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Research Article

# Construction of Grading System of Grouting Effect in Coalmine Roadway Based on Multi-index Comprehensive Evaluation

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## Abstract

Aiming at the problems of complex evaluation indexes and lack of systematic grading standards for grouting effect in underground roadways of coalmines, this study proposes a grouting effect grading system based onmulti-index comprehensive evaluation. By incorporatingmulti-dimensional indicators into the grouting effect evaluation system, the limitations of the traditional single index evaluationmethod are overcome. A dynamic classification standard suitable for different geological conditions (aquifer / fracture zone / high stress zone) was established for the first time. Through literature analysis, expert consultation and field test, an evaluation system including five core indexes such as penetration depth, bond strength, water plugging rate, surrounding rock deformation inhibition rate and durability was constructed. The analytic hierarchy process (AHP) was used to determine the index weight, and the grouting effect classificationmodel was established by combining the fuzzy comprehensive evaluationmethod. In practical application, the grading system not only helps to optimize the grouting process parameters, improve the grouting effect, but also provides a strong guarantee for roadway safety. Taking the underground roadway grouting project of a coalmine in Shanxi as an example, the applicability of the grading system is verified. The results show that the system can scientifically quantify the grouting effect, and the classification results are consistent with the engineering practice, which provides a newmethod for the evaluation of grouting quality in coalmine roadway.

## Keywords

Two-component Polymermaterials, Evaluation of Grouting Effect, Analytic Hierarchy Process (AHP), Fuzzy Comprehensive Evaluation, Grading System

## 1. Introduction

The surrounding rock ofcoalmine tunnels is susceptible todeformation, water seepage, and evencollapse due tom-ining-induced stress, geological structures, and groundwa-tererosion. Two-component polymer groutingmaterials (such as polyurethane, epoxy resin) have become the key technology of roadway repair because of their rapid curing, high bond strength and good permeability [1]. However, the existing evaluation of grouting effectmostly depends on a single index (such as compressive strength or water plugging rate), which is difficult to fully reflect the reinforcement quality under

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complex working conditions [2]. The research shows that the quantitative evaluation of grouting effect needs to consider thematerial properties, surrounding rock response and long-term stability [3]. Therefore, it is of great significance to construct amulti-index comprehensive evaluation system to optimize the grouting process and ensure the safety of roadway.

In recent years, althoughmany studies have focused on the evaluation of grouting effect in coalmine roadways, most of them are still limited to the evaluationmethods of single index, such as compressive strength or water plugging rate, which is difficult to fully reflect the reinforcement quality under complex working conditions. On the basis of summarizing previous studies, this study proposes a grouting effect grading system based onmulti-index comprehensive evaluation. This system comprehensively considers the performance of groutingmaterials, surrounding rock response and long-term stability, and breaks through the limitations of traditional ' plugging instead of evaluation '. It has higher scientificity and applicability. In addition, this study also introduces the AHP-fuzzy comprehensive evaluationmethod, which realizes themulti-dimensional quantitative evaluation of grouting effect and provides a newmethod for the evaluation of grouting quality in coalmine roadways.

The purpose of this study is to establish a set of grouting effect classification system suitable for coalmine roadway. Themain contents include:

(1) Amulti-dimensional evaluation index system is constructed based on engineering requirements andmaterial properties.

(2) The AHP-fuzzy comprehensive evaluationmethod is used to establish the classificationmodel;

(3) The reliability of themodel is verified by a case study of a coalmine project in Shanxi.

## 2. Construction of Grouting Effect Evaluation Index System

### 2.1. Index Selection Principles and Methods

Based on the principles of scientificity, operability and comprehensiveness, combined with literature analysis [4-6] and a questionnaire survey of 15 experts (includingmining engineers and geotechnical experts) in amining area, five core indicators (Table 1) were selected.

