Design and Construction of Protective Coating for Qiongle Concrete Expressway Bridges in Hainan Province

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Abstract. Through analysing the characteristics of the corrosion environment where Qiongle concrete expressway bridges work, and its influence on the durability of the concrete structure, this paper made a comparison among common coating systems, and put forward a reasonable coating design scheme as well as the corresponding technical requirements. Focused on the problems encountered in the trial tests, solutions were proposed to ensure the coating quality, which enabled it to play a long-term and effective role in protecting the concrete structure under corrosive environment, avoiding or procrastinating the occurrence of durability disease, and ultimately improving the safety and durability of the concrete structure.

1. Introduction
Expressway from Qiongzhong to Ledong in Hainan province (abbreviated as Qiongle expressway) is composed of the main line and Wuzhishan connections. The main line starts from Hainan Midline Expressway (Tunchang to Qiongzhong part of), winds through Maoyang, Wanchong, Baoyou, Qianjia to the east of Liguo Town in Ledong, and finally connects with the west part of Hainan Ring Expressway. Qiongle expressway is about 128.8 kilometres and adopts four-lane-wide expressway construction standard.

Adhering to the design concept of ecological line selection, environmental protection and investment saving, this project aims to make Qiongle expressway an integration of tourism road, landscape road, and ecological road through flexibly adjusting the measures to local conditions. In order to highlight the eco-friendly characteristics of the project and make the main line harmonize with the surrounding landscape, protective coating is applied to the expressway bridges, which is expected to improve the appearance as well as the safety and durability of the concrete structure.

2. Concrete bridge’s corrosive environment and durability disease

2.1. Characteristics of corrosive environment
The project is in a tropical maritime monsoon climate with perennial average temperature about 25°C and annual rainfall about 1000 to 1800 mm. Generally, precipitation is lower than evaporation. The rainy season is from May to October, the precipitation of which accounts for more than 80% of the whole year. The typhoon season starts from July to September, during which the average wind force is...
9-10 degrees, while gusts can be 11-12 degrees. The coastal wind is slightly stronger than the mountain wind. Typhoons are often accompanied by heavy rain or rainstorm.

According to the above environmental characteristics, the corrosion environment type of the project is determined as strong corrosion (iii-2) according to “Specification of Anti-corrosive Coating for Concrete Bridge Structure” (JT/t695-2007) [1].

2.2. Analysis of concrete structure’s durability disease

The impact of local climate characteristics on the concrete structure’s durability is listed as follows:

1. The relative air humidity (RH) is high. The annual average RH is 85%, and in some areas, the RH in summer is even higher than 95%. Water vapor is the carrier of quite a few corrosive media in the environment. Higher RH leads to the generation and accelerates the deterioration of the bridge’s durability disease.

2. The chlorine ion content in the atmosphere is high. Chloride ion’s invasion into the concrete interior can easily cause the steel bars to rust. As the rust expansion develops to a certain extent, the concrete will crack consequently, which provides the outside erosion media with an entrance into the structure. As a result, the durability disease will be further deteriorated, thus the safety of the concrete structure will be seriously threatened.

3. A moist environment is prone to breeding mildew. Moist in the air provides conditions for the growth of mildew, making the concrete structure’s bare surface be easily covered by mildew, which is out of harmony with the beautiful scenery.

3. Coating scheme design

3.1. Design life of protective coating

After Qiongle expressway is opened to traffic, the traffic volume is very large. Once the bridge structure is damaged, it will be difficult to repair and maintain it. Therefore, the coating system is designed as long-lasting type (H) according to “Specification of Anti-corrosive Coating for Concrete Bridge Structure” (JT/t695-2007) [1], with the design life of 20 years.

3.2. Coating parts

In this project, protective coating was applied to the bridges along the main line and all the interchanges of Qiongle expressway. For the superstructure, the coating covers both the inside and outside of guardrails, and the outside of beam body; while for the substructure, the coating parts include cover beams, piers, the outside of abutments above the ground, as well as the outside of cushion stones and anti-collision blocks.

