Assessment of Outdoor Exposure Effects on the Long-term Durability of Epoxy Resin Adhesives Used for Steel-plate Bonding

Daisuke Yamazaki¹*, Mitsuyasu Iwanami² and Masaaki Isa³

Received 27 January 2020, accepted 6 August 2020 doi:10.3151/jact.18.463

Abstract

The steel-plate bonding method used to reinforce concrete slabs in bridges has a long record of adoption, and has played an important role for many years. Favorable conditions have been observed with this method in periodic inspections; however, as part of durability tests, decreases in strength of the epoxy resin adhesive (which is one of its component materials) have been observed following over time outdoor exposure under standard environmental conditions. Investigations into the causes of decreased strength of epoxy resin adhesive are useful for increasing long-term durability in future infrastructure maintenance. The estimation of environmental factors that incorporate exposure conditions and the results of conducting accelerated tests revealed that the performance of epoxy resin adhesive was influenced by humidity. Additionally, decreases in strength accompanying reaction progress of epoxy resin were also observed. These results indicate that the degradation due to water absorption and the generation of internal stress due to the progress of the curing reaction of the epoxy resin are the causes of the decrease in the strength of the epoxy resin.

1. Introduction

Epoxy resin adhesive has been used since the 1960s as a material for concrete repair and reinforcement work in the civil engineering and architectural fields, owing to its superior mechanical characteristics and alkali resistance. In an early example, following the Showa Bridge collapse at the time of the Niigata Earthquake in 1964, the collapsed bridge span was salvaged, the cracks were repaired with epoxy resin, and the span was reused. Follow-up surveys have been conducted every 10 years, during which time the bridge has been shown to be structurally sound. The bridge is available for public use even today, and its structural soundness has been maintained (Yamazaki et al. 2015).

Among the repairing and reinforcing methods that use large quantities of epoxy resin adhesive, steel-plate bonding is a bridge slab reinforcing method that has used epoxy resin for the purpose of integrating the steel plates and the existing slab. Material tests, where adhesive test pieces used for construction are exposed outdoors, have been conducted by road administrator to assess the durability of epoxy resin adhesive. These tests have shown that the strength of the adhesive decreases over time (Fujita et al. 2012). However, steel-plate sections implemented in existing structures show favorable conditions, and no correlations between the exposed test pieces and the existing structure have been observed. The difference in the environmental conditions of the exposed test piece and the adhesive used in the existing structure was whether there was direct exposure to air. Given these different exposure conditions, sweeping generalizations on decreased strength in the exposed test piece reflecting adhesive characteristics in existing structures cannot be made. For these reasons, understanding the causes of decreased strength in exposed test pieces will be effective information for determining the durability of adhesives in actual use, and will be useful for ensuring the longevity of social infrastructure. Thus, the present study investigates the causes of decreased strength in exposed test pieces.

2. Test piece

The exposed test piece assessed in the present study is an epoxy resin adhesive used for the steel plate bonding method. Steel plates are attached to existing concrete with post-installed anchors, adhesive is injected in the space between the existing concrete and steel plates, and the structure is integrated. Because it is constructed via press fitting with pumps, the adhesive can be injected into cracks in the existing concrete, which can improve its durability. The adhesive is divided into a main agent and a curing agent, and these are mixed in specified
The main agent is composed of epoxy resin, reactive diluent and hydrocarbon plasticizer. The curing agent is composed of an amine-based curing agent such as polyaminoamide resin.

The test piece sampled in the present study, shown in Fig. 1, had been stored in an air-exposed state in an outdoor storage facility under an inner-city expressway bridge. UV rays do not hit the inside of the storage facility, and direct exposure to rainwater is reduced because there is a roof installed. Environmental measurements (illuminance, UV ray amount, temperature, and humidity) over the course of 1 month showed that there was no UV infiltration, and illuminance was equivalent to roughly that of night streetlight. Additionally, temperature and humidity were those of the average environment in the area at the same time of each year. Measurement results are shown in Fig. 2. When the storage facility was opened, the test pieces were covered in sediment despite the presence of the roof, perhaps due to slanting wind and rain, and evidence of partial immersion was observed. The storage conditions are shown in Figs. 3 and 4.