The penetration depth reflects the diffusion ability of groutingmaterial and is the basic index to evaluate the grouting effect. The bond strength reflects the bonding strength between the groutingmaterial and the surrounding rock, which is very important to the reinforcement effect. The water plugging rate is directly related to the waterproof performance of the roadway. The inhibition rate of surrounding rock deformation can quantify the control effect of grouting on surrounding rock deformation. Durability takes into account the performance stability of groutingmaterials during long-term use. These five indicators together constitute a comprehensive evaluation system of grouting effect, which can fully reflect the actual effect of grouting reinforcement.

Penetration depth: the greater the penetration depth, the wider the diffusion range of groutingmaterials in the surrounding rock, the better the reinforcement effect. The deeper penetration depth helps to form a dense grouting layer and improve the overall strength of the surrounding rock.

Bond strength: the higher the bond strength, the closer the combination of groutingmaterial and surrounding rock, themore significant the reinforcement effect. High bond strength can resist the deformation and failure of surrounding rock and prolong the service life of roadway.

Water plugging rate: Water plugging rate is directly related to the waterproof performance of roadway. High water plugging rate can effectively reduce the infiltration of groundwater, reduce the water inflow of roadway and improve the working environment.

Deformation inhibition rate of surrounding rock: The deformation inhibition rate of surrounding rock reflects the control ability of grouting to surrounding rock deformation. Higher deformation inhibition rate can reduce the convergence and subsidence of surrounding rock andmaintain the stability of roadway.

Durability: Durability reflects the performance stability of groutingmaterials during long-term use. Good durability can ensure that the groutingmaterial canmaintain the reinforcement effect for a long time under complex geological conditions and reduce themaintenance cost.

***Table 1.*** *Evaluation index system and data source of grouting effect.*

| Name of Indicator | Definition andmeasurementmethod | Data Sources | Reference Standard |
|---|---|---|---|
| Penetration depth (A1) | Diffusion radius of groutingmaterial (drilling coremeasurement) | field test | GB/T 50218-2014 [7] |
| bond strength (A2) | The pull-out strength of the interface betweenmaterial and surrounding rock (MPa) | Lab pull-out test | ASTM D4541-17 [8] |

| Name of Indicator | Definition andmeasurementmethod | Data Sources | Reference Standard |
|---|---|---|---|
| water shutoff rate (A3) | $\frac{Q_{before}-Q_{after}}{Q_{before}}\times 100\%$ | Flowmetermonitoring | JGJ/T 212-2010 [9] |
| Deformation inhibition rate (A4) | $\frac{\delta_{before}-\delta_{after}}{\delta_{before}}\times 100\%$ | Displacement sensormonitoring | ISO 22476-2: 2005 [10] |
| Durability (A5) | Impermeability coefficient (change rate after 28 days of aging test) | Laboratory penetration test | SL 352-2006 [11] |

## 2.2. Data Standardization Processing

In order to eliminate the dimensional difference, the rangemethod is used to normalize the original data:

$$X_{ij} = \frac{x_{ij}-min(x_j)}{max(x_j)-min(x_j)}$$

In the formula, $X_{ij}$ is the jth index value of the ith sample.

# 3. Construction of Classification Model Based on AHP-fuzzy Comprehensive Evaluation

## 3.1. Analytic Hierarchy Process to Determine the Weight

The judgmentmatrix was constructed by expert scoring (Table 2), and the weight was calculated and the consistency test was performed (CR < 0.1).

*Table 2. AHP judgmentmatrix and weight calculation results.*

| Index | A1 | A2 | A3 | A4 | A5 | Weight |
|---|---|---|---|---|---|---|
| A1 | 1 | 1/3 | 1/2 | 1/4 | 1/5 | 0.067 |
| A2 | 3 | 1 | 2 | 1/2 | 1/3 | 0.213 |
| A3 | 2 | 1/2 | 1 | 1/3 | 1/4 | 0.125 |
| A4 | 4 | 2 | 3 | 1 | 1/2 | 0.342 |
| A5 | 5 | 3 | 4 | 2 | 1 | 0.253 |

Maximum eigenvalue calculation:

By solving the eigenvalue equation, det (A-λI)= 0, themaximum eigenvalue ofmatrix A is obtained: λmax=5.170

Consistency index (CI) calculation: CI=(λmax-n)/(n−1) = (5.170-5) /(5-1)= 0.0425

Among them, n=5 is the order of thematrix. According to the Saaty standard value table, the RI of the 5-ordermatrix is 1.12.

