Study on mechanical properties of typical steel bridge deck pavement waterproof bonding system

Licheng Guo¹, Guodong Zeng² *

¹Foshan Highway & Bridge Construction Co. Ltd, Foshan 528313, China
²Foshan Transportation Science and Technology Co. Ltd, Foshan 528041, China

* Corresponding author email: lic@whut.edu.cn

Abstract. MMA and epoxy resin waterproof bonding system are widely used in steel bridge deck pavement at present. Based on the qualification test of raw materials, the quality control research under the influence of multiple factors such as drawing rate, roughness, thickness, temperature and humidity was carried out through pull-out and shear tests. The research showed that: (1) the drawing rate of steel plate + primer + waterproof layer + adhesive layer and epoxy resin should be 10mm/min and 50 mm/min, respectively. (2) the steel plates should be sandblasted to a roughness of level III. The thickness of primer, MMA waterproof layer and adhesive layer should be 60 μm, 2.5mm and 80 μm respectively. The thickness of epoxy resin adhesive layer should be 0.05mm. (3) The construction quality of waterproof bond system was greatly affected by temperature and humidity. The construction temperature should be 25℃, and the relative humidity should not exceed 60%. The research results can provide reference for the selection and quality control of the waterproof bonding system of steel bridge deck.

Keywords: Bridge engineering; steel deck pavement; waterproof adhesive system; quality control; pull-out test; Shear test.

1. Introduction

Steel bridge deck paving is an important part of steel structure bridge engineering, and the waterproof bonding system plays an important role in the life cycle of steel bridge decks, which is required to have good waterproof and adhesive properties in steel bridge deck paving projects. Due to ignoring the performance of the waterproof bonding system, early diseases such as rolling, crowding and pits frequently cur in the engineering cases of steel bridge decks [1].

Many researches have been carried out on the performance of waterproof bonding materials at home and abroad. Zhang et al. [2] selected four kinds of waterproof materials: solvent-based adhesive, epoxy resin, Eliminator waterproof membrane, and epoxy asphalt adhesive to conduct a comparative test study. According to the results, Eliminator waterproof membrane has the best performance. Li et al. [3] conducted mechanical performance tests on high temperature resistant epoxy resin adhesives, which showed that it has good performance on high temperature shear resistance, pullout strength and toughness. Li et al. [4] studied the influence of factors such as steel plate surface cleanliness, roughness, coating amount and curing time on the bonding strength of polymer waterproof adhesive layers. Zhao[5] compared the structural strength and road performance of methyl methacrylate resin (MMA) waterproof
adhesive material and Eliminator waterproof material, the results showed that MMA is better than Eliminator, and is suitable for poured asphaltic concrete pavement structures. Li et al. [6] analyzed the application of MMA waterproof bonding material in poured asphaltic concrete bridge deck pavement, and proved that the waterproof bonding system composed of primer, MMA and adhesive layer has good mechanical properties.

In summary, epoxy asphalt concrete and poured asphaltic concrete are the typical steel bridge deck paving materials in recent years, while epoxy resin and MMA are the corresponding waterproof bonding systems. Though a lot of researches have been reported, studies concerning the comprehensive mechanical performance evaluation of them are rarely involved.

In this work, the two most commonly used waterproof bonding systems are comprehensively compared and analyzed through pull-out and shear tests. The influence of five factors has been taken into consideration, those are loading rate, roughness, thickness, temperature and humidity. By comparing the mechanical properties, the strength and pavement performance of two different types of waterproof bonding system are fully clarified, which provides significant reference information for the selection and quality control of waterproof bonding system.

2. Materials

2.1. MMA waterproof bonding system
The MMA waterproof bonding system of steel bridge deck is composed of primer, waterproof layer and adhesive layer. In this work, the primer was epoxy zinc rich paint Zed S94, a single-component zinc phosphate primer. It could be naturally cured in the air, and was required to be used within 3 hours after the steel plate had been sandblasted. The waterproof material was a kind of two-component acrylic resin (MMA), that could be directly sprayed on the primer layer, and form a tough and flexible seamless protective layer by reacting with curing agent. The adhesive layer material was a solvent-based coating product Tack Coat No.2 adhesive. It could be directly cold sprayed or applied to the MMA using a roller. After curing, a closed system was formed, and tightly bonded with the subsequently thermal constructed poured asphaltic concrete.