3. Changes in strength of the test piece over time

The exposed test pieces have been stored upon each construction work, and material tests have been conducted at the time of storage and every few years afterwards, with a total of approximately 30 years’ worth of accumulated data. Each test category, standard value, and test method is shown in Table 1. In this investigation, we used the same JIS standard as the test method used in the previous investigation. The test piece was shaped at the time of starting the storage, and was used for the test in its original shape. Additionally, each test has three specimens.
The results of the material tests on the exposed test piece are shown in Table 2, and its changes over time are shown in Fig. 6. The “Test piece number” shown in Table 2 is the year when that test piece was formed. Additionally, as multiple construction works are usually conducted in a single year, secondary numbers have been assigned in Table 2 to certain test pieces distinguish them from each other.

A surface and interfacial cutting analysis system (SAICAS) was used to analyze the changes in strength in the depth direction of the test piece cross-section in addition to the material tests conducted in the present investigation. The analysis results are shown in Fig. 7. SAICAS is a device that scratches a test piece surface with a blade and uses its resistance to assess the hardness of an object. The obtained results were converted into deemed shear strength and evaluated (Kishima and Nishiyama 2005).

As a result of the material test, there was no significant change in specific gravity. As for the compressive yield strength, the strength increased until about 5 years, and thereafter decreased gradually. The flexural strength and tensile strength showed a significant decrease. The flexural strength decreased by up to 44% compared to the initial stage. The tensile strength decreased to 38% of the initial. Tensile lap-shear strength showed a tendency to increase compared to the initial value, although the strength once decreased in the middle of the exposure duration.

The SAICAS analysis results in Fig. 7 show the results of cutting from the surface to a maximum of 3 mm with a 1 mm pitch on the test piece cross-section; the results reveal clear decreases in strength in the 1 mm-section on the surface.

Table 1 Test standards and test conditions*1.

| Category                | Test standard          | Standard value (MPa)*2 | Test-piece dimensions (mm) | Displacement velocity (mm/min) |
|------------------------|------------------------|------------------------|---------------------------|--------------------------------|
| Specific gravity       | JIS K 7112-1999        | 1.0 to 1.3             | 15 × 15 × 43              | 1 ± 0.5                        |
| Compressive strength   | JIS K 7181-1994        | 60                     | 15 × 15 × 43              |                                |
| Flexural strength      | JIS K 7171-2008        | 50                     | 160 × 8 × 15              |                                |
| Tensile strength       | JIS K 7113-1995        | 30                     | See Fig. 5                |                                |
| Shearing strength      | JIS K 6850-1999        | 10                     | See Fig. 5                |                                |

Note: *1: Based on the standard specification of the Hanshin Expressway Company Ltd. for civil engineering work.
*2: Quality standards set by the administrator.
*3: Only the specific gravity is dimensionless.

Table 2 Material test results.

| Elapsed exposure time | Test piece number |
|-----------------------|-------------------|
| 1985                  | 1985              |
| 1986                  | 1986              |
| 1987                  | 1987              |
| 1989                  | 1989              |
| 1990                  | 1990              |
| 1991                  | 1991              |
| 1992                  | 1992              |

Note: The shaded cells are categories where the values obtained were below the standard value.
4. Estimated causes of degradation

Factors considered as the cause of the decrease in the strength of the exposed test piece are environmental conditions and the composition change of the adhesive itself. The phenomena that could occur during long-term storage were estimated, and the cause of the strength decrease was verified.

4.1 Estimated causes of degradation due to external environmental factors

Heat, oxygen (ozone), water, ultraviolet light, chemicals, radiation, and microorganisms can be the causes of degradation of polymer materials (including epoxy resins) due to environmental conditions (Honma 2004). The influences of heat, UV rays, radiation, and microorganisms were excluded, considering the exposure conditions in the present investigation. In addition, the effects of acidic substances due to ozone and air pollutants were confirmed, and no decrease in strength was observed even when exposed to high concentrations of ozone. In addition, the penetration of sulfate ions (SO₄²⁻), which may be derived from air pollutants detected from the sediment on the surface of the test specimen, into the exposed test specimen was not confirmed, and no effect on the strength was observed. The effects of water are described here.

Water-based degradation is also well known, but its extent varies with the plastic type. The plastic softens with the initial stages of water absorption, which then undergoes hydrolysis over time and advances degradation. Alternatively, there are structural methods where adhesives are used in conjunction with spot welding in sections where spot welding cannot be conducted (weld bonding) to ensure the body stiffness and strength of automobiles, but degradation was confirmed in weld-bonded areas of old automobiles used for 7 years in regions of high temperature and humidity (Himuro et al. 2012). Given the storage conditions in the present investigation, it is thought that atmospheric moisture and stagnant rain water from storms may have influenced this degradation.

