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STATE OF THE ART IN REPAIR AND STRENGTHENING METHODS OF DETERIORATED CONCRETE BRIDGE STRUCTURES

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This paper summarizes the current development for repairing and strengthening deteriorated concrete bridge structures in Japan, especially those deteriorated due to alkali-silica reaction (ASR) and chloride attack. Generally, surface treatments are applied as the repair method due to ASR and chloride attack. Barrier coating and penetrating sealer are two methods that are actively applied as surface treatments in Japan. An investigation of repaired concrete bridge structures using these methods indicate that acrylic-based surface coatings are the most suitable method for repairing concrete structures, and the silicon-based compounds repair concrete structures with low risk of corrosion. Furthermore, the use of sodium or potassium for silicate-based surface treatments should be avoided, as these solutions may exacerbate ASR. This finding was backed up by an accelerated mortar bar test experiment under a modified ASTM C1260 test method. The results show that large ASR expansion occurred on mortar bars immersed in sodium silicate solution (Na_2SiO_3). In regards to strengthening, CFRP sheet bonding, concrete jacketing and PC-confined method with prestressing steel wire were applied for concrete bridge structures. Especially for the PC-confined method, this method can be applied not only as an earthquake strengthener but also an ASR expansion controller on deteriorated bridge piers.

Keywords: ASR, Chloride attack, Barrier coating, Penetrating sealer, CFRP sheet bonding, Concrete jacketing, PC confined method.

1 INTRODUCTION

Between the 1960s and the 1980s, Japan experienced a rapid economic growth driven by the rapid expansion of heavy manufacturing and construction industries. With a construction boom, large numbers of concrete structures such as bridges were built. Unfortunately, at that time there was a lack of awareness of some degradation phenomena in concrete. Problems such as alkali-silica reaction (ASR) and chloride attacks were not taken as seriously as they are now. Before 1980s, there was no standard or guidance for countermeasures to these problems (Tanabe *et al.* 2009). Therefore, many of the concrete structures built before the 1980s was severely damaged by ASR and chloride attacks.

In the Hokuriku region of Japan, ASR-affected PC bridges appeared from the 1980s. Serious ASR problems involving fractures of the reinforcing bar (rebars) were found on the Noto Expressway and National Highway Route 249. As shown in Figure 1, fracture of rebars and surface cracking occur especially on the footing of bridge piers. In addition, in Toyama Prefecture, deterioration due to ASR was observed in bridge structures built between the 1960s and the 1970s (Daidai *et al.* 2012).

Moreover, Japan is also prone to natural disasters, with many concrete structures damaged by earthquakes and tsunami. This situation led to the fast development of repair and strengthening methods and technology for concrete structures in Japan. Unfortunately, practically speaking, the selection of repair and reinforcement methods have become a difficult task.

To repair ASR-affected structures in the Hokuriku region, surface coating by epoxy resin or acrylic rubber, and also crack injections, have been used from the 1990s. However, some researchers reported an ineffectiveness of epoxy-resin material for controlling ASR expansion in ASR-affected structures (Nomura *et al.* 2013). In addition, the use of CFRP sheet-bonding method and cathodic protection method has been actively applied in a saline environment (Torii *et al.* 2012). Furthermore, strengthening methods such as PC-confined method have also been applied effectively (Torii *et al.* 2000).

Regarding this, the first part of this paper will summarize the current development for repairing and strengthening methods of deteriorated concrete bridge structures in Japan, especially those deteriorated by ASR and chloride attack. The investigation results from repaired concrete bridge structures in Japan using these methods will be discussed. The second part of this paper will discuss the experiment results from the laboratory studies regarding the effect of sodium silicate (Na_2SiO_3) material as surface treatment for repairing ASR-affected structures.

2 REPAIR METHOD OF DETERIORATED CONCRETE BRIDGES

There are many types of surface treatments that can be used for repairing ASR-affected structures. Due to the usual surface treatment