Design of Waterproof System for Cement Concrete Bridge Deck Pavement Based on Layer Functional Requirements

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Abstract: Currently, there is no unified standard for the design and testing of bridge deck waterproofing systems in China. In the application of waterproofing systems, there are many types of materials to be selected, and the selection of schemes is blind, with varying quality inspection and control standards. Therefore, a unified evaluation system should be determined based on the characteristics of each waterproofing material, combined with usage conditions and construction, to select suitable waterproofing materials, and to optimize the bridge deck waterproofing system based on the AHP analytic hierarchy process. By analyzing the various factors and related indicators that affect the bridge deck pavement waterproof system, a multi-level and multi-index evaluation structure model is established. Relevant experts in the field are used to score the multi-level indicators and evaluate the importance of each indicator. Then, a judgment matrix of each level of indicators is constructed by using the analysis method promoted layer by layer by AHP to calculate its importance and conduct consistency test. Finally determine the importance of each program, to achieve quantitative selection of more reasonable programs.

Keywords: Cement Concrete; Layer Function; Waterproof System; Analytic Hierarchy Process; Gravel Seal

1. Introduction

The current design specifications and construction technical specifications for asphalt pavement on highways only put forward principle requirements for the waterproof system of bridge deck pavement. This waterproof system mainly refers to the setting of the undercoat and waterproof layer, focusing on the "protection" issue after external water enters, and lacking corresponding detailed design for the "diversion" before preventing external water from entering. Unreasonable design of pavement layers and insufficient compaction during construction can lead to excessive voids in the surface mixture, which can easily cause cracking during use and induce moisture entry [1-3]. If the drainage system of the bridge deck is not set properly, the incoming water cannot be discharged in a timely manner, resulting in a "bathtub effect", which will inevitably exacerbate the damage to the pavement layer. In recent years, the bridge deck has experienced severe water seepage, especially for urban elevated bridges [4, 5]. In order to improve the service life of bridges and reduce maintenance, the specification stipulates that a waterproof layer should be installed on the bonding layer, with a thickness of 1.0-1.5mm for the bridge deck waterproof layer. Through investigation, it was found that the bonding layer of the bridge deck set in this way is weak, has poor water stability, and is easily damaged by subsequent construction vehicles, damaging the original interlayer connection. The pavement layer slides with the cement concrete bridge deck under the horizontal load of vehicles, which is also an important reason for the displacement and support of the carriageway [6].

2. Type of Waterproof Layer for Cement Concrete Bridge Deck Pavement

The research on waterproof coatings for domestic roads and bridges began in 1991 at the Nanpu Bridge in Shanghai. The research results of this project were successfully applied

to the bridge deck of the Nanpu Bridge and quickly promoted. In 1999, the Ministry of Transportation entrusted Chang'an University to establish a special research group to conduct a special study on the waterproof layer. The research results of this topic were included in the new specification of the Ministry of Transportation - "Quality Inspection and Evaluation Standards for Highway Engineering" (JTGF80/1-2004) (implemented on January 1st, 2005).

At present, the relevant specifications and standards for waterproofing of concrete bridges mainly include [7-8].

Cement based permeable crystalline waterproof materials (GB 18445-2001), polyurethane waterproof coatings (GB/T 19250-2003), water-based asphalt waterproof coatings for roads and bridges (JT/T535-2004), modified asphalt waterproof rolls for roads and bridges (JC/T974-005), waterproof coatings for roads and bridges (JT/T975-2005), test methods for building waterproof coatings (GB/T16777-1997) Technical Specification for Waterproofing Engineering of Urban Bridge Deck (2010 Edition)[9-11].

At present, the domestic market is relatively representative, and waterproof materials have been applied in large-scale projects (such as large bridges or super large bridges), including emulsified asphalt or modified emulsified asphalt film adhesive layer, flexible waterproof coating type, waterproof roll/hot polymer modified asphalt+protective board, etc., waterproof coating+fiber reinforced waterproof layer, hot asphalt (SBS, Rubber)+asphalt mortar (2-3mm), organic primer+pouring asphalt concrete, Polymer modified asphalt or epoxy modified asphalt film (<3mm), epoxy resin/methyl methacrylate (MMA), and other cement concrete polymer material penetrating agents.