4.2 Decreases in strength during the epoxy resin curing process

The epoxy resin tested in the present investigation is a heat-cured resin that uses an amine-based curing agent, and curing is facilitated with the addition of heat. The characteristic stable mechanical properties of epoxy resin are due to its 3D mesh structure. The formation process of the 3D mesh structure is consistently observed as follows: (1) straight-chain elongation, (2) side-chain formation, and (3) mesh formation. However, in the case of amine-based curing agents, a majority of the structures are chain polymers such as (1) and (2) up to a reaction rate of around 80%, after which the mesh structure is rapidly formed (Shimbo 1987). Meanwhile, reports have suggested the occurrence of problems at
the time of mesh formation, such as contraction, possible cracking and peeling, void formation and internal stress generation (Shimbo 1987). Although their occurrence varies according to the curing agent type, the reaction rate does not always reach 100%, and reports have indicated a reaction rate of around 80% in cases where adhesives are used under standard environments where forced heat is not applied. This is said to be due to the occurrence of the glass-transition point as the reaction progresses, and the fact that the reaction stops at temperatures below the glass-transition point (Shimbo 1987). However, the results revealed that strength increased, and the reactions continued until around year 10 in the exposed test pieces. Increased reaction rates were thought to induce potentially problems associated with mesh formation (e.g., contraction).

5. Test methods

Assorted accelerated tests were conducted to estimate causes of degradation and investigate its occurrence potential. Ideally, the materials to be assessed would be the adhesives at the time of use. However, as some of the mixed materials have already been discontinued, the mixtures could not be reconstructed. For this reason, we selected epoxy resin adhesives among those available on the market that had the same intended purpose (and which used the same curing agent type) as the test pieces in this study.

5.1 Estimated causes of degradation due to external environmental factors

The exposed surface of the test piece is constantly exposed to the atmosphere and is affected by moisture. It is considered that absorption of water gradually depopulates the surface and further causes hydrolysis. In order to confirm the influence of deterioration of the surface part on the strength characteristics, the test piece was immersed in hot water at 90°C as an acceleration condition. The curing conditions are shown in Table 3. The standard conditions for quality control implementation of curing for 7 d at 20°C and 65% RH were implemented for the reference test piece. Additionally, considering the influence of material age at the time of warm water immersion, a test piece with curing conditions of 14 d at 20°C and 65% RH was created. To investigate the influence of heat addition when the test pieces are immersed in 90°C water, a test piece cured in 90°C air was created. To confirm the influence of drying on strength, three drying periods of 24, 48, and 96 h were implemented; furthermore, to investigate the influence of expansion and contraction during water absorption and drying periods, repeated water absorption-drying conditions were implemented. The flexural and tensile tests, which exhibited large decreases in exposed test piece strength, were implemented for the tests. Each test had three specimens.

5.2 Decreases in strength during the epoxy resin curing process

5.2.1 Influences of forced heating-based reaction rate

To elucidate the fracture morphology due to reaction rate differences, comparisons between test pieces cured at room temperature and those cured at high temperature were conducted. For the room temperature curing conditions, the test pieces were formed and cured at 20°C and 65% RH, after which compression, flexural, and tensile tests were conducted. For the high temperature curing conditions, using previous reports as a reference, the test piece was cured for 1 d at 20°C and 65% RH; then, it was cured at 80°C for 2 h, and finally cured at 180°C for 4 h (see 180°C Air, Table 4). The test piece was then set aside at 20°C and 65% RH for 24 h, after which the same tests were conducted. A total of three trials were conducted for each test.

5.2.2 Internal stress of exposed test piece

In order to measure the internal stress generated in the exposed specimen, the internal stress was measured by the drilling method specified in ASTM E837-13a (ASTM 2013). In the drilling method, a rosette strain gauge as shown in Fig. 8 is attached to a test specimen, and the strain released when a center part is drilled with a 2 mm diameter drill is measured and converted to stress.
The test conditions were: drill diameter: 2 mm, rotation speed: 200 rpm, drilling step: 0.05 mm × 20 = 1 mm. For the test piece, 1985-2, which was actually exposed was used and a 7-day-old adhesive (similar to that used in Section 5.1) was also used for comparison.