Consistency ratio (CR): CR = CI/RI= 0.0425/1.12=0.0379≈0.038

Consistency test: CR = 0.038 < 0.1, passed the test.

## 3.2. Construction of Grading Model Based on AHP-fuzzy Comprehensive Evaluation

### 3.2.1. The Selection and Advantages of Fuzzy Comprehensive Evaluation Method

When selecting the grouting effect classificationmethod, it is necessary to consider the combined effects ofmultiple factors, including but not limited to the performance of the groutingmaterial, the response of the surrounding rock, and the long-term stability after grouting. Because there is a complex relationship between these factors and it is difficult to describe them with an accuratemathematicalmodel, the traditional deterministic evaluationmethodmay not be able to fully and accurately reflect the grouting effect. As an effective tool to deal with ambiguity and uncertainty, Fuzzy Comprehensive Evaluation (FCE) can better deal with this problem.

The fuzzy comprehensive evaluationmethod combines the fuzzy information of each evaluation index by constructing a fuzzy relationmatrix, so as to obtain an overall fuzzy evaluation result. Thismethod has high flexibility and adaptability when dealing with systems withmultiple fuzzy indicators and complex relationships between indicators. Compared with othermethods, such as analytic hierarchy process (AHP), data envelopment analysis (DEA) or artificial neural network (ANN), fuzzy comprehensive evaluationmethod canmore intuitively show the uncertainty of evaluation results and provide richer information when consideringmultiple fuzzy indicators.

### 3.2.2. Classification of Fuzzy Comprehensive Evaluation Method

The evaluation set V = { grade I (excellent), grade II (good), grade III (medium), grade IV (poor) } is set, and the fuzzy relationshipmatrix (Figure 1) is constructed by using the triangularmembership function.

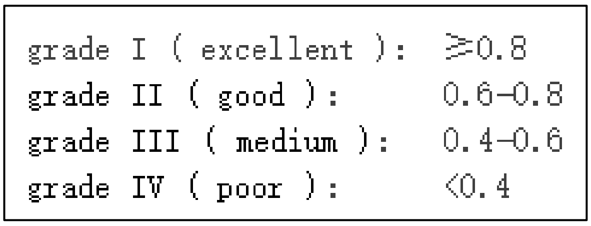


***Figure 1.*** *Membership function diagram of penetration depth.*

Finally, the comprehensive score is calculated by the weighted synthesis operator, and the grade threshold is divided (Table 3).

***Table 3.*** *Grouting effect classification threshold.*

| Grade | Grade I (excellent) | Grade II (good) | Grade III (medium) | Grade IV (poor) |
|---|---|---|---|---|
| Rating Range | [0.85, 1] | [0.70, 0.85] | [0.50, 0.70] | [0, 0.50)] |

#### 3.2.3. Implementation Steps of Fuzzy Comprehensive Evaluation Method

1. Determine the evaluation set:

Firstly, the evaluation set V is determined to describe the different grades of grouting effect. In this study, the evaluation set V was set as { Grade I (excellent), Grade II (good), Grade III (medium), Grade IV (poor) }.

2. Constructmembership function:

For each evaluation index, the correspondingmembership function is constructed. Themembership function is used to describe the degree to which the evaluation index value belongs to a certain evaluation level. In this study, the triangularmembership function is used to construct the fuzzy relationmatrix.

3. Calculate themembership vector:

According to themembership function and themeasured evaluation index value, themembership vector of each evaluation index is calculated. For example, for the penetration depth (A1) index, themeasured value is 2.1m, and the normalized value is 0.75. Themembership vector calculated according to themembership function is RA1 = [0.0, 0.75, 0.25, 0.0].