3. Problems in Waterproofing System and Pavement Structure

The main problems currently existing in the application of waterproof layers in physical engineering include:

In terms of theoretical support: the diversity of waterproof layer materials and construction processes, the lack of comprehensive and unified bridge deck waterproofing design, construction, and monitoring norms and standards in various regions, the lack of systematic understanding of bridge deck waterproofing, insufficient attention to its important role in bridge deck pavement, and great blindness in design, such as not considering the waterproofing and drainage treatment of bridge details, ultimately leading to the overall failure of the waterproofing system, etc;

In terms of the selection of waterproof materials, it mainly relies on the experience of engineers and the recommendations of manufacturers to make judgments, lacking scientificity. The technical indicators and standards provided by manufacturers have limitations, and most of them are professional technical indicators that are beneficial for this material. There is a lack of a set of performance indicators, testing methods, and engineering technical standards suitable for selecting and evaluating bridge deck waterproof materials, leading to market chaos and uneven quality of bridge deck waterproof materials, A large number of counterfeit and inferior products have entered the bridge deck waterproofing market, burying engineering risks;

In terms of construction technology: Currently, the ideas and technical standards for bridge deck waterproofing are mostly transformed from roof waterproofing projects. The construction technology is simply copied, and there is insufficient understanding of bridge deck treatment, often only simple treatment is done or even no treatment is done. The low quality of construction technicians, inability to fully execute the design intent, or the simple and outdated construction equipment often make the work more difficult;

In terms of quality control: There are almost no testing and control measures for on-site construction quality, relying solely on the observation and experience of supervision personnel. There is a lack of quantitative testing and control of construction quality, resulting in the inability to determine the reliability of the expected performance of the waterproof layer material after the surface layer is laid.

4. Design of Waterproof System for Bridge Deck Pavement Based on Layer Functional Requirements

Based on the existing research results at home and abroad, the waterproof bonding layer is

usually composed of the following structural levels from a functional perspective:

4.1 Bottom Coating

Bottom coating refers to improving the adhesion characteristics of the concrete surface by allowing the base material to penetrate or adhere to the concrete bridge deck, thereby enhancing the adhesion between the waterproof film and the bridge deck. The bottom coating material mostly uses diluted asphalt. Diluted asphalt is a liquid material that dilutes asphalt with organic solvents such as kerosene or gasoline, and its fineness is at the molecular level. During construction, the organic solvent evaporates to form the bottom coating. The permeability of this diluted asphalt is affected by viscosity. When the viscosity is too low, timely penetration depth cannot achieve the best effect, and it is easy to retain oil that can affect the bonding and reinforcement.

4.2 Lower Bonding Layer

Some rolls (mainly synthetic polymer rolls constructed by non hot melt methods) have their own matching adhesives to enhance the bonding with the bridge deck, and most of the adhesives are made of oxidized asphalt or polymer modified asphalt. Some rolls have self-adhesive properties and pressure sensitive adhesive layers.

The bonding strength of the adhesive layer decreases with the increase of thickness, so the adhesive layer should not be too thick under the condition of meeting the shear strength.

For coating materials, this layer is not required due to its inherent multi-layer spraying of polymer modified emulsified asphalt.

4.3 Breathable Layer

The function of the breathable layer is to emit air and water vapor under the waterproof layer to prevent the formation of air pressure and the appearance of bubbles or hollows in the waterproof layer. It is only applicable to roll waterproofing systems and not to film coatings, mainly used in some foreign countries.

4.4 Waterproof Layer

The waterproof layer is the main body of the entire waterproof system and the key level of bridge deck waterproofing. Other layers only serve to improve the bonding performance between the waterproof layer and the upper and lower layers and prevent other defects.

4.5 Protective Layer

Due to the need to lay an asphalt surface course on the waterproof layer, and when laying an asphalt surface layer, high-temperature rolling is required. High temperatures (about 120-170 ℃) may cause the waterproof layer to age, soften, or flow, and the aggregates in the asphalt mixture may also puncture the waterproof layer. Therefore, it is considered to set a protective layer on the waterproof layer.

The type of protective layer is related to the type of surface layer, waterproof layer type, and thickness. The protective layer mainly consists of materials such as asphalt chips, asphalt sand, rubber asphalt protective boards, waterproof rolls, etc.

4.6 Upper Bonding Layer

In order to ensure good adhesion between the waterproof layer and the asphalt surface layer, sometimes a bonding layer is also set up between the waterproof layer (or protective layer) and the surface layer. Due to the susceptibility of most waterproof membranes to damage by organic solvents, asphalt solutions (emulsified asphalt or modified emulsified asphalt) are generally used as binders.