In addition, in order to investigate the relationship between the internal stress and the mechanical strength near the surface, measurements using SAICAS were made at a depth of 15 μm from the surface of the specimen.

6. Test results and discussion

6.1 Estimated causes of degradation due to external environmental factors

The changes in flexural and tensile strength over time when the test pieces were immersed in water are shown in Fig. 9. The blue and orange colors indicate strength and elasticity, respectively, of each test piece. Assessments are conventionally made on day 7 in material tests, so when the 20°C, 7 day curing condition (20°C 7 d) is used as the standard, the 14 d curing condition (20°C 14 d) increased the flexural and tensile strength. These results reveal that reactions are not completed on day 7 at 20°C.

Meanwhile, test pieces that were force-heated at 90°C (90°C Air) exhibited lower strengths than those cured for 14 d at 20°C. The reactions become more active with increased temperature because the reaction of epoxy resin curing is a chemical reaction. However, one cause of decreased strength despite high temperature curing may be the formation of internal stresses accompanying the curing contraction mentioned in Section 4.2. The strengths of the test pieces immersed in water (90°C Water) were approximately 80% of those of pieces cured in air at 90°C (90°C Air), and their tensile strengths were lower than those of pieces cured for 7 d. The extent of water absorption-based degradation was higher than the extent of strength increases. Breakage of the adhesive composition due to water absorption-based swelling and hydrolysis was thought to have occurred.

In the tensile tests, test pieces that were vacuum-dried for 96 h exhibited increases in their moduli of elasticity but decreases in their tensile strengths. It is thought that extreme drying removes the buffering actions of water and hardens the curing material; furthermore, increases in the modulus of elasticity allow for stress to be more easily concentrated in defect regions, resulting in failure due to bubbles within the test piece. In addition, the tensile strength of the wet and dry repeated test piece was slightly lower than that of the water-immersed test pieces (90°C Water). The water immersion time was the same, but the number of drying times was different. It was considered that the increase in the number of drying times reduced the degree of water saturation inside the test piece, leading to a slight decrease in strength.

The results of observing the surface of the specimen under a microscope (at 2500 magnification) are shown in Figs. 10, 11 and 12. Figure 10 is an image of the surface of the oldest exposed test piece showing fine cracks. It is considered that fine cracks occurred because the internal stress generated by the curing reaction acted on the deteriorated part of the surface over time.

Figures 11 and 12 are images near the fracture surface of the bending test piece after the accelerated test. By increasing the drying time, not only the fracture surface but also fine cracks can be seen at a position away from the fracture surface. As the drying progressed, the stress relaxation disappeared as the water evaporated, and local stress concentration occurred. As a result, the fine cracks occurred on the surface of the test piece as

![Fig. 8 Rosette strain gauge installation status.](image)

![Fig. 9 Influence of water immersion.](image)
well as the exposed test pieces. In the accelerated test specimen, no cracks were observed in the stress-free state, so the deterioration did not progress as much as in the oldest exposed test piece, but when stress occurred, fine cracks appeared on the surface. It is considered that the same phenomenon as that of the exposed test piece will occur if the deterioration of the sample progresses, and that the progress of deterioration could be reproduced. Although considerably higher temperatures relative to standard temperatures were used to accelerate the curing process, the significant influence of water was confirmed.

6.2 Factors relating to decreases in strength during the epoxy resin curing process

6.2.1 Influences of forced heating-based reaction rate

Figure 13 shows the results of the material test using forced heating. In both the flexural test and the tensile test, the strength of the heat-cured test specimen (180°C Air) was increased, and the strength was higher than that of the 7 days curing (20°C 7 d). However, compared to 14 days curing (20°C 14 d), it showed a decrease. The reaction rate increased by heat curing, but did not show the maximum value of strengths. It was confirmed that the strength decreased after reaching the maximum value due to reaction enhancement. It was suggested that the strength decreased due to the internal stress.

6.2.2 Internal stress of exposed test specimen

Figure 14 shows the results of the internal stress measurement of the exposed test piece 1985-2 by the drilling method. In addition, the results of 7-day old test specimens are also shown for comparison. The vertical axis shows the internal stress, and the horizontal axis shows the drilling depth.