The properties of primer, waterproof layer and adhesive layer were characterized refer to the Building waterproof coating test method (GB/T 16777-2008) [7], and relevant results are shown in Table 1. According to the results, the raw materials met the requirements of various technical indexes in the Technical Guide for Design and Construction of Highway Steel Box Girder Bridge Deck Pavement [8].
Table 1. Technical requirements of waterproof adhesive system

| Properties                                      | Technical requirements | Test results | Test method          |
|-------------------------------------------------|------------------------|--------------|----------------------|
| Primer (Epoxy zinc rich paint, Zed S94)         |                        |              |                      |
| Construction temperature/℃                      | -10~40                 | -            |                      |
| Film appearance                                 | Uniform color          | Qualified    | Visual observations  |
| Surface drying time (23 ℃)/min                  | ≤ 15                   | 12           | GB/T16777-2008       |
| Bond strength with steel plate (23 ℃)/MPa       | ≥ 5.0                  | 9.32         | Appendix C           |
| Waterproof layer (Methacrylate resin, MMA)      |                        |              |                      |
| Tensile strength/ MPa                          | ≥ 10                   | 10.34        | GB/T16777-2008       |
| Elongation at break/ %                          | ≥ 100                  | 140.12       | GB/T16777-2008       |
| Shore hardness D                                | 50~70                  | 56           | GB/T2411-2008        |
| Bond strength with steel plate coated by primer (23 ℃)/MPa | ≥ 2.0                  | 4.39         | Appendix C           |
| Bond strength with adhesive layer (23 ℃)/MPa    | ≥ 0.9                  | 2.7          | Appendix C           |
| Low temperature flexibility                     | No crack               | No crack or fracture on the surface of specimen | GB/T16777-2008 |
| adhesive layer (Tack Coat No.2)                 |                        |              |                      |
| Viscosity (23 ℃)/s                             | ≤ 40                   | 32.0         | JTG E20-2011         |
| Solid content (%)                               | ≥ 40                   | 53.0         | JC/T975-2005         |
| Surface drying time (23 ℃)/h                    | ≤ 4.0                  | 1.6          | GB/T16777-2008       |
| Bond strength with substrate (25 ℃)/MPa         | ≥ 0.9                  | 2.6          | Appendix C           |
| Low temperature bending test (-10 ℃, 3mm)       | No cracks and spalling at bend | No cracks and spalling at bend | GB/T16777-2008 |

2.2. Epoxy resin waterproof bonding system

The main component of epoxy resin waterproof bonding system was KD epoxy waterproof adhesive layer, which composed of epoxy resin main agent and curing agent. As a thermosetting adhesive material, the KD epoxy waterproof adhesive layer obtained its initial strength as the mixing of main agent and curing agent. The above process was regarded as the first reaction stage, after which the adhesive layer was initially cured, and opened to transport vehicles for construction operation. In the second stage of reaction, the hot-mix epoxy asphalt mixture was spread on the adhesive layer, and the initially cured adhesive layer was softened rapidly and bonded with the hot-mix epoxy asphalt mixture of the pavement layer. Then, during the compaction process of the roller, the secondary solidification occurred and formed higher strength. Its technical indexes are shown in Table 2.

Table 2. Technical requirements of KD epoxy adhesive layer

| Properties                                | Technical requirements | Test results | Test method           |
|-------------------------------------------|------------------------|--------------|-----------------------|
| Mass ratio of A and B                     | 50/50                  | 50/50        | Weighing method       |
| Tensile strength (23 ℃, MPa)              | ≥3.0                   | 3.9          | GB/T2568-1995         |
| Elongation at break (23 ℃, %)             | ≥100                   | 128          | GB/T2568-1995         |
3. Method

Previous studies have demonstrated that the bonding performance and shear resistance of the waterproof adhesive layer material of bridge deck are the most critical issues, and commonly evaluated by shear and pull-out test. Considering the working environment, the influence factors such as loading rate, thickness, roughness, temperature and humidity were selected to analyze the bonding and shear properties of waterproof adhesive layer.

