Research Article

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Calculation Model for the Mixing Amount of Internal Curing Materials in High-strength Concrete based on Modified MULTIMOORA

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Abstract: The internal curing technology has been widely applied to high-strength concrete, for it can make the high-strength concrete marked by low shrinkage and durable frost resistance. The key to its extension and application lies in the reasonable mixing amount of internal curing materials. To address this problem, scholars have proposed a method for determining the water demand in internal curing; however, the water release of internal curing materials is difficult to obtain by measurement due to the mixing method. Therefore, this paper proposed a calculation model for the mixing amount of internal curing materials based on the modified MULTIMOORA method (Multi-Objective Optimization on the basis of Ratio Analysis plus full multiplicative form). First, different internal curing materials (super absorbent polymer (SAP), lightweight aggregate (LWA)) and pretreatment methods were selected to calculate their compressive strength, self-shrinkage and frost durability according to a proposed test scheme on the mixing amount of internal curing materials, and in such case, the comprehensive performance evaluation of the above indexes was turned into a multi-attribute decision-making problem. Second, the ordered weighted averaging (OWA) method and the entropy weight method were used to determine the subjective and objective weights of the indexes respectively, to eliminate the impact of outliers in the subjective evaluation values. Finally, the comprehensive performance of each test group was sorted using MULTIMOORA, and based on the sorting results and the calculation model, the mixing amount of internal curing materials was determined. The numerical example application results showed that the mixing amount of SAP curing material calculated based on the model herein was 1.276 kg/m³, and the mixing method adopted the pre-water absorption method with the total water-binder ratio unchanged. The numerical example evaluation results were in good agreement with the test results. The internal curing effect of SAP was better than that of LWA, and reached the best when the mixing amount was calculated at 25 times the water release rate and the requirement for the maximum total water diversion was met. The study may provide new ideas for extension and application of the internal curing technology.

Keywords: high-strength concrete, internal curing, compressive strength, index weight, mixing amount calculation model

1 Introduction

The “internal curing” was first put forward by American scholar Philleo [1] in 1991. The internal curing technology refers to adding internal curing materials to concrete under pre-stored water conditions to increase the internal humidity of the concrete through water release, thereby promoting the hydration of cementing materials and reducing the self-shrinkage of the concrete, and finally improving the overall performance of the concrete [2, 3]. In 2003, the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) defined the internal curing technology, and divided it into two main categories: super absorbent polymer (SAP) and lightweight aggregate (LWA) according to different internal curing materials. An appropriate amount of internal curing materials mixed can improve the performance of the high-strength concrete, but too many will reduce the strength or durability of the concrete. 

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performance of the concrete structure. Therefore, the key to the extension and application of the internal curing technology is to determine the reasonable amount of internal curing materials mixed.

At present, the mixing amount of internal curing materials is mostly determined based on D.P. Bentz’s [4] maximum water diversion theory. In 1999, Bentz [5] et al. for the first time established a formula for calculating the mixing amount of lightweight aggregates based on the amount of water required for the complete curing of the concrete and the water absorption capacity of the LWA. In 2002, Jensen and Hansen [6] proposed a method for determining the amount of SAP as an internal curing material, and found that the water adsorbed by SAP is free water and can be released when the concrete becomes dried. Zhutosky et al. [7] determined the mixing amount of internal curing materials according to the different aggregate sizes, and concluded that fine aggregates have higher internal curing efficiency than coarse aggregates. Cusson et al. [8] found that when the internal curing water-binder ratio (the mass ratio of water diversion to cementing material) is 0.06, the self-shrinkage of concrete in the early stage can be significantly eliminated, and on this basis, they calculated the mixing amount of internal curing materials. Said theories and methods for calculating the mixing amount of internal curing materials were all based on the theoretical water demand required by the complete hydration of cementing materials, which was proposed by American scholar T. C. Powers [9]. However, in practical applications, the amount of water pre-absorbed by internal curing materials is not totally equal to the amount of water released, and the latter is hard to obtain accurately during the hydration process, which leads to a great uncertainty in calculating the mixing amount of internal curing materials. To tackle this problem, this paper put forward a calculation model of internal curing materials mixed in high-strength concrete based on modified MULTIMOORA. In this paper, evaluation indexes were first processed, and index weights were coupled using the OWA operator method and the entropy weight method. The OWA operator method can reduce the impact of outliers in the process of determining subjective weights. Based on the MULTIMOORA theory, multi-factor problems were sorted by the decision-making, and the dominant theory was adopted to make a final evaluation of the overall performance of the internally cured concrete. Through the calculation model in this paper, an optimal internal curing material and its corresponding mixing amount were determined. The overall performance of internal curing materials was determined by MULTIMOORA evaluation method, and the optimal internal curing material and its mixing amount were obtained by an inverse model, which would promote the extension and application of internal curing materials.

