Evaluation level | water-corrosion resistance coefficient | impermeability pressure (MPa) | Volume change parameter (%) |
|------------------|---------------------------------------|-----------------------------|----------------------------|
| excellent        | 0.9–1                                 | 0.8–1                       | 0.9–1                      |
| good             | 0.8–0.9                               | 0.6–0.8                     | 0.8–0.9                    |
| general          | 0.7–0.8                               | 0.4–0.6                     | 0.7–0.8                    |
| difference       | 0.6–0.7                               | 0.2–0.4                     | 0.6–0.7                    |
| Very poor        | <0.6                                  | <0.2                        | <0.6                       |

Determination method of membership degree of each factor:

When \( i = 2, 3, 4 \), the membership \( \mu_{\mu_i} \) range of a factor is within the interval \([0.8, 1.0]\), which can be determined by the following linear interpolation principle:

\[
1 - \frac{\mu_{\mu_i}}{\mu - \min} = \frac{\mu - \max}{\max - \min}
\]

(1)

Where \( \mu_{\mu_i} \) is the membership degree of a factor \((i = 2, 3, 4)\); \( \mu \) is the test value of a factor; \( \max \) and \( \min \) are the boundary values of the membership range of the test values.

Determination of membership degree adjacent to \( \mu_{\mu_i} \):

\[
\mu < \frac{1}{2} (\max + \min), \quad \mu_{\mu_{i+1}} = 1 - \mu_{\mu_i} \quad \mu > \frac{1}{2} (\max + \min), \quad \mu_{\mu_{i-1}} = 1 - \mu_{\mu_i} \quad (2)
\]

\[
\mu = \frac{1}{2} (\max + \min), \quad \mu_{\mu_{i+1}} = \mu_{\mu_{i-1}} = \frac{1}{2} (1 - \mu_{\mu_i}) \quad \text{The other membership degrees are 0.} \quad (3)
\]

The membership degree of each influencing factor is obtained as Table 3:

| Membership | C T S R | C-S T S R | JS T S R | C1.0 T S R | C1.5 T S R | C2.0 T S R |
|------------|---------|----------|----------|------------|------------|------------|
| \( \mu_{\mu_1} \) | 0 1 1 0 | 0.05 0.09 | 0 0 0 1 | 0 1 1 0 | 0 1 1 0 | 1 0 0 0 |
| \( \mu_{\mu_2} \) | 0.054 0 0 0 | 0.9 0.91 | 0.98 | 0 0 0 | 0.01 0 | 0 0 0 0 | 0 0 0 0 |
| \( \mu_{\mu_3} \) | 0.946 0 0 0 | 0.05 0 | 0.02 0.95 | 0.8 0 | 0 0.05 | 0 0 0.25 0 | 0 0 0 0 |
| \( \mu_{\mu_4} \) | 0 0 0 | 0.96 0 | 0 0 | 0 0 | 0.05 0 | 0.1 0.9 | 0 0.5 0 |
| \( \mu_{\mu_5} \) | 0 0 0 | 0.04 0 | 0 0 | 0.1 0 | 0 0 | 0.05 0 | 0 0.25 0 |

(2) Determine the evaluation matrix

The evaluation matrix of a certain influencing factor \( R \) is established between the factor set and the comment set, each element in the matrix represents the primary factor \( T, S, R \), which belongs to
each element $V_i$ in the comment set. Three vectors ($R_1$, $R_2$ and $R_3$) were obtained from the primary evaluation results, which respectively represent the evaluation results of the water-corrosion resistance, impermeability and volume stability of the grouting material. The comprehensive evaluation matrix $R$ can be composed of these three results.