![Figure 1. Schematic diagram of the bridge coating.](image)

3.3. Coating system design

3.3.1. Coating types. Proposing a reasonable coating design system for this project requires a better understanding of the coating types and the corresponding technical properties. A detailed investigation was conducted on the existing coating materials in the market, as shown in Table 1.
Table 1. Properties of the existing coating types.

| Type                                      | Water resistance | Acid resistance | Anti-aging time | Adhesion force | 28d carbonation depth | Environment al performance | Construction technology and application property |
|-------------------------------------------|------------------|-----------------|-----------------|----------------|------------------------|---------------------------|--------------------------------------------------|
| Common paint                              | Poor             | Poor            | Poor            | Poor           | /                      | Not Environmental -friendly; High VOC content     | Brush construction is simple                      |
| Environmental waterborne coating         | 240h: no change  | 240h: no change | 1000 h          | ≤ Level 1      | 0 mm                  | Environmental -friendly   | Spray, roller, brush construction is simple        |
| Acrylate coating                          | 168h: no change  | 168h: no change | 1000 h          | ≤ Level 1      | /                      | Environmental -friendly   | Thermostetting acrylate coating needs a bicomponent mixture before spray, roller, brush construction |
| Polyurethane coating                      | 168h: no change  | 48h 10% H₂SO₄: no obvious change | 1000 h          | ≤ Level 2      | /                      | Not Environmental -friendly; Above average VOC content | Thinner is necessary during spray, roller, brush construction |
| Epoxy coating                             | 168h: no change  | 48h 10% H₂SO₄: no obvious change | 800h            | ≤ Level 1      | /                      | Solvent type; Not Environmental -friendly         | Special thinner is necessary during brush or spray construction |
| Modified organosilicon resin coating      | 168h: no change  | 168h 10% H₂SO₄: no change | 1000 h          | ≤ Level 2      | /                      | Not Environmental -friendly                          | High temperature curing or curing agent is necessary during spray, roller, brush construction |
| Fluoropolymer coating                     | 168h: no change  | 168h 10% H₂SO₄: no change | 1000 h          | ≤ Level 1      | /                      | Low VOC content                                     | Bicomponent mixture, curing and dilution are necessary before spray, roller, brush construction |
| Cement-based polymer composite            | 168h: no change  | 168h 10% H₂SO₄: no change | /               | ≤ Level 1      | /                      | Inorganic environmental - friendly material        | Roller, brush construction is simple               |
After taking overall consideration of the properties of each coating type, the merits and demerits of the existing coating material types are summarized in Table 2.