3.1. Samples

Since MMA waterproof bonding system was composed of primer, waterproof layer and adhesive layer, the sample was made layer by layer. For epoxy resin waterproof bonding system, the main component was KD epoxy waterproof adhesive layer, and the sample was made in a single layer.

3.1.1. Sample preparation and test methods of MMA waterproof bonding system

(1) Pull-out test

The dimension of the steel plate for pull-out test was 10cm×10cm×0.3cm, and its surface was cleaned and dedusted beforehand. Angle grinder was used to simulate the roughness of steel plate surface during construction, and the roughness of the steel plate after grinding was determined by test press-o-flim test sheet. According to the grinding results, the unpolished surface and surfaces with the roughness value of 20–38μm, 38–64μm and 64–115μm were denoted as level І, level ІІ, level ІІІ, and level ІV, respectively.

A primer was applied to the treated steel plate, silicon mold frames with different thicknesses were fixed around the steel plate after the primer was dried, then, the prepared waterproof layer was poured into the mold and scraped with a glass rod. After the waterproof layer was dry, silicon mold frames with different thicknesses were fixed around the steel plate as the same way and poured the prepared adhesive layer into the mold, the surface was smoothed with a glass rod and a fine brush afterwards.

After the sample was totally dried, glue the slider with acrylate, and perform a pull test on a universal testing machine after curing.

Shear test

According to the pull-out test sequence and the optimum proportion of materials of each structural layer, the "steel plate+ primer+ waterproof layer+ adhesive layer" specimen was made in advance, and iron plates were fixed around it to form a mold as shown in Figure 1(b). The poured asphaltic concrete was then irrigated into the preformed mold, and a "steel plate+ primer+ waterproof layer+ adhesive layer+ asphalt mixture" specimen was finally obtained after cooling and demoulding. The oblique shear test was performed on the universal testing machine after standard curing.
3.1.2. Sample preparation and test methods of epoxy resin waterproof bonding system

(1) Pull-out test

The steel plate for pull-out test of epoxy resin waterproof bonding system was treated the same way as that of MMA. The main agent and curing agent of the KD epoxy waterproof adhesive layer were cured in an oven at 60°C for 2 hours and mixed at a weight ratio of 1:1, then, applied to the mould that had been surface preprocessed.

After being placed at room temperature for 1 day, and curing in a oven at 60°C for 4 days, the sample was clamped in a tensile testing machine for pull-out test.

(2) Shear test

The main agent and curing agent of the KD epoxy waterproof adhesive layer were cured in an oven at 60°C for 2 hours and mixed at a weight ratio of 1:1, then, applied to the mould that had been surface preprocessed (as shown in Figure 2). The specimen used was No. 45 steel sheet that has a dimension of 100×25×1.6mm (length×width×thickness), and the length of the bonding region was 12.5±0.25mm. The thickness of the adhesive layer was 0.05mm, 0.2mm, 0.4mm, respectively, and was controlled by short iron wires the diameter of which was equal to the thickness. The direction of the iron wires was parallel to the direction of force to minimize the influence on the bonding region.

![Fig 2. Scheme of shear test](image)

The specimen was placed at room temperature for 1 day, and curing in a oven at 60°C for 4 days. The remaining glue flowing outside the glue seam of the sample was removed, and the length and width of the bonding region were measured with a caliper. The shear test was then carried out using a tensile testing machine and the distance from the clamping position to the edge of the bonding region was 50±1mm.

3.2. Experiment procedure

3.2.1. MMA waterproof bonding system

For scientific study of the quality control, the indoor tests of multilayer structural MMA waterproof bonding system were conducted according to the construction sequence from bottom to top and its combinations under the influence of multiple factors. For the pull-out test, the strength and failure area of three combinations at different tensile rates were compared to determine the best loading rate, that were steel plate+ primer, steel plate+ primer+ waterproof layer and steel plate+ primer+ waterproof layer+ adhesive layer marked as combination 1, 2, 3). On this basis, the strength and failure area of each combination with different roughness were analyzed to determine the best roughness of the steel plate. The strength and failure area with different thickness were also compared to determine the best thickness of each layer. The influence of temperatures and humidity were studied in detail in the same way. Finally, a comprehensive report about the influence of various factors on the mechanical properties of the MMA waterproof bonding system was obtained.