2 Modified MULTIMOORA decision-making method

2.1 Decision representation set

According to JGJ55-2011 Specification for Mix Proportion Design of Ordinary Concrete, the mix proportion design of concrete shall meet the requirements for strength, long-term performance and durability. As for internal curing of high-strength concrete, the selected decision representation set includes compressive strength, self-shrinkage, mass loss rate and relative dynamic elastic modulus. Due to the differences of indexes in units and dimensions, it was proposed to employ the vector normalization method [10] to normalize the data. That is, first establish an index set \( A = \{a_1, a_2, \ldots, a_m\} \) and a scheme set \( C = \{c_1, c_2, \ldots, c_n\} \), then define the initial matrix \( V = [v_{ij}]_{m \times n} \), in which \( v_{ij} \) represents the evaluation value of the scheme \( c_j \) under the index \( a_i \), \( i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \), and normalize \( V \) to obtain a normalized matrix.

\[
v'_{ij} = \frac{v_{ij}}{\sqrt{\sum_{j=1}^{n} v_{ij}^2}}
\]

2.2 Determination of weights

2.2.1 OWA operator theory

There are subjective uncertainties and randomness in experts’ determining the evaluation index weights. The ordered weighted averaging (OWA) operator is a subjective assignment method that weakens the adverse effect of experts’ outliers through the combinatorial number formula or the normal distribution function [11]. Here are the steps of the OWA method:

1. Select \( Z \) experts to score index \( a_i \), and the result is recorded as \((e_1 e_2 \cdots e_z)\) of the index \( a_i \) given by \( Z \) experts, and arrange them in descending order to obtain a new array represented by vectors \( b_i \), \( b_i = [b_{i1} b_{i2} \cdots b_{iz}] \), \( l = 0, 1, 2, \cdots, z - 1 \).

2. Use the combinatorial number formula (2) to eliminate the effect of outliers and obtain the weighted
vector $\mathbf{w}_i = [w_{i1}, \ldots, w_{inz}]$ of the vector $\mathbf{b}_i$

$$w_{i1} = \frac{C_i}{\sum_{k=0}^{z-1} C_k} = \frac{C_i}{2^{z-1}},$$

$$l = 0, 1, 2, \cdots z - 1$$

(3) Weight the evaluation indexes through the weighted vector $\mathbf{w}_i$ to obtain the absolute weight $\bar{w}_i$ of the index $a_i$

$$\bar{w}_i = \sum_{l=1}^{z} w_{i1} \cdot b_{i1} \cdot [0, 1], l[0, n - 1]$$

(4) Calculate the subjective weight $w^1_i$ of each index in the index set $A$

$$w^1_i = \frac{\bar{w}_i}{\sum_{i=1}^{m} \bar{w}_i} i = 1, 2, \cdots m$$

2.2.2 Entropy weight theory

The entropy weight method is to determine the objective weight of an index [12]. The main steps are as follows:

1. Construct a judgment matrix and normalize the data using the range method
2. Determine the entropy value $H_i$ of the i-th index

$$H_i = -\frac{1}{\ln n} \left( \sum_{j=1}^{n} f_{ij} \ln f_{ij} \right)$$

$$i = 1, 2 \cdots m; j = 1, 2 \cdots n$$

Where: $m$ represents the evaluation index, $n$ represents the test scheme, $f_{ij} = \frac{1}{\sum_{i=1}^{n} (1+k_i)}$, $x_{ij}$ represents the normalized result of the i-th index under the j-th test scheme.