| Type                        | Merits                                      | Demerits                                           |
|-----------------------------|---------------------------------------------|----------------------------------------------------|
| Ordinary paint              | • Cheapest                                  | • Easy to effloresce and fade                      |
|                             | • Easy to effloresce and fade               | • Not environmental-friendly                       |
| Environmental waterborne coating | • Environmental-friendliness                 | • Exclusive for concrete structure surface         |
|                             | • Weather resistance                        |                                                   |
|                             | • Good protective effect                     |                                                   |
|                             | • Color mixture ability                      |                                                   |
| Acrylate coating            | • UV radiation resistance                   | • Become brittle in low temperature               |
|                             | • Strong adhesion                           | • Become sticky in high temperature               |
|                             | • High gloss                                | • Poor stain resistance                           |
|                             | • Abrasion resistance                       |                                                   |
|                             | • Ability to work at low temperature (-5℃)  |                                                   |
| Polyurethane coating        | Aliphatic polyurethane coating:             | Aromatic polyurethane coating:                    |
|                             | • Excellent gloss retention                 | • Easy to fade, powder, yellow                     |
|                             | • Excellent color retention                 | • Poor aging resistance                           |
|                             | • Weather resistance                        | • Poor water resistance                           |
|                             | • Low-temperature flexibility               |                                                   |
|                             | • Excellent adhesion                        | • Poor UV aging resistance                        |
|                             | • Chemical corrosion resistance (especially alkali and salt resistance) | • Easily degradable                             |
|                             | • High material strength                    | • Easily fracture                                 |
|                             | • Weather resistance                        | • Easily tarnish                                  |
|                             | • Heat resistance                           | • High requirements for construction technology   |
|                             | • Hydrophobicity                            | • Poor low-temperature curability                 |
|                             | • Chemical corrosion resistance             |                                                   |
| Modified organosilicon resin coating | • Low adhesion                              |                                                   |
|                             | • Poor resistance to organic solvents       |                                                   |
|                             | • Complex construction technology           |                                                   |
|                             | • Poor color mixture ability                |                                                   |
| Fluoropolymer coating       | • Weather resistance                        | • Bicomponent                                     |
|                             | • Corrosion resistance                      | • Be deployed right before usage                  |
|                             | • Easily adhering to a variety of substrate surface | • Contain flammable substances                    |
|                             | • Maintenance-free                          |                                                   |
|                             | • Self-cleaning                             |                                                   |
| Cement-based polymer composite | • Easy construction                         | • Poor weather resistance                         |
|                             | • Poor color mixture ability                | • Poor color mixture ability                      |
|                             | • Short service life                        |                                                   |
According to the comparative analysis of the material properties in Table 1 and Table 2, despite cheapness, ordinary paint is not environmental-friendly at all, and will suffer serious pulverization and color fading after sun exposure. For cement-based polymer composite, its poor weather resistance, short service life and poor color mixture ability also make it evidently inferior to other materials. Therefore, ordinary paint and cement-based polymer composite were not considered as candidate coating materials in this project.

Acrylate coating becomes sticky at high temperature and brittle at low temperature, but it has excellent anti-aging performance; while polyurethane coating has excellent low-temperature flexibility. In practical projects, crosslinking modified acrylate-polyurethane is often used as the finishing coat in a coating system. Epoxy, which has poor aging resistance but excellent adhesion, is often utilized as the intermediate or priming coat in a coating system.

Therefore, the subsequent comparative analysis was conducted on the coating systems consisting of either two or three of environmental waterborne coating, epoxy coating, acrylate-polyurethane coating and fluorocarbon coating.

3.3.2. Comparison analysis of the coating systems. The analysis results of the coating systems which consist of either two or three of environmental waterborne coating, epoxy coating, acrylate-polyurethane coating and fluorocarbon coating are listed in Table 3.

| Scheme | Components of the coating system | Merits | Demerits |
|--------|---------------------------------|--------|----------|
| I      | •Prime coat: waterborne acrylate penetration primer  
        •Finishing coat: waterborne acrylate protective finish | •Waterborne materials, environmental-friendly  
        •Single component, easy construction, high efficiency  
        •Rich colors, landscape improvement  
        •Fairly good protection performance  
        •Reasonable price, economical efficiency | •The paint film is matte, with relatively low gloss (not reflective, conducive to driving safety) |
| II     | •Prime coat: epoxy closed primer  
        •Intermediate coat: epoxy  
        •Finishing coat: acrylate-polyurethane | •High gloss  
        •Fairly good protection performance | •Not environmental-friendly  
        •Bicomponent; complex construction  
        •Oil paint; poor compatibility with concrete interface  
        •Epoxy primer is easy to age; if the finishing coat is damaged, the coating system is easy to peel off  
        •Relatively high price |
| III    | •Prime coat: epoxy closed primer  
        •Intermediate coat: epoxy  
        •Finishing coat: fluorocarbon | •High gloss  
        •Fairly good protection performance | •Not environmental-friendly  
        •Bicomponent; complex construction  
        •Oil paint; poor compatibility with concrete interface  
        •Epoxy primer is easy to age; if the finishing coat is damaged, the coating system is easy to peel off  
        •High price |