For the shear test, combination 3 was selected to investigate under different temperatures and humidity.
3.2.2. Epoxy resin waterproof bonding system

The epoxy resin waterproof system was single layer structure. For the pull-out test, the optimal tensile rate, roughness and thickness were successively determined, and then the strength at different temperature and humidity was compared to analyze the mechanical properties of epoxy resin waterproof bonding system under the influence of various factors.

For the shear test, the shear strength of the epoxy resin waterproof system under different temperatures and humidity was examined. Since the epoxy resin waterproof bonding system was brittle, the failure area ratio was commonly 100% and not necessary to further compare.

4. Results

4.1. Pull-out test results

4.1.1. Drawing rate

(1) MMA waterproof bonding system

According to the determined experiment procedure above, the experimental temperature and relative humidity were 25°C and 60% (hereinafter denoted as indoor standard test condition). The steel plate was ground to reach a roughness of level III, and coated with primer, waterproof layer and adhesive layer at thickness of 60μm, 2.5mm and 80μm correspondingly. Then, the strength and the proportion of the failure area were recorded and analyzed under the drawing rate of 10mm/min, 30mm/min and 50mm/min. Relatively data are listed in Table 3. The data in and outside parentheses were the proportion of the damaged area and the drawing strength separately.

| Drawing rate (mm/min) | 10  | 30  | 50  |
|-----------------------|-----|-----|-----|
| Combination 1 (MPa)   | 1.4(35%) | 1.8(45%) | 9.3(86%) |
| Combination 2 (MPa)   | 2.9(83%) | 1.6(64%) | 0.8(51%) |
| Combination 3 (MPa)   | 2.2(81%) | 1.5(62%) | 0.7(49%) |

The drawing rate had a great influence on the drawing strength. For combination 1, the higher the drawing rate, the greater the drawing strength. For combination 2 and 3, the drawing strength became smaller as the drawing rate increased. Therefore, different drawing rate should be used for different structural combinations.

At the drawing rate of 50mm/min, the proportion of failure area of combination 1 was 86%, which indicated that the corresponding drawing strength at a drawing rate of 50mm/min could effectively reflect the interlayer bonding strength of combination 1. The drawing rate of 50mm/min was the optimum rate. Similarly, the proportion of failure area for combinations 2 and 3 were over 80% at 10mm/min, thus the pull-out test rate should be carried out at 10mm/min.

(2) KD epoxy resin waterproof bonding system

On the basis of the previously identified experiment procedure, the steel plate was ground to reach a roughness of level III, and coated with KD epoxy resin to a thickness of 0.1mm under the indoor standard test conditions. The strength and the proportion of the failure area were recorded and analyzed under the drawing rate of 10mm/min, 30mm/min and 50mm/min. Relatively data are listed in Table 4.

| Drawing rate (mm/min) | 10  | 30  | 50  |
|-----------------------|-----|-----|-----|
| Drawing strength (MPa)| 11.4(42%) | 13.5(55%) | 15.1(88%) |

With the increase of the loading rate, the tensile strength and the proportion of failure area were both increased. When the drawing rate was 50mm/min, the proportion reached 88%.
It could be concluded that the drawing rate of 50mm/min was the optimum rate for the pull-out test and the data obtained at this condition could better reflect the truly strength of the waterproof adhesive layer.

4.1.2. Roughness of steel plates

Under the indoor standard test conditions, the steel plate was polished to different level of roughness, and then coated with primer and KD epoxy resin at thickness of 60μm and 0.1mm, respectively. The drawing test was carried out after curing at a drawing rate of 50 mm/min. The test results are demonstrated in table 5.

| Roughness level | I     | II    | III   | IV    |
|-----------------|-------|-------|-------|-------|
| drawing strength of MMA (MPa) | 1.6   | 6.5   | 8.8   | 9.0   |
| drawing strength of epoxy resin (MPa) | 9.6   | 12.5  | 15.1  | 16.4  |

It could be seen from Table 5 that the rougher the surface of the steel plate, the higher the drawing strength between the steel plate and the primer. When the roughness level exceeded level III, the increase rate of the drawing strength decreased. Considering the feasibility and economy of construction, the steel plate should be sandblasted and polished to the roughness level III in the steel bridge deck paving project.