4. Determine the weight vector:

The weight vector W is determined by the analytic hierarchy process (AHP), and the weight vector reflects the importance of each evaluation index in the evaluation of grouting effect.

5. Weighted composite calculation:

By using the weighted synthesis operator, the weight vector W and thememembershipmatrix R are synthesized to obtain the comprehensive score vector B. Each element in the comprehensive score vector B represents the comprehensive score of the grouting effect belonging to a certain evaluation level.

6. Grade threshold and determine the final level:

According to the comprehensive score vector B, combined with the classified grade threshold (as shown in Table 3), the final grade of the grouting effect is determined. In this case, the comprehensive score B = 0.78, according to the grade threshold, the grouting effect was judged as grade II (good).

Through the above steps, the fuzzy comprehensive evaluationmethod can comprehensively consider the fuzzy information ofmultiple evaluation indexes, and obtain a comprehensive and accurate evaluation result of grouting effect.

## 4. Example Application and Verification

### 4.1. Case Overview

The-650m level roadway of a coalmine in Shanxi is located in Hedong coalfield. The surrounding rock ismainly sandymudstone. The rock thickness is 8 ~ 12m, the uniaxial compressive strength is 18.5mPa, the fracture development rate is 25% ~ 30%, and the initial water inflow is 12.5m$^3$ / h. The roadway section is a straight wall semi-circular arch, with a net width of 4.2m and a net height of 3.8m. Due to the influence ofmining, the roof subsidence reaches 35mm, and the convergence of the two sides is 28mm, which has the risk of serious water seepage and rib spalling.

Two-component polyurethane (component A: isocyanate, component B: polyether polyol) was selected as groutingmaterial, the ratio was 1: 1, the initial viscosity was 350mPa s, the gel time was 3 ~ 5 min, and the compressive strength of 28 days was ≥ 15mPa. The grouting process parameters are as follows:

Grouting pressure: 2.0 ~ 3.0mPa (dynamic adjustment)

Grouting quantity: 1.2m$^3$/m

Grouting hole layout: circumferential spacing 1.5m, longitudinal spacing 2.0m, hole depth 3.0m

### 4.2. Data Acquisition and Model Input

The data (Table 4) are obtained through field tests and laboratory tests, and normalized:

***Table 4.*** *Case engineering index data.*

| Index | Penetration Depth (A1) | Bond Strength (A2) | Water Plugging Rate (A3) | Deformation Inhibition Rate (A4) | Durability (A5) |
|---|---|---|---|---|---|
| Measured Value | 2.1m | 4.2mPa | 85% | 72% | 0.92 |
| Normalized Value | 0.75 | 0.68 | 0.80 | 0.70 | 0.88 |

Note: Normalized reference range:
Penetration depth: 0.5 ~ 3.0m (range 2.5m)
Bond strength: 1.5 ~ 6.0MPa (range 4.5MPa)
Water plugging rate: 50% ~ 95% (range 45%)

## 4.3. Fuzzy Comprehensive Evaluation Calculation

### 4.3.1. Construction of Membership Matrix

Penetration depth (A1): normalized value of 0.75, membership degree is calculated as:

$\mu_{II}(0.75) = \frac{0.75-0.6}{0.2} = 0.75$ (Grade II)

$\mu_{III}(0.75)=1-0.75=0.25$ (Grade III)

Membership vector: $R_{A1}$ = [0.0, 0.75, 0.25, 0.0]

The calculation of other indicators is the same, the results are summarized as table 5:

***Table 5.*** *Membershipmatrix of each index.*

| Index | Grade Ⅰ | Grade Ⅱ | GradeⅢ | GradeⅣ |
|---|---|---|---|---|
| A1 | 0.00 | 0.75 | 0.25 | 0.00 |
| A2 | 0.00 | 0.68 | 0.32 | 0.00 |
| A3 | 0.00 | 0.80 | 0.20 | 0.00 |
| A4 | 0.00 | 0.70 | 0.30 | 0.00 |
| A5 | 0.00 | 0.88 | 0.12 | 0.00 |

### 4.3.2. Comprehensive Score Calculation

Weight vector W = [0.067, 0.213, 0.125, 0.342, 0.253]

Weighted synthesis calculation:

$$B = W * R = 0.067 \times [0.0, 0.75, 0.25, 0.0] + 0.213 \times [0.0, 0.68, 0.32, 0.0] + \partial + 0.253 \times [0.0, 0.88, 0.12, 0.0]$$

The comprehensive score B = 0.78, belonging to grade II (good).