(3) Determine the weight: assume $w^2_i$ as the entropy weight of the i-th evaluation index.

$$w^2_i = \frac{1 - H_i}{n - \sum_{j=1}^{n} H_j}, \quad i = 1, 2 \cdots m$$

2.2.3 Weight optimization model

The above weight determination methods respectively reflect the subjective and objective effects of the evaluation. To reduce such effects, the OWA operator method and the entropy weight method are coupled to establish a weight optimization model, namely:

$$w_i = \frac{w^1_i w^2_i}{\sum_{j=1}^{m} (w^1_i w^2_i)}, \quad i = 1, 2, \cdots m$$

Where, $w^1_i$ and $w^2_i$ respectively represent the weight of the i-th index calculated using the OWA operator method and the entropy weight method, and $w_i$ represents the comprehensive weight of the i-th index.

2.3 Sorting theory based on the modified MULTIMOORA

MULTIMOORA is used to solve multi-criteria decision-making problems. However, the traditional MULTIMOORA does not consider the effect of weights on decision-making results. In view of the overall performance of concrete, this paper extended the MULTIMOORA theory by combining all performance requirements in engineering design [13].

1. Ratio system method: calculate the evaluation value $y_j$ of the scheme $c_j$

$$y_j = \sum_{i=1}^{g} w_i y_{ij} - \sum_{i=g+1}^{m} w_i y_{ij}$$

Where, $w_i$ represents the index weight, and $g$ and $n-g$ represent the index beneficial and harmful to the overall performance of the concrete respectively. The larger the $y_j$ is, the better the overall performance of the concrete is.

2. Reference point method: First, determine the optimal reference point for each index:

$$r_i = \begin{cases} \max v^*_{ij} & i \leq g \\ \min v^*_{ij} & i > g \end{cases}$$

Second, determine the evaluation value $z_j$ of the test scheme: $z_j = \max_i |w_i (r_i - v^*_{ij})|$

Where, the smaller the value $z_j$ is, the better the test scheme is. Finally, sort the schemes according to the value $z_j$.

3. Perfect multiplication method

$$u_j = \frac{\prod_{i=1}^{g} v^*_{ij} w_i}{\prod_{i=g+1}^{m} v^*_{ij} w_i}$$

Where, the larger the value $u_j$ is, the better the corresponding test scheme is.
(4) Dominant theory
The dominant theory can combine several sorts into one sort by modes of dominating, dominated, balancing, and transferring, and integrate the above results to obtain the optimal sort.

3 Calculation model for the mixing amount of internal curing materials considering the mixing method

3.1 Determination of the initial amount of internal curing materials mixed

According to the additional water-binder ratio formula proposed by D.P. Bentz [14] the amount of water required for internal curing was calculated, as shown in the formula (11):

\[ V_w = \frac{0.18 \times (w/c) \times J}{\rho_w} \]  

(11)

Where, \( V_w \) is the maximum water diversion (m^3); \( w/c \) is the water-binder ratio, \( w/c \leq 0.36 \); \( J \) is the amount of cementing materials; \( \rho_w \) is the density of water, 1,000 Kg/m^3 used in this paper.

The mixing amount of LWA is calculated according to the formula (12):

\[ M_{LWA} = \frac{M_w}{S_c \times \phi_{LWA}} \]  

(12)

Where, \( M_{LWA} \) is the amount of lightweight aggregates required for concrete per cubic meter, kg/m^3; \( M_w \) is the amount of water for internal curing of concrete per cubic meter, kg/m^3; \( S_c \) is the saturation (0-1) of lightweight aggregates; \( \phi_{LWA} \) is the water absorption rate of lightweight aggregates.

The mixing amount of internal curing materials depends on the amount of water released by the internal curing materials during the hydration of the cementing materials, but this value is difficult to obtain due to the complex water release mechanism of the internal curing materials. To determine the mixing amount of internal curing materials, it was assumed that the water release rate is equal to the water absorption rate [15]. Based on the balance of water released and water absorbed, the mixing amount of internal curing materials was obtained finally. The mixing amount of SAP was calculated by 25 times its water absorption rate. LWA kept its surface dry before mixed into the water for internal curing, and its mixing amount was calculated at 10% of its water absorption rate.