4.1.3. Thickness

(1) MMA waterproof bonding system

After the drawing rate and roughness of steel plate was confirmed, the drawing strength of the bonding system at different primer thicknesses (60μm, 80μm, 100μm, 120μm), different waterproof layer thickness (0.5mm, 1.0mm, 1.5mm, 2.5mm, 3.5mm) and different adhesive layer thickness (60μm, 80μm, 100μm, 120μm) were studied. After curing for 12 hours under standard conditions, the pull-out test was carried out at a drawing rate of 10 mm/min. The results are shown in Table 6.

| Thickness of primer (μm) | 40   | 60   | 80   | 100  | 120  |
|--------------------------|------|------|------|------|------|
| drawing strength (MPa)   | 8.56 | 9.32 | 7.16 | 5.28 | 3.01 |
| Thickness of waterproof layer (mm) | 0.5  | 1.0  | 1.5  | 2.5  | 3.5  |
| drawing strength (MPa)   | 2.01 | 2.47 | 2.95 | 4.39 | 2.88 |
| Thickness of adhesive layer (μm) | 40   | 60   | 80   | 100  | 120  |
| drawing strength (MPa)   | 1.06 | 1.39 | 1.76 | 1.55 | 1.31 |

The optimal thickness of the primer, waterproof layer, and adhesive layer for the MMA waterproof adhesive system were 60 μm, 2.5 mm, and 80 μm, respectively.

(2) KD epoxy waterproof bonding system

As the reasonable drawing rate and roughness level were selected as 50mm/min and level III, KD epoxy resins with thicknesses of 0.05mm, 0.2mm, and 0.4mm were coated on the steel plate, and the drawing test was carried out after curing. The results are shown in Table 7.

| Thickness of waterproof layer (mm) | 0.05 | 0.2  | 0.4  |
|-----------------------------------|------|------|------|
| drawing strength (MPa)            | 16.1 | 12.3 | 9.9  |
As the thickness of the waterproof layer increased, the drawing strength of the specimen continued to decrease according to Table 7, and reached the maximum when the thickness was 0.05mm. Comparing the results of MMA and epoxy waterproof bonding system, it could be seen that the thinner the thickness of epoxy resin, the higher its strength, while MMA had a suitable thickness. The thickness corresponding to the maximum strength of MMA was greater than epoxy resin.

4.1.4. Temperature
After determining the drawing rate, the thickness of each layer, and the roughness of the steel plate, the experimental conditions for the MMA waterproof bonding system were 60μm for the thickness of the primer, 2.5mm for the thickness of the waterproof layer, and 80μm for the thickness of the bonding layer. The drawing rate of combination 1 was 50mm/min while that of combinations 2 and 3 was 10mm/min. For epoxy resin waterproof bonding system, the thickness was 0.05mm, and the drawing rate was 50mm/min. Conducting the pull-out tests at 25°C, 40°C, 60°C, and 80 °C, and the results are exhibited in Table 8.

| Classification                     | Temperature (℃) | 25  | 40  | 60  | 80  |
|------------------------------------|-----------------|-----|-----|-----|-----|
| MMA waterproof bonding system      | Combination 1   | 9.3 | 7.0 | 5.5 | 4.8 |
|                                    | Combination 2   | 3.2 | 2.4 | 1.9 | 1.4 |
|                                    | Combination 3   | 2.9 | 2.3 | 1.8 | 1.4 |
| Epoxy waterproof bonding system    |                 | 15.1| 9.8 | 2.2 | 1.8 |

The drawing strength of both MMA and epoxy waterproof bonding systems were decreased greatly as the temperature increased. Comparing the corresponding strength at different temperatures of MMA waterproof bonding system (combination 3) and epoxy resin waterproof bonding system, the latter was greater than the former, while the latter was more susceptible to temperature.