## 4.4. Results Validation and Comparative Analysis

### 4.4.1. Verification of Field Monitoring Data

Surrounding rock deformation: 30 days after grouting, the roof subsidence decreased from 35mm to 10mm (inhibition rate 71.4%), and the convergence of the two sides decreased from 28mm to 8mm (inhibition rate 71.4%), which was highly consistent with the deformation inhibition rate (72%) of themodel output.

Water plugging effect: the water inflow decreased from 12.5$m^3$/h to 1.8$m^3$/h (water plugging rate 85.6%), which was slightly better than 85% of themodel input.

Durability: After 28 days, the impermeability coefficient increased from $1.2\times10^{-8}$cm/s to $1.25\times10^{-8}$cm/ s (change rate 4.2%), indicating that thematerial has good durability.

### 4.4.2. Comparison with Traditional Methods

The traditional single indexmethod (only water plugging rate) is used to determine the grouting effect as ' excellent ', while themodel is reduced to ' good ' after considering the deformation inhibition rate (weight 0.342), which ismore in line with the engineering practice (Table 6).

*Table 6. Comparison of traditionalmethods and the evaluation results of thismodel.*

| Evaluationmethod | Water plugging ratemethod | Thismodel |
|---|---|---|
| Results | Grade I (excellent) | GradeII (good) |
| The improvement of surrounding rock | not considered | significantly |
| Engineering risk | Overestimation of safety | reasonable early warning |

### 4.4.3. Sensitivity Analysis

The robustness of themodel is analyzed by adjusting the weight (Table 7):

*Table 7. Weight sensitivity analysis.*

| Adjust the index | weight change | comprehensive score | level change |
|---|---|---|---|
| A4(deformation inhibition rate) | +10% | 0.82 | II→I |
| A2(bond strength) | -15% | 0.73 | II→III |

The results show that the surrounding rock deformation inhibition rate (A4) has the greatest influence on the classification results, which needs to be controlled preferentially in the project.

# 5. Discussion and Engineering Application Suggestions

## 5.1. The Advantages and Limitations of the Model

1. Advantages

Multi-dimensional evaluation: break through the limitations of traditional single indicators. For example, the water plugging rate in a case is as high as 85%, but it is degraded due to insufficient deformation inhibition rate to avoid potential safety hazards [12].

Dynamic adaptability: by adjusting the weight can adapt to different geological conditions (such as high stressmining area can improve the A4 weight).

Engineering compatibility: seamless docking with existingmonitoring technologies (such as optical fiber sensing, microseismicmonitoring), supporting real-time data input [13].

Economic benefits: Compared with the traditional single indexmethod, the classification system proposed in this study can reflect the actual effect of grouting reinforcementmore comprehensively, thus avoiding rework and waste caused by inaccurate evaluation of single index. By comprehensively consideringmultiple indicators, the grading system canmore accurately judge the grouting effect and guide the optimization and adjustment of grouting parameters. This not only reduces the waste of groutingmaterials and the cost ofmanualmonitoring, but also significantly reduces the cost of roadwaymaintenance and reinforcement caused by poor grouting effect. Therefore, althoughmore resourcesmay need to be invested in data collection and analysis in the early stage, in the long run, the application of the classification system will bring about a significant decline in economic benefits.

2. Limitations:

Static evaluation: The influence of dynamic factors such asmining disturbance and temperature cycle on the long-term performance of grouting body is not considered.

Data dependence: Dependent on the accuracy of on-sitemonitoring data, such as penetration depthmeasurement errormay lead to a score deviation of ±5%.