3.2 Calculation model for the mixing amount of internal curing materials

A corresponding calculation model for the mixing amount needs to be established to find the correspondence between the test scheme and the evaluation results of each test group. During the test, data of different indexes were obtained according to the corresponding specifications and measurements, and the evaluation results of each test group were sorted according to the calculation model. The modified MULTI MOORA decision result and the mixing amount of internal curing materials were linked to obtain a nonlinear model, as shown in the formula (13):

\[ V = f \left[ \min x_{yj} + x_{zj} + x_{uj} \right], \quad j = 1, 2, 3 \ldots, n \]  

(13)

Where, \( V \) means the mixing amount of internal curing materials considering the pretreatment method, kg/m^3, \( x_{yj}, x_{zj}, x_{uj} \) and mean the sequence number of the scheme \( j \) obtained through the ratio system method, reference point method and perfect multiplication method respectively, and \( f \) means the non-linear relationship between the mixing amount of internal curing materials and the mixing method in the corresponding scheme.

4 Example analysis

4.1 Test analysis

4.1.1 Raw materials and mix proportion

See Table 1 for the mix proportion of internally cured concrete, in which the cement was P.O42.5 ordinary Portland cement; the fly ash was at Grade I with specific surface area of 455 m^2/kg; the silica fume’s specific surface area was 20000 m^2/kg; the fine aggregate was the Yaohe river sand with fineness modulus of 2.8, grading zone II; the coarse aggregate was the limestone gravel (5~20mm); QS80-20 polycarboxylic acid water reducing agent produced by Shanghai Softening Chemical was used, with water-reducing rate of 30% when its content accounted for 0.1% of the cement content; the super absorbent polymer had 60-100 meshes (particle size 0.01-0.25 mm), and the water absorption in the test was set to 25 times its mass. The test used 5-20mm gravel shale ceramsite produced by Yichang Baozhu Ceramsite Company, with apparent density of 1,570 kg/m^3 and saturated water absorption of 12%.

The maximum water requirement for internal curing calculated according to the mix proportion was 32kg/m^3. The initial mixing amount of internal curing materials [16] is
shown in Table 1. Considering the mixing method of the internal curing water [17], it was designed that the total water-binder ratio of HSC 12.5- and HSC 25- groups remained unchanged. Partial coarse aggregates were replaced by LWA with equal quality, mixed with additional SAP. The test scheme was designed as shown in Table 1.

4.1.2 Test methods and results

The compression test was performed in accordance with GB/T50081-2019 Standard for Test Methods of Concrete Physical and Mechanical Properties, and the antifreezing test and self-shrinkage test were performed in accordance with GBT 50082-2009 Standard for Test Methods of Long-term Performance and Durability of Ordinary Concrete. One-side freezing-thawing method was used to test the quality loss and relative dynamic elastic modulus of test blocks after 28 days of curing and 25 freezing-thawing cycles in the antifreezing test. In the self-shrinkage test, the non-contact method was adopted. Because the self-shrinkage was intense during the high-strength coagulation and at an early age, the measurement was carried out in the first 3 days when the shrinkage was basically stable. The final shrinkage value was determined by fitting. The test results are shown in Table 2.

Based on the analysis of the results in the table, it is found that: (1) the compressive strength is positively correlated with the relative dynamic elastic modulus and inversely correlated with the quality loss rate; the self-shrinkage is greatly affected by the internal curing; (2) compared with the baseline group, due to the diversion of additional water, the water-binder ratio increases and the strength of concrete in the test group (additional water diversion) decreases; however, because the pore structure can be improved by the secondary hydration through internal curing water release, its freezing resistance is enhanced; (3) compared with SAP, LWA is porous, low in strength and inadequate in water release [18], so it has poor strength, shrinkage and freezing resistance; and (4) compared with the baseline group, the total water-binder ratio of HSC 12.5- and HSC 25- groups remains unchanged, and because the internal curing material can continuously maintain the cement during hydration, the performance of the two groups was better.