The specimen of 1985-2 showed internal stress of about 6 MPa near the surface. On the other hand, in the 7-day-old specimen, internal stress of about 2 MPa was generated at 0.125 mm, but it was almost zero near the surface. This suggests that in the 1985-2 sample, the curing reaction was continued and the reaction rate increased. As a result, it is considered that internal stress was generated due to curing shrinkage. Figure 15 shows the results of SAICAS near the surface. The vertical axis shows the horizontal load during cutting, and the horizontal axis shows the cutting depth. A degraded layer was observed up to 4.35 μm from the surface.

Figure 16 shows the deemed shear strengths of test piece 1985-2(1). The deemed shear strength of only 4.35 μm from the surface was significantly lower than that of the inside, indicating that the degradation was progressing.
The paste 1985-2 showed the maximum tensile strength of 47 MPa, and it is considered that the internal stress of about 6 MPa does not cause a significant decrease in tensile strength. However, a degraded layer was confirmed on the surface, and it was considered that the surface layer was initially cracked by the internal stress and the acting force of the test. Therefore, it is considered that the strength was unexpectedly lowered by stress concentration on the defect. The same applies to the flexural test, and it is considered that the strength was reduced due to stress concentration at the deteriorated part near the surface on the tensile side. On the other hand, in the tensile lap-shear strength test, the specimens were made by overlapping the bonded parts with iron pieces. Therefore, the surface of the epoxy resin was not affected by water, causing slight deterioration due to water. Consequently, the tensile lap-shear strength did not decrease.

From the results of the exposure test pieces, it was found that the bending and tensile strengths were improved up to about 5 years. The curing reaction continued for a long time. Epoxy resin is said to form a three-dimensional network when the reaction rate reaches 80%, and it has been reported that internal stress increases with the formation of the three-dimensional network (Shimbo 1987). From this, the first about 5 years will be the period of increasing strength as the hardening reaction progresses and increasing internal stress as the three-dimensional network structure is formed. In this initial stage, the influence of surface deterioration is small and the strength increase with the continuation of the curing reaction is distinguished.

After that, it is considered that when the reaction stopped, the tensile strength and bending strength showed the maximum strength, and the internal stress was generated. From this point onward, the surface deterioration due to water absorption over time and the stress concentration due to drying cause the surface defects to decrease strength gradually.

7. Consideration on soundness of epoxy resin adhesive for steel plate bonding used for a long time in actual structures

Follow-up tests revealed that test pieces with outdoor exposure decreased in strength. Strength decreases were also observed in test pieces subjected to water immersion tests conducted to investigate degradation causes. In environments with seasonally high temperature and humidity such as Japan, it is thought that water absorption-based degradation due to humidity occurs when test pieces are directly exposed. Additionally, when the reaction acceleration by applying heat was conducted to recreate long-term strength characteristics, these test pieces had lower strength than those under standard temperature curing conditions. Although the strength can be improved with material age until a certain time, and even reaches the maximum, the long-term strength subsequently decreases. We learned that strength decreases must be considered when used in the long-term.

The test pieces evaluated in the present study are adhesives used for steel-plate bonding, and its role is to transfer the force received by the existing concrete to the reinforcing steel plate. Generally, to reinforce existing concrete effectively, the integrated concrete/reinforcing steel plate structure must follow the

---

Fig. 13 Change in strength under each test condition.

Fig. 15 Change in horizontal load near the surface of the exposed test piece no. 1985-2 by SAICAS.

Fig. 16 Deemed shear strength of test piece no. 1985-2(1).
Bernoulli-Navier hypothesis. According to the previous research, if the adhesive length or width is not sufficiently secured, the steel plate will begin to detach from the edge without sufficiently displaying its yield strength and result in failure (Sano and Miura 1996). Conversely, if the adhesive length of the steel plate edge is sufficient, then detachment is controlled, and given the dominant tensile-shear strength of the steel plate, the failure mode shifts from shear failure to concrete tensile failure (Ando et al. 2008). Thus, regarding the physical properties of the adhesive, if its tensile strength exceeds that of the concrete, and if its shear strength is high, the existing deck slab and the reinforcing steel plates will be integrated. As a result, the structure will be able to resist active loads such as automobiles, and the dead loads due to the increased weight after reinforcement. In conclusion, the current strength of the exposed test pieces of epoxy resin adhesive is sufficient enough compared to that of concrete used in deck slab and the epoxy resin adhesive used in this study is suitable as an adhesive for steel plate bonding methods.