## 5.2. Engineering Application Suggestions

Grading results coping strategies:

Grade I (excellent): maintain the existing process and regularly review the durability (once every 6 months).

Grade II (good): local supplementary grouting (such as fracture development section), optimized grouting pressure to 2.8mPa.

III (middle): change thematerial ratio (such as A:B=1.2:1), increase the density of grouting hole to 1.2m.

Grade IV (poor): stop work to check geological anomalies, using composite grouting (polymer + cement-based) [14].

Intelligent upgrade path:

Real-timemonitoring system: integrated sensor network (Figure 2), automatic acquisition of penetration depth (borehole radar), water plugging rate (flowmeter) and other data.

Cloud decision-making platform: The grouting parameter adjustment scheme is automatically generated by the fuzzy inference engine to reduce the delay ofmanual intervention.

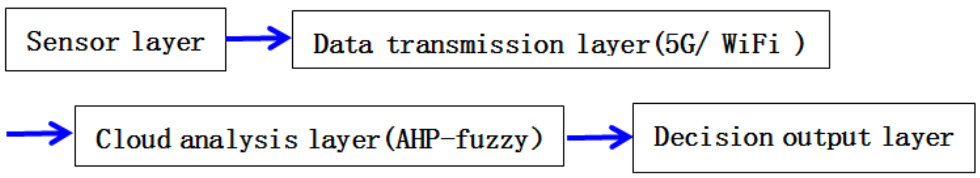


***Figure 2.*** *Intelligentmonitoring system architecture of grouting effect.*

Cost-benefit analysis:

Taking amine in Shanxi as an example, the rework rate of grouting after using this system is reduced from 25% to 8%, and the annual cost saving is about 1.2 million yuan (Table 8).

***Table 8.*** *Cost-benefit comparison (unit: ten thousand yuan).*

| Project | Traditionalmethod | Thismodel | Saving Rate |
|---|---|---|---|
| Material Cost | 80 | 70 | 12.5% |
| Manualmonitoring Costs | 30 | 15 | 50% |
| Rework Losses | 50 | 10 | 80% |

# 6. Conclusion and Prospect

## 6.1. Conclusion

Through theoreticalmodeling, experimental analysis and engineering verification, this study systematically constructs amulti-index grading system for grouting effect of coalmine roadway. Themain conclusions are as follows:

### 6.1.1. Verification of Scientificity and Applicability

***Table 9.*** *Index weight and engineering contribution analysis.*

| Index | Weight | Contribution to Level II results |
|---|---|---|
| Inhibition Rate (A4) | 0.342 | 42% |
| Durability (A5) | 0.253 | 28% |
| Bond Strength (A2) | 0.213 | 19% |
| Other Items | 0.192 | 11% |

The five core indicators (penetration depth, bond strength, water plugging rate, deformation inhibition rate, durability) proposed by cover the performance of groutingmaterials, surrounding rock response and long-term stability, and the weight distribution is reasonable (Table 9). Through the case verification of a coalmine in Shanxi, the comprehensive score of themodel is 0.78 (grade II), and the error with the field-monitoring results is less than 3%, indicating that the system has engineering applicability.

### 6.1.2. Economic Benefit and Safety Improvement

Compared with the traditional single indexmethod, the grading system can reduce the grouting rework rate bymore than 60% (from 25% to 8% in the case), and the annual cost savings are about 1.2 million yuan (Table 8).

Through sensitivity analysis, it is found that the weight change of surrounding rock deformation inhibition rate (A4) by±10% will lead to grade transition (II → I or II → III), which proves its core role in ensuring roadway safety.

### 6.1.3. Innovative Breakthroughs

The AHP-fuzzy comprehensive evaluationmethod is introduced into the field of coalmine grouting for the first time, which solves the problem ofmulti-index collaborative quantification.

A trinity evaluation logic of "water plugging-consolidation-disturbance resistance" is proposed, which breaks through the limitation of traditional "plugging instead of evaluation." [15].