5. Optimization of Bridge Deck Waterproof System Based on AHP Analytic Hierarchy Process

By analyzing various factors and related indicators that affect the waterproof system of bridge deck pavement, a multi-level and multi indicator evaluation structure model was established. Relevant experts in this field were used to score multi-level indicators and evaluate the importance of each indicator. Then, the AHP layer by layer analysis method was used to construct a judgment matrix for each level of indicator to calculate its importance and conduct consistency testing, ultimately determining the importance of each scheme, Thus, it is possible to quantitatively select more reasonable solutions.

5.1 Determination of AHP Evaluation Indicators and Framework

Based on existing research results, classify

them from a functional perspective, the waterproof system structure is usually composed of a bottom coating, a lower bonding layer, a waterproof layer, a protective layer, and an upper bonding layer. It needs to have efficient waterproof performance, good bonding performance, and meet technical requirements such as low temperature sensitivity, strong deformation resistance, good construction integrity, and strong bridge deck adaptability. This article mainly examines the application of four waterproofing system structural schemes, and the specific content is shown in Figure 1 and Table 1.

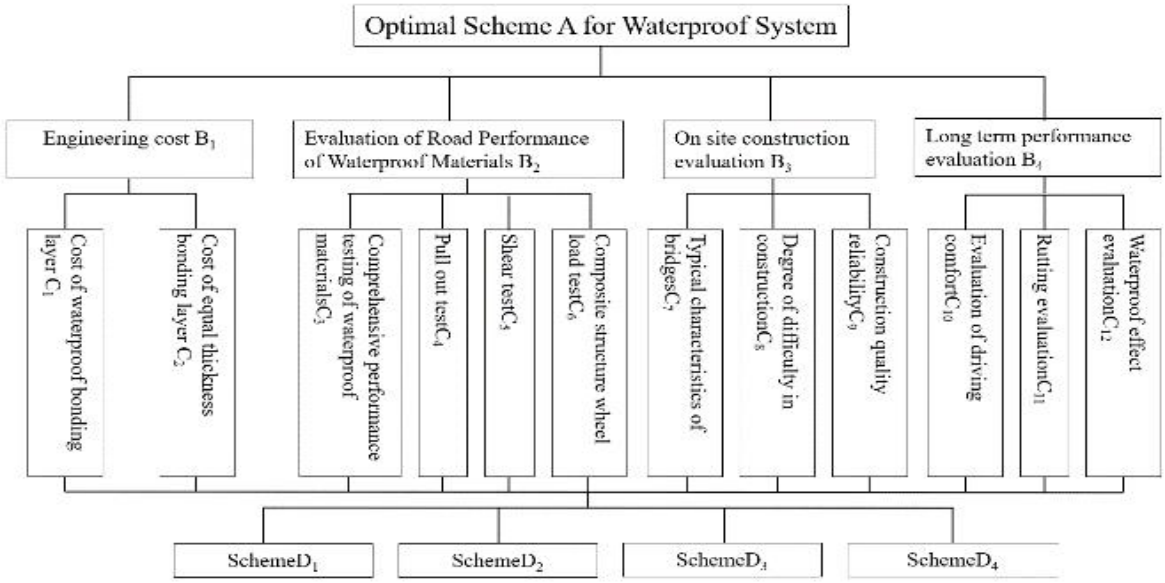

Figure 1. Hierarchy Structure Diagram of Bridge Deck Pavement Waterproofing System Evaluation

Table 1. Waterproof System Scheme

Scheme	Concrete content
D_1	Hot SBS modified asphalt&0.5% single particle pre mixed crushed stone+2cm asphalt sand+modified emulsified asphalt
D_2	Diluted asphalt primer+5mm rubber asphalt+3.6mm protective board+modified emulsified asphalt
D_3	GIS-I type primer+3.0cm cast asphalt concrete
D_4	0.12cm reinforced waterproof coating (five layer spraying)

5.2 Calculation and Optimization of the Importance of Different Bridge Deck Waterproof System Schemes

5.2.1 Expert scoring to determine the importance of each indicator

In order to meet the needs of AHP evaluation, 18 experts in this field were invited to rate the evaluation indicators at all levels through a survey questionnaire to determine the importance of each level of indicator. In order to ensure the comprehensiveness of the evaluation results, the invited experts involve researchers, managers, and construction unit personnel from multiple fields. Among them, the importance level is set to four scales, represented by integers 1-4, where 1 represents the most important, and the importance level of 2, 3, and 4 gradually decreases. Through statistical analysis of expert evaluation results, the importance of indicators at all levels was obtained, as shown in Figure 2- Figure 6. The ranking results of the importance of indicators at all levels can be obtained as follows in Table 2.