Since this project mainly focused on landscape protection and improvement, it can be seen from Table 3 that Scheme I is the most appropriate considering environmental protection, construction
difficulty and economic efficiency. The components of Scheme I coating system are shown in Table 4, and the schematic diagram is illustrated in Figure 2.

| Coating      | Material type                  | Coat number/Minimum thickness of dry film (μm) |
|--------------|--------------------------------|-----------------------------------------------|
| Prime coat   | Waterborne acrylate penetration primer | 1/≤10                                         |
| Finishing    | Waterborne acrylate protective finish | 1/≥40                                         |
| coat         | Waterborne acrylate protective finish | 1/≥40                                         |

Total thickness of dry film (μm) ≥80

**Table 4.** Components of the selected coating system.

**Figure 2.** Schematic diagram of the coating system components.

### 3.4. Technical requirements

The project adopted the waterborne acrylate protective coating system, which was composed of penetration primer and protective finish. The technical performance of all the coating materials should meet the requirements in the related standards such as “Specification of Anti-corrosive Coating for Concrete Bridge Structure” (JT/t695-2007). Furthermore, the environment where the coating system works is easy to breed mildew due to its high humidity and high temperature. Therefore, wet and heat resistance are also necessary for the coating system [3]. See Table 5 for specific technical requirements and test methods.
### Table 5. Specific technical requirements and test methods of the coating system.

| No | Property                  | Technical requirement                                                                 | Test method                  |
|----|---------------------------|---------------------------------------------------------------------------------------|------------------------------|
| 1  | Condition in container    | • No caking after stirring                                                            | Visual inspection            |
|    |                           | • Presenting uniform state                                                            |                              |
| 2  | Fineness                  | ≤80μm                                                                                 | GB/T 1724-197                |
| 3  | Paint film appearance     | • Presenting uniform state                                                            | Visual inspection            |
|    |                           | • No sagging, floating, pinholes, cracking and other phenomena                        |                              |
| 4  | Drying time (surface)     | ≤2h                                                                                   | GB/T 1728-1979               |
| 5  | Water resistance          | • After 240h film test, no bubbling, peeling and pulverization;                       | GB/T 1733-1993               |
|    |                           | • 2-grade discoloration and loss of gloss is allowed                                   |                              |
| 6  | Alkali resistance         | After 720h film test, no bubbling, cracking and pulverization                         | JT/T 695-2007                |
| 7  | Acid resistance           | • After 720h film test, no bubbling, cracking and pulverization;                      | GB/T 9274-1988               |
|    |                           | • 2-grade discoloration and loss of gloss is allowed                                   | Use H₂SO₄ solution with pH of 2-3|
| 8  | Adhesion                  | ≥1.5MPa                                                                                | JT/T 695-2007                |
| 9  | Environmental friendliness| VOC content ≤120g/L                                                                    | GB 24408-2009                |
| 10 | Mildew resistance         | Grade 0                                                                                | GB/T 1741-2007               |
| 11 | Humidity and heat resistance| After 720h film test, no bubbling, cracking and peeling                              | GB/T 1740-2007               |

4. Coating construction requirements

4.1. Construction process

![Figure 3. Construction process.](image)

4.2. Coating requirements

4.2.1. Requirements for base treatment. Interarea treatment is essential after acceptance and interarea inspection of the concrete structure. The concrete interarea is required to be hard, compact, smooth and clean. Sags, crests and faulting slab can be polished by angle grinders. Dust, laitance and smears can be washed by high-pressure water guns and polished using wire brushed or angle grinders. The hollowing and peeling parts should be chipped away and repaired with patching materials. Larger defects need to be mended with materials like polymer mortar, while uneven places like honeycombed spots and pitting surface can be leveled with putty.