Meanwhile, considering the operating environment conditions of the adhesive used in existing structures, bridge-deck waterproofing is the standard practice when conducting steel plate bonding so that water does not seep into the structure. It is considered that the adhesive strength is maintained for a long time if it is not affected by water as shown by the tensile lap-shear strength. From this, the strength of the adhesive itself used in existing structures is thought to be higher than that of the exposed test pieces.

However, if cracks occur in the deck slab due to deterioration over time such as fatigue, water may penetrate from the top surface of the deck slab, and water retention may occur. Since the water deteriorates the performance of the adhesive, it is considered that the durability of the adhesive in the water retaining part becomes lower than that of the adhesive in the non-water retaining part. Furthermore, if the adhesive is delaminated, water or salt water will enter the gap between the deck slab and the adhesive, and it is concerned about corrosion of the steel plate or the steel post-installed anchors that fix the steel plate to the deck slab.

8. Conclusions

The causes of strength decrease in epoxy resin test pieces that had undergone outdoor exposure were investigated. The following results were obtained as a result of the current investigation:

1. The strength of the exposed test pieces decreased with time. However, the exposed test piece is an adhesive for the steel plate bonding method, and the objective of its use is to integrate existing concrete and reinforcing steel plates. To achieve this objective, the adhesive must have a tensile strength that is greater than that of the concrete as well as a high shearing strength. However, the strength of the exposed test pieces at the time of their use is sufficiently high relative to that of concrete, and it is thought that the epoxy resin maintains its performance as an adhesive for the steel plate bonding method.

2. The cause of degradation due to external environmental factors was found to be susceptible to water. From the results of the SAICAS, a decrease in the strength of the surface of the exposed specimen was observed. It is considered that water absorption degradation has occurred due to long-term exposure to the atmosphere.

3. Regarding strength decrease factors related to the curing process, it is thought that curing contraction and internal stresses occurred with increase in reaction rate. When the internal stress and the load at the time of the test acted on the deteriorated layer on the surface, cracks were generated, and the stress was concentrated on the cracks. For this reason, it was considered that a remarkable decrease in strength occurred.

4. It is considered that the remarkable decrease in strength is due to two factors: surface degradation due to water absorption and internal stress. On the contrary, since it is difficult to be affected by water and the tensile shear strength tends to increase, the adhesive used in the steel plate bonding method is less likely to be affected by water, and its strength of the adhesive itself used in existing structures is thought to be higher than that of the exposed test pieces.

References

Ando, Y., Urata, M., Yamamoto, K. and Matsuda, H., (2008). “Study of the peeling edge of steel plate bonded width.” Proceedings of the Japan Concrete Institute, 30(3), 1603-1608. (in Japanese) ASTM, (2013). “ASTM E837-13a: Standard test method for determining residual stresses by the hole-drilling strain-gage method.” West Conshohocken, PA, USA: ASTM International. Fujita, R., Sakamoto, N. and Suzuki, H., (2012). “Quality changes in epoxy resin used for RC deck repair work over time.” In: Proceedings of the 44th Hanshin Expressway Engineering Research Conference, Osaka, Japan May 2012. Osaka: Hanshin Expressway Company Limited, 333-336. (in Japanese) Himuro, K., Sadai, M., Matsu, K., Sumita, H. and Yamamoto, K., (2012). “Clarification of deterioration mechanism of structural adhesives by water absorption.” Transactions of the Society of Automotive Engineers of Japan, (43), 2, 543-548. (in Japanese) Honma, S., (2004). “Applied strength and durability of plastic.” Plastics, 55(4), 143-152. (in Japanese) Kishima, Y. and Nishiyama, I., (2005). “Characteristic evaluation for interface of different materials by SAICAS system.” Journal of the Adhesion Society of Japan, (41)6, 234-240. (in Japanese)
Sano, M. and Miura, T., (1996). “A study on a design method for strengthening concrete members by steel-plate-bonding.” _Journal of Materials, Concrete Structures and Pavements, JSCE_, 550/V-33, 117-129. (in Japanese)

Shimbo, M., (1987). “Epoxy resin handbook.” Tokyo: Nikkan Kogyo Shimbun. (in Japanese)

Yamazaki, D., Katayama, M. and Maruyama, K., (2015). “Follow-up test report of the ‘Showa Bridge’ 50 years after the Niigata Earthquake and restoration.” _Proceedings of the 70th Annual Meeting of JSCE_, 70/V-575, 149-1150. (in Japanese)