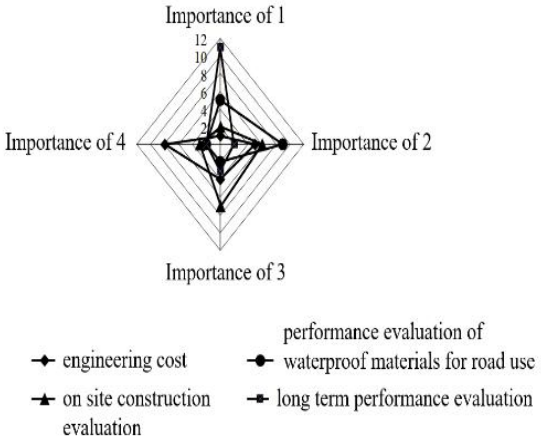

Figure 2. Statistical Results of the Importance of Primary Evaluation

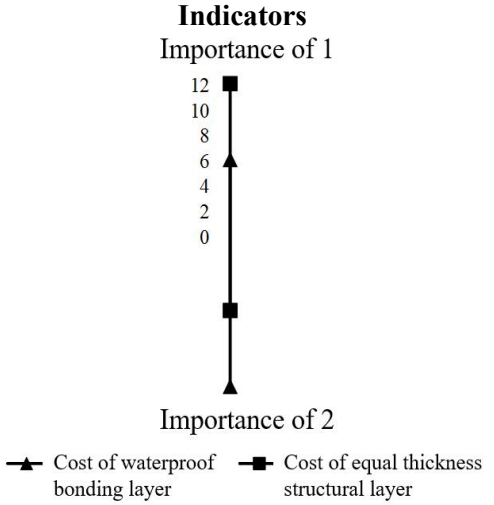

Figure 3. Statistical Results of the Importance of the Secondary Evaluation Indicators Corresponding to B1

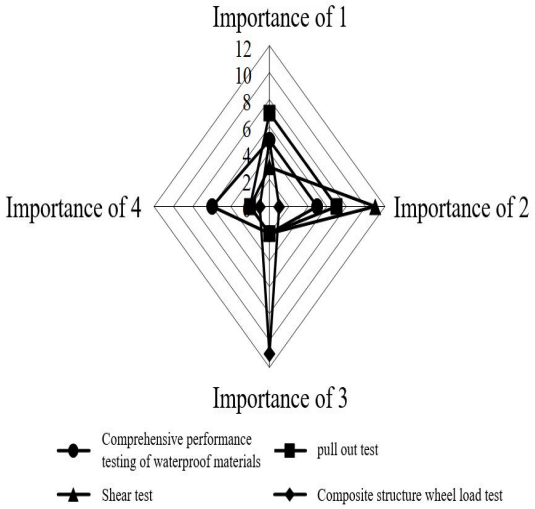

Figure 4. Statistical Results of Secondary Evaluation Indicators Corresponding to B2

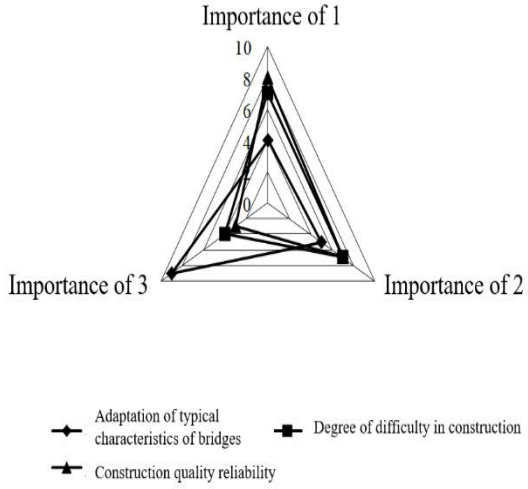

Figure 5. Statistical Results of Secondary Evaluation Indicators Corresponding to B3