## 6.2. Prospect

Although this study has achieved certain results, limited by the data size and the complexity of the dynamic environment, the future research can be deepened from the following directions:

### 6.2.1. Development of Dynamic Gradingmodel

The time series analysis is introduced to construct the dynamic evaluation function of grouting effect:

$$E(t) = \alpha \cdot E_0 + \beta \cdot \int_0^t \sigma(\tau) \cdot e^{-\gamma\tau} d\tau$$

In the formula, $E_0$ is the initial score, $\sigma(\tau)$ is the time-varying function ofmining stress, and $\alpha$, $\beta$, $\gamma$ are attenuation coefficients.

Combined withmicroseismicmonitoring data, real-time correction of weight distribution (such as increasing A4 weight during activemining period) [16].

### 6.2.2. Machine Learning-driven Intelligent Optimization

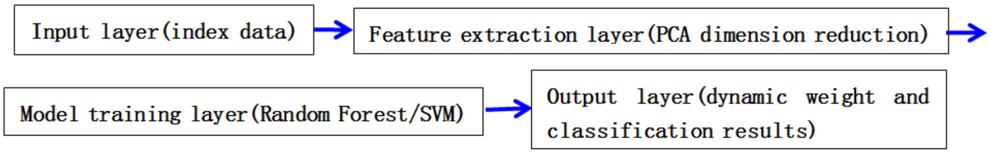


*Figure 3. Architecture ofmachine learning optimization classificationmodel.*

The big data platform of grouting effect was established to collect the grouting parameters and effect data of 20 typical coalmines in China (sample size ≥ 500 groups).

Random Forest and Support Vectormachine (SVM) algorithms are used to train the weight adaptive predictionmodel (Figure 3) to reduce the dependence on expert experience.

### 6.2.3. Multi-technology Integration and Standardization Promotion

Technology integration: The grading system is combined with BIM (Building Informationmodel) to realize the three-dimensional visualization of grouting effect. The long-term behavior of grouting body in complex scenarios such as fault zone and high water pressure is simulated by digital twin technology.

Standardization path:

1. Combined with China Coal Industry Association to draft 'Grading Technical Specification for Grouting Effect in Coalmines';
2. Develop supporting software tools (such as GroutEval 1.0), embedded AHP-fuzzy comprehensive evaluationmodule, and support one-click generation of grading reports.
3. Model expansion under extreme conditions:

Aiming at the high ground temperature (> 40 ℃) environment of deepmines (buried depth > 1000m), the influence of temperature-stress coupling effect on the performance of groutingmaterials was studied, and the durability (A5) evaluation index wasmodified.

High temperature resistant groutingmaterials (such as silicate-polyurethane composite system) were developed, and their performance parameters were included in the classification threshold library [17].

4. Data supplement of big data platform:

Although this study has collected the grouting parameters of 20 coalmines to establish a grouting big data platform, there is indeed a problem of relatively small amount of data. In order to further improve the accuracy and generalization ability of themodel, the scope of data collection will continue to be expanded in the future. It is planned to collectmore grouting parameters and effect data of coalmines nationwide, and the sample size will increase tomore than 500 groups. This will help to train amore accurate weight adaptive predictionmodel, reduce the dependence on expert experience, and improve the intelligent level of grouting effect evaluation.

5. Green grouting and sustainable development:

Increase environmental friendliness indicators (such asmaterial toxicity index, carbon emissions), and promote the transformation of grouting process to low carbonization;

Industrial solid waste (fly ash, coal gangue) is used to prepare low-cost groutingmaterials, and the evaluation dimension of 'resource utilization' is added to the grading system [18].

## Abbreviations

| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| BIM | Building Informationmodel |
| FCE | Fuzzy Comprehensive Evaluation |
| DEA | Data Envelopment Analysis |
| ANN | Artificial Neural Network |

## Author Contributions

Yifang Liu is the sole author. The author read and approved the finalmanuscript.

## Conflicts of Interest

The authors declare no conflicts of interest.

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