| Group     | Water-cement ratio | Mix proportion (kg·m⁻³) | Cement | Slag | Fly ash | Silica fume | Water | Sand | Coarse aggregate | Internal curing | Internal curing | Water reducing agent |
|-----------|--------------------|--------------------------|--------|------|---------|-------------|-------|------|------------------|-----------------|-----------------|---------------------|
| HSC       | 0.34               |                          | 371.2  | 79.6 | 53      | 26.4        | 180   | 625  | 1065             | 0               | 0               | 0.53                |
| HSC12.5   | 0.34               |                          | 371.2  | 79.6 | 53      | 26.4        | 180   | 625  | 1065             | 0.638           | 16              | 0.53                |
| HSC25     | 0.34               |                          | 371.2  | 79.6 | 53      | 26.4        | 180   | 625  | 1065             | 1.276           | 32              | 0.53                |
| HSC12.5-  | 0.31               |                          | 371.2  | 79.6 | 53      | 26.4        | 164   | 625  | 1065             | 0.638           | 16              | 0.53                |
| HSC25-    | 0.28               |                          | 371.2  | 79.6 | 53      | 26.4        | 148   | 625  | 1065             | 1.276           | 32              | 0.53                |
| LWA5      | 0.34               |                          | 371.2  | 79.6 | 53      | 26.4        | 180   | 625  | 745              | 320             | 16              | 0.53                |
| LWA10     | 0.34               |                          | 371.2  | 79.6 | 53      | 26.4        | 180   | 625  | 745              | 320             | 16              | 0.53                |

Table 2: Measurement results of concrete performance indexes

| Group     | HSC       | HSC12.5   | HSC25     | HSC12.5-  | HSC25-    | LWA5     | LWA10    |
|-----------|-----------|-----------|-----------|-----------|-----------|----------|----------|
| Compressive strength /MPa | 65.80     | 64.20     | 60.60     | 68.00     | 73.00     | 62.00    | 58.60    |
| Quality loss | 3.92%     | 2.86%     | 1.98%     | 2.14%     | 1.23%     | 3.72%    | 4.72%    |
| Relative dynamic elastic modulus | 88.17%    | 90.04%    | 95.39%    | 98.45%    | 98.93%    | 90.78%   | 89.10%   |
| Self-shrinking /mm | 2.540     | 0.683     | 0.411     | 0.626     | 0.351     | 0.940    | 0.630    |
4.2 Model analysis

4.2.1 Establishment of evaluation indexes

In this paper, the performance of internally cured concrete was evaluated and analyzed based on the Multimoora theory with four indexes measured in the test as evaluation indexes.

4.2.2 Determination of the weight of indexes

(1) Determination of index weight by the OWA operator method

Six experts (university professors who had been engaged in concrete research for more than 10 years) were invited to score each index. The scoring range was limited to 0–5, with one decimal place reserved. The higher the evaluation score is, the greater the effect of the index on the overall performance of internally cured high-strength concrete is, see Table 3.

Take the compressive strength index as an example, it was arranged subject to the descending order: $\mathbf{b}_1 = (4.5, 4.2, 4.0, 4.0, 3.8, 3.5)$, $n=6$. According to formula (2), the weighted vector was calculated as: $\mathbf{w}_1 = (0.03125, 0.15625, 0.3125, 0.3125, 0.15625, 0.03125)$. According to formula (3), the absolute weight $\mathbf{w}_1 = 4.0$ was obtained.

Similarly, the absolute weight of other indexes was: Quality loss $\mathbf{w}_2 = 0.628$; relative dynamic elastic modulus $\mathbf{w}_3 = 1.469$; self-shrinkage $\mathbf{w}_4 = 1.063$. According to formula (4), the subjective weighted vector of each index was obtained: $\mathbf{W}_1 = (0.559, 0.088, 0.205, 0.148)$.

(2) Determination of index weight by the entropy weight method

First, the judgment matrix $\mathbf{A}$ was constructed according to the test results in Table 2. By normalizing the data of different indexes using the range method and eliminating the dimensional difference of indexes, the new judgment matrix $\mathbf{X}$ was constructed. The data of $\mathbf{X}$ judgment matrix are shown in Table 4.