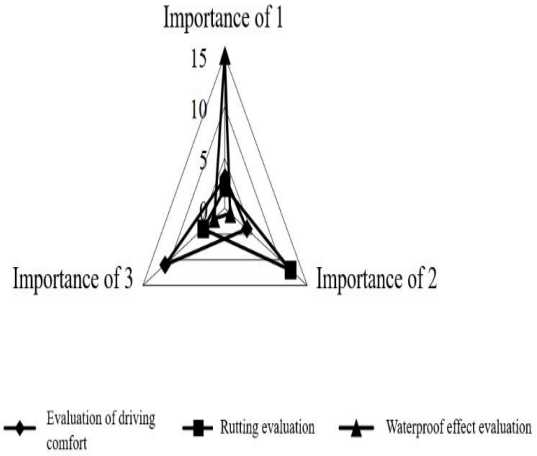

Figure 6. Statistical Results of the Importance of the Secondary Evaluation Indicators Corresponding to B4

Table 2. Ranking of Importance of Indicators at all Levels

index	Importance ranking
Primary indicators	$B_4 > B_2 > B_3 > B_1$
Secondary indicators	$C_2 > C_1$
	$C_4 > C_5 > C_6 > C_3$
	$C_9 > C_8 > C_7$
	$C_{12} > C_{11} > C_{10}$

5.2.2 Calculation of relative weights of indicators at all levels

Establish a corresponding judgment matrix by comparing the impact of the upper level indicators on the lower level related indicators in pairs. For the first level indicator of bridge pavement waterproofing system structure, by comparing the degree of impact of B on A, the judgment matrix for target A is established as follows:

$$\begin{array}{c} \\ B_1 \\ B_2 \\ B_3 \\ B_4 \end{array} \begin{array}{c} \begin{array}{cccc} B_1 & B_2 & B_3 & B_4 \end{array} \\ \begin{bmatrix} 1 & 1/4 & 1/3 & 1/5 \\ 4 & 1 & 3 & 1/3 \\ 3 & 1/3 & 1 & 1/4 \\ 5 & 3 & 4 & 1 \end{bmatrix} \end{array} \quad (1)$$

According to the formula and its calculation, the relative weight vectors W_{ci}^0 of B_1, B_2, B_3, and B_4 are equal to $[0.06826 \quad 0.26867 \quad 0.13433 \quad 0.52874]^T$. The consistency of the judgment matrix is verified using the formula, and the value of the consistency ratio C.R. is 0.068, which meets the consistency requirements.

The calculation of relative weights for secondary indicators takes the calculation of

relative weights for C_1 and C_2 as an example. The judgment matrix constructed by comparing C_1 and C_2 is as follows:

$$\begin{matrix} & \boldsymbol{C_1} & \boldsymbol{C_{12}} \\ \boldsymbol{C_1} & \boldsymbol{1} & \boldsymbol{1/3} \\ \boldsymbol{C_2} & \boldsymbol{3} & \boldsymbol{1} \end{matrix} \quad (2)$$

The relative weight vectors $W_{C_{12}}^0 = (0.25\ 0.75)^T$ of C_1 and C_2. Similarly, calculate the relative weights of other secondary indicators and conduct consistency checks. The specific calculation results are shown in Table 3.

Table 3. Ranking of Importance of Indicators at all Levels

Primary indicators B_i	Secondary indicators C_i	Relative Weight W_{Ci}
B_1	C_1	0.25
	C_2	0.75
B_2	C_3	0.0682
	C_4	0.5288
	C_5	0.2687
	C_6	0.1343
B_3	C_7	0.1172
	C_8	0.2684
	C_9	0.6144
B_4	C_{10}	0.1172
	C_{11}	0.2684
	C_{12}	0.6144

Calculate the comprehensive weight of secondary indicators according to the formula, and the calculation result of the comprehensive weight R_{ci} of secondary indicators is as follows:

R_{ci}=(0.017 0.051 0.018 0.142 0.072 0.036 0.016 0.036 0.083 0.062 0.142 0.325)

5.2.3 Calculation of scheme importance

(1) Calculation of relative weights of scheme indicators

Based on the method established by the above judgment matrix, a judgment matrix for each secondary indicator is constructed by comparing the importance of each element of the secondary evaluation indicator on schemes D_1, D_2, D_3, and D_4 through pairwise comparison. Then calculate the relative weight of the scheme indicators according to formula and perform consistency testing. Taking the impact of C_1 on D_1, D_2, D_3, and D_4 as an example, calculate the relative weights of D_1, D_2, D_3, and D_4. By comparing the importance of the four schemes, construct a relevant judgment matrix and perform consistency testing. The specific analysis process is as follows:

The cost per square meter of waterproof bonding layer for the four schemes is shown in Table 4. Based on this table, a judgment matrix for the second level rating index waterproof bonding layer cost C_1 is constructed, as shown below. Based on the judgment matrix, the relative weight vectors of D_1, D_2, D_3, and D_4 with respect to C_1 are calculated as (0.317 0.156 0.058 0.469) ^{T}. Similarly, construct the judgment matrices of C_2~C_{12} and calculate the relative weights of the schemes.

Table 4. Cost of Waterproof Bonding Layer Per Square Meter (Yuan)

D_1	D_2	D_3	D_4
55	95	158	38

$$\begin{matrix} & D_1 & D_2 & D_3 & D_4 \\ D_1 & 1 & 3 & 5 & 1/2 \\ D_2 & 1/3 & 1 & 4 & 1/3 \\ D_3 & 1/5 & 1/4 & 1 & 1/6 \\ D_4 & 2 & 3 & 6 & 1 \end{matrix} \quad (3)$$

(2) Calculation of Comprehensive Weights of Scheme Indicators

Calculate the total weight R_{Di} of the four options based on the formula, and the specific calculation method is as follows:

$$R_{Di} = \sum_{i=1}^{12} w_i r_{ij} = R_{ci}^T \cdot w_{CD} \quad (4)$$

Among them, W_{CD} represents the relative weight matrix of the corresponding schemes for each secondary indicator obtained, with specific values as follows:

R_{ci}^T = (0.017 0.051 0.018 0.142 0.072 0.036 0.016 0.036 0.083 0.062 0.142 0.325)

$$w_{CD} = \begin{bmatrix} 0.317 & 0.489 & 0.250 & 0.269 & 0.120 & 0.136 & 0.529 & 0.520 & 0.571 & 0.269 & 0.552 & 0.310 \\ 0.156 & 0.137 & 0.250 & 0.058 & 0.058 & 0.253 & 0.068 & 0.078 & 0.143 & 0.190 & 0.127 & 0.310 \\ 0.058 & 0.070 & 0.250 & 0.553 & 0.269 & 0.075 & 0.134 & 0.201 & 0.143 & 0.420 & 0.236 & 0.310 \\ 0.469 & 0.304 & 0.250 & 0.120 & 0.553 & 0.536 & 0.269 & 0.201 & 0.143 & 0.121 & 0.085 & 0.070 \end{bmatrix} \quad (5)$$

After calculation, R_{di}=(0.357 0.183 0.292 0.168)^T, it can be concluded that the importance ranking of the four schemes is D1>D3>D2>D4.

5.2.4 Calculation of scheme importance

By using the AHP analysis method to quantitatively analyze the importance, comprehensive engineering cost, road performance of waterproof materials, on-site construction, and long-term performance of the bridge deck pavement waterproofing system scheme, the first scheme is obtained: hot SBS modified asphalt&0.5% single particle pre mixed crushed stone+2cm asphalt

sand+modified emulsified asphalt, which is the optimal scheme. This scheme can be used to quantify qualitative indicators under the influence of multiple factors, providing reference value for the selection and evaluation of relevant schemes.

6. Conclusion

(1) The requirements for an ideal waterproof layer can be simply summarized as being impermeable after construction and within the design period, and being economical and long-lasting throughout the entire life cycle.

(2) In short, it should have the following requirements: efficient water tightness, good bonding performance, poor temperature sensitivity, strong resistance to bridge deck deformation, good integrity after construction, strong adaptability to bridge type and deck, good durability, simple and fast construction process, and good construction coordination. In addition to these technical indicators, the economic factor of reasonable price is also an important advantage in promoting waterproof materials.

(3) By using the AHP analysis method to achieve the importance of the waterproof system scheme for bridge deck pavement under the influence of multiple factors, taking into account various factors such as engineering cost, road performance of waterproof materials, on-site construction, and long-term performance, it is concluded that the optimal scheme is hot SBS modified asphalt&0.5% single particle pre mixed crushed stone+2cm asphalt sand+modified emulsified asphalt.

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