4.2.2. Environmental requirements for coating. Appropriate construction temperature is 5°C-35°C, while RH should be less than 85%. Construction is forbidden under adverse weather conditions, such as strong wind, heavy rain and large dusts, which requires paying continuous attention to weather forecast for information collection before construction. The coating should avoid getting wet, soaking
water, contacting with other corrosive media or being scratched by heavy objects during hard drying time.

4.2.3. Process requirements for coating
(1) The viscosity of the penetration primer should be suitable to ensure permeability. Uniformity and full coverage should be guaranteed during the coating process. Difficult parts like nooks and flanches can be completed by brush coating.
(2) In order to ensure the colour consistency, moist bonding should be applied to the working plane’s joints during the spray coating of protective finish, and coatings with the same batch number should be utilized for the working plane of a single colour. Flatness and smoothness are strictly required after coating process, with no defects like holidays, cracking and bubbling.
(3) When the coating is damaged by external forces and needs to be repaired, it should be assured that the repaired parts are dry and clean. Furthermore, the repaired surfaces should be treated by grinding to ensure the firmness and reliability of the interarea.
(4) Coating interval:
During the coating process, the next construction can not start until the coating of the previous construction becomes dry. At the temperature of 30℃, the construction interval should be larger than 30min and less than 48h.
(5) Coating maintenance:
When the operation is completed, the coating still cannot be put into use until specified maintenance time later. During hard drying time, the coating should avoid getting wet or directly contacting with other corrosive media.
(6) Other cautions:
- It is recommended to test coating and verify the construction process before formal construction.
- In order to ensure the coating quality, interval time of each coating process should not be too long.

4.3. Problems and solutions during construction
Before the formal coating construction, the bridges were divided by coating parts. A 20m² working plane was selected as the trial area for each part to evaluate the feasibility of construction process, determine the related construction parameters, anticipate the consumption of coating materials, etc. Focused on the problems found during the trial process, the causations were summarized and analysed, based on which countermeasures were proposed to ensure the coating quality.

4.3.1. Interarea hollowing and cracking. Hollowing and cracking appeared on some parts, which had a negative influence on the protective and decorative effects (as shown in Figure 4 and Figure 5). Through site investigation and disease analysis, the main reasons are summarized as follows: (1) the putty thickness of single construction was too large, which was more than 2mm in the hollowing parts. The drying rate difference between the interior and exterior (drying rate of the interior is lower than that of the exterior) resulted in the cracking; (2) the moisture content of the interarea was high. After the coating was completed, the water vapor began to volatilize outwards, causing the putty to hollow; and (3) large amount of dust was found on the hollowing part after the putty was removed, which was likely to reduce the putty’s adhesion and thus lead to hollowing and cracking.
4.3.2. Coating sagging and floating. Curtain-like and stripe-like sages could be seen on coating parts like piers, while some construction parts appeared floating phenomenon (as shown in Figure 6 and Figure 7). Problems of sagging and floating are mainly related to the viscosity of coating materials, the tools used during construction and the thickness of single construction. Sagging and floating easily occur as a result of low viscosity, large thickness and Low viscosity and large thickness of the coating make sagging and floating occur easily under the action of gravity.

Therefore, workers with coating construction experience should be employed. Training and trial coating are necessary before formal construction. In order to solve the sagging and floating of film, the viscosity of coating materials, the pressure and speed of the spray gun need to be carefully adjusted to the coating parts and methods.

5. Conclusion
(1) Through analysing the working environment of Qiongle expressway bridges and its impact on the durability of concrete bridge structure, the coating requirements are made clear.

(2) Through the comparative analysis of the technical properties of the existing coating material types, combined with this project’s requirements for environmental protection and ecological
landscape, waterborne acrylate coating system is recommended as the best coating scheme, and the corresponding technical requirements are put forward.

(3) According to the problems existing in the process of trial coating, solutions are proposed to ensure coating construction quality of bridge coating, which enables the coating to play a long-term and effective role in decorating and protecting the concrete structure under corrosive environment.

References
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