4.1.5. Humidity
From the above experimental results, the experimental conditions of MMA waterproof bonding system were 60μm for the thickness of the primer, 2.5mm for the thickness of the waterproof layer, and 80μm for the thickness of the bonding layer. The experimental temperature was 25 ℃, and the drawing rate was 50 mm/min for combination 1, and 10 mm/min for combination 2 and 3. The experimental conditions of epoxy waterproof bonding system was 0.05mm for the thickness, 50mm/min for the drawing rate, and the temperature was 25 ℃. The formed specimens were divided into three groups, which were maintained in environments with relative humidity of 60%, 100% and immersed in water. After curing, the pull-out test was conducted. For the convenience of comparison, the specimens immersed in water was recorded as relative humidity of 120% and relevant results are shown in Table 9.

| Classification                  | Humidity (%) | 60  | 100 | 120 |
|---------------------------------|--------------|-----|-----|-----|
| MMA waterproof bonding system   | Combination 1| 9.3 | 1.5 | 0.3 |
|                                  | Combination 2| 3.3 | 2.5 | 2.0 |
|                                  | Combination 3| 3.0 | 2.1 | 1.6 |
| Epoxy waterproof bonding system |               | 15.1| 8.4 | 2.6 |

The drawing strength of each specimen was decreased greatly as the humidity increased. Comparing the corresponding strength at different humidity of MMA waterproof bonding system (combination 3) and epoxy resin waterproof bonding system, the latter was greater than the former, but the latter decreased in a higher rate, indicating that it was more susceptible to humidity.
4.2. **Shear test results**

4.2.1. **Shear strength at different temperatures**

For MMA waterproof bonding system, the combination 3 was selected to explore the shear strength at different temperatures. The specimens of combination 3 and epoxy resin were cured at 25°C, 40°C, 60°C, and 80°C, and then subjected to shear test. The humidity was controlled at 60%, and the thickness of each layer was the optimal value. The results are shown in Table 10.

| Table 10. Shear strength at different temperatures |
|-----------------------------------------------|
| Temperature (℃) | 25  | 40  | 60  | 80  |
| MMA waterproof bonding system (Combination 3) | 3.04 | 1.67 | 0.75 | 0.20 |
| Epoxy waterproof bonding system                | 5.50 | 3.23 | 1.78 | 0.81 |

As the temperature increased, the shear strength of the two systems decreased significantly. The shear strength of combination 3 at different temperatures were lower than that of epoxy resin, but the latter decreased at a higher rate, indicating that it was more susceptible to temperature.

4.2.2. **Shear strength at different humidity**

The specimens of combination 3 and epoxy resin waterproof bonding system were maintained in environments with relative humidity of 60%, 100% and 120%, and then subjected to the shear test. The experimental temperature was 25°C, and the thickness of each layer was the optimal value. Relevant data are recorded in Table 11.

| Table 11. Shear strength at different temperatures |
|-----------------------------------------------|
| Humidity (%) | 60  | 100 | 120 |
| MMA waterproof bonding system (Combination 3) | 3.04 | 2.42 | 2.41 |
| Epoxy waterproof bonding system                | 5.50 | 4.10 | 3.55 |

The shear strength of the two systems decreased significantly as the increase of humidity. The shear strength of combination 3 at different humidity was lower than that of epoxy resin, but the latter decreased at a higher rate, indicating that it was more susceptible to humidity.

5. **Conclusion**

(1) For MMA waterproof bonding system, the drawing rate of pull-out test for steel plate+ primer, steel plate+ primer+ waterproof layer, and steel plate+ primer+ waterproof layer+ adhesive layer should be 50mm/min, 10mm/min, 10mm/min respectively. For the test of epoxy waterproof bonding system, the drawing rate should be 50mm/min.

(2) The steel plate should be sandblasted and polished to a roughness of level III. The optimal thickness of the primer, waterproof layer and adhesive layer was 60μm, 2.5mm, and 80μm respectively. The thickness of the epoxy resin adhesive layer should be 0.05mm.

(3) The construction quality of the waterproof bonding system was significantly affected by temperature and humidity. For better quality, the construction should be carried out at 25°C with a relative humidity of no more than 60%.

(4) Compared with MMA, epoxy resin bonding system had higher strength, but was more brittle and more sensitive to temperature and humidity.
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