(3) Determine the evaluation model
In the durability evaluation of grouting stone body, in order to objectively evaluate the importance and safety degree of each factor, the operator $(+, \cdot)$ is comprehensively considered. The operator has the function of weighted average, comprehensive degree, prominent weight and can make full use of the fuzzy comprehensive evaluation matrix $R$. The fuzzy evaluation matrix of each factor is multiplied by the weight vector, and then the results are added up, which belongs to the weighted average type and can comprehensively integrate the evaluation results of each factor, "+" means addition, and "." is ordinary multiplication, $b_j = \sum_{i=1}^{m} a_i r_{ij}$, $(j=1, 2, \ldots, n)$, $\sum_{i=1}^{m} a_i = 1$. Further confirm the comprehensive fuzzy evaluation model as $B = A (+, \cdot) R$. The fuzzy set $B$ is the comprehensive fuzzy evaluation result, and the evaluation grade corresponding to the maximum value in the material evaluation result $B$ is the durability evaluation grade of the material.

4.5. Evaluation results
In this paper, the durability of four grouting materials, new type grouting materials, pure cement grout (C), cement-sodium silicate (C-S) and cement-sand (JS) under the combined action of multiple factors was comprehensively evaluated. Taking pure cement mortar as an example, the water-resistance coefficient is 0.928, the impermeability pressure is 0.92MPa, and the volume change coefficient is 0.727. The membership degree was calculated by these parameters, and the primary evaluation matrix was calculated by combining with the corresponding evaluation model.

It can be determined from the calculation results of membership: $R_1=(0,0.054, 0.946, 0,0)$; $R_2=(1, 0, 0, 0)$; $R_3=(1, 0, 0, 0)$, and then obtain the fuzzy synthesis matrix $R$ of cement (C):

$$R = \begin{bmatrix} 0 & 0.054 & 0.946 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

According to weight $A = (0.588, 0.322, 0.090)$, the evaluation results of cement (C), $B = A (+, \cdot) R = (0.412, 0.032, 0.556, 0, 0)$, by the principle of maximum membership can be seen that the durability of cement grouting material under the "general" the extent of the maximum 0.556, therefore its durability as a kind of pure cement grouting material or the problems facing at present. The evaluation results of other materials can be calculated by the same method, and the specific results are given in the table4.

Table 4. Summary of evaluation grade of grouting material durability

| Evaluation level | material type | C | C-S | JS | C1.0 | C1.5 | C2.0 |
|-----------------|---------------|---|-----|----|------|------|------|
| excellent       | C             | 0.412 | 0.024 | 0 | 0.678 | 0.678 | 0.678 |
|                 | good          | 0.032 | 0.372 | 0.577 | 0.032 | 0 | 0 |
|                 | general       | 0.556 | 0.016 | 0.096 | 0.258 | 0.016 | 0.081 |
|                 | difference    | 0 | 0.562 | 0.005 | 0.032 | 0.290 | 0.160 |
|                 | Very poor     | 0 | 0.026 | 0.322 | 0 | 0.016 | 0.081 |

It can be seen from the results in the table4, the durability evaluation of the new type grouting materials with three water-cement ratios is the most excellent, and the durability of pure cement grouting materials is general. The durability of cement-sodium silicate was evaluated as poor, and the durability of the glue sand as a grouting material was evaluated as good.
5. Conclusion

(1) Under the condition of single factor, three water-cement ratio new type grouting materials have better water-corrosion resistance than other grouting materials. In terms of impermeability, cement has the best performance. However, impermeability of new type grouting material with a water-cement ratio of 1.0 has also reached 0.6MPa, which is less different from cement and meets impermeability requirements. From the experimental results of volume stability, it can be seen that the volume stability of the three new type grouting materials is better than that of the other three grouting materials.

(2) Under the combined action of three factors, the durability of the three water-cement ratio new type grouting materials is better than that of the other three kinds of grouting materials.

(3) This paper adopts the multi-factor fuzzy comprehensive evaluation method, which overcomes the limitation and one-sidedness of the durability research only considering the single influence factor to some extent. As a scientific and effective evaluation method, it will be helpful for the further research on the durability of back wall grouting materials.

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