By solving the formulas (5)–(6), the index weight $\mathbf{W}_2$ was obtained: $\mathbf{W}_2 = (0.274, 0.227, 0.364, 0.135)$

(3) By coupling $\mathbf{W}_1$ and $\mathbf{W}_2$ according to formula (7), the comprehensive weight of index $\mathbf{W}$ was obtained:

$$\mathbf{W} = (0.572, 0.074, 0.279, 0.075)$$

4.2.3 Sequencing of each test group’s scheme through Multimoora

When evaluating the overall performance of each test group through Multimoora, the test data should be normalized to eliminate the dimensional difference between indexes first. In this paper, the test data were normalized by the vector normalization method to obtain the matrix $\mathbf{B}$. The data of the matrix $\mathbf{B}$ are shown in Table 5.

The test groups in the matrix $\mathbf{B}$ were sorted by the modified Multimoora ratio system method, reference point method and perfect multiplication method through formulas (8), (9) and (10), respectively. The rating values and ranking results of each test group were determined, and the comprehensive performance evaluation results of internally cured concrete are shown in Table 6.

| Table 3: Expert score of comprehensive performance indexes of internally cured concrete |
|---|---|---|---|---|---|---|---|
| Index | Expert 1 | Expert 2 | Expert 3 | Expert 4 | Expert 5 | Expert 6 |
| Compressive strength | 4.0 | 3.8 | 4.2 | 4.0 | 3.5 | 4.5 |
| Quality loss | 0.6 | 1.2 | 0.8 | 0.6 | 0.4 | 0.5 |
| Relative dynamic elastic modulus | 1.5 | 1.0 | 1.4 | 2.0 | 1.4 | 1.6 |
| Self-shrinking | 1.0 | 0.8 | 0.5 | 1.5 | 1.2 | 1.2 |

| Table 4: Judgment matrix |
|---|---|---|---|---|---|---|---|
| Index | HSC | HSC12.5 | HSC25 | HSC12.5- | HSC25- | LWA5 | LWA10 |
| Compressive strength | 0.500 | 0.389 | 0.139 | 0.653 | 1.000 | 0.236 | 0.000 |
| Quality loss | 0.187 | 0.434 | 0.641 | 0.603 | 0.816 | 0.234 | 0.000 |
| Relative dynamic elastic modulus | 0.000 | 0.152 | 0.588 | 0.837 | 0.877 | 0.213 | 0.076 |
| Self-shrinking | 0.000 | 0.849 | 0.973 | 0.874 | 1.000 | 0.729 | 0.875 |
Table 5: Data normalization by vector normalization method

| Index                              | HSC    | HSC12.5 | HSC25  | HSC12.5- | HSC25-  | LWA5   | LWA10   |
|------------------------------------|--------|---------|--------|----------|---------|--------|---------|
| Compressive strength               | 0.384  | 0.375   | 0.354  | 0.397    | 0.426   | 0.362  | 0.342   |
| Quality loss                       | 0.470  | 0.343   | 0.237  | 0.256    | 0.147   | 0.446  | 0.565   |
| Relative dynamic elastic modulus    | 0.358  | 0.366   | 0.387  | 0.400    | 0.402   | 0.369  | 0.362   |
| Self-shrinking                     | 0.852  | 0.229   | 0.138  | 0.210    | 0.118   | 0.317  | 0.210   |

Table 6: Evaluation value of each test group

| Group | HSC   | HSC12.5 | HSC25  | HSC12.5- | HSC25-  | LWA5   | LWA10   |
|-------|-------|---------|--------|----------|---------|--------|---------|
| Yi    | 0.221 | 0.274   | 0.283  | 0.304    | 0.336   | 0.253  | 0.239   |
| Zi    | 0.055 | 0.029   | 0.041  | 0.017    | 0.000   | 0.037  | 0.048   |
| Ui    | 0.465 | 0.521   | 0.546  | 0.567    | 0.644   | 0.490  | 0.478   |

Table 7: Ranking of each test group by overall performance

| Group                                   | HSC   | HSC12.5 | HSC25  | HSC12.5- | HSC25-  | LWA5   | LWA10   |
|-----------------------------------------|-------|---------|--------|----------|---------|--------|---------|
| Ratio system method                     | 7     | 4       | 3      | 2        | 1       | 5      | 6       |
| Reference point method                  | 7     | 3       | 5      | 2        | 1       | 4      | 6       |
| Perfect multiplication method           | 7     | 4       | 3      | 2        | 1       | 5      | 6       |
| Sum of rankings                         | 21    | 11      | 11     | 6        | 3       | 14     | 18      |
| Final ranking                           | 6     | 3       | 3      | 2        | 1       | 4      | 5       |

The dominant theory [19] was adopted to finally rank the overall performance of internally cured high-strength concrete. In this paper, the ranking results were accumulated for sequencing and final ranking. The ranking results are shown in Table 7.

4.3 Determination of the mixing amount of internal curing materials considering the mixing method

As to the comparative analysis of Table 2 and Table 7, when SAP was used as the internal curing material, the HSC25- and HSC12.5- groups with a certain total water-binder ratio ranked 1st and 2nd respectively in terms of the overall performance, and their strength and relative dynamic elastic modulus were significantly better as shown in the test results. The reasons why these two groups had a better performance were that their water-binder ratio, free water and holes of concrete were relatively small. Although the reduced water quantity would lead to the decrease in fluidity, the existence of internal curing water had made up for such defect; therefore, they showed better performance during freezing and thawing. With the same water-binder ratio, test groups HSC12.5 and HSC25 containing SAP took the same ranking, a bit lower than HSC25- and HSC12.5- groups, showing that the difference between their performances was small, which was attributed to the bi-nature of adding internal curing water: on the one hand, the added internal curing water optimized the hydration of the cementing material and improved the pore structure; on the other hand, the total water-binder ratio increased due to the addition of extra water, which was consistent with the test results as well as the studies of other scholars [20]. When LWA was used as the internal curing material, the data of relevant indexes of relevant test groups were poor, and with the increase of LWA content, other indexes showed the deteriorating tendency except the self-shrinkage index. Compared with the SAP group, the LWA group showed quite different performance due to its low strength, small water release and a lot of holes, which were unfavorable to both strength and freezing resistance. Compared with the baseline group, when the water diverted did not exceed the maximum amount for internal curing, the internal curing material could effectively reduce the self-shrinkage of the high-strength concrete.

According to the above ranking results, the effect of SAP group was better than that of LWA group with the same water diversion; HSC25- was the optimal test group with SAP curing materials, and the best effect was achieved when
the mixing amount was calculated with the value of the maximum water absorption. The pre-wetting method was adopted, with the same total water-binder ratio. For the LWA group, the optimum mixing amount was calculated with the water absorption of 5%. According to the model in this paper, SAP should be selected as the curing material according to the mix proportion, and the best mixing amount was 1.276 kg/m³ after deducting the pre-wetting water.

5 Conclusions

By evaluating and ranking the overall performance of internally cured high-strength concrete based on relevant models, this paper intended to figure out the optimum mixing amount of internal curing materials through test and theoretical analysis. The main conclusions are as follows:

(1) By test, the values of strength, self-shrinkage and freezing resistance of internally cured high-strength concrete were obtained, and it was found that when SAP and LWA were used as the internal curing material, under the same water-binder ratio, the compressive strength decreased if the mixing amount of the internal curing material increased; SAP was better than LWA in mixing effect if the water diversion was the same; the mixing method of the internal curing material had a great impact on the mixing effect, and the overall performance of concrete was best when the internal curing water was part of the mixed water.

(2) Based on the coupling of subjective and objective weights-MULTIMOORA theory, with compressive strength, quality loss rate, relative dynamic elastic modulus and self-shrinkage rate as indexes, it was found that HSC25- was the optimal test group for the optimization of internally cured high-strength concrete, which was consistent with the test results; the ranking results of each test group met expectations, indicating that the method was reasonable for evaluating the overall performance of internally cured high-strength concrete.

(3) Based on the calculation model of the mixing amount of internal curing materials in high-strength concrete, the test group with the optimum mix proportion of internally cured concrete could be determined; the ranking results primarily established on the subjective and objective comprehensive weights of indexes in the model were scientific and reasonable. This method is widely applicable, and can be used to evaluate the test results of different internal curing materials, different water pre-absorption quantities and different water pre-absorption methods, so as to obtain the optimum internal curing water quantity and mixing amount of internal curing materials, thereby providing theoretical basis for engineering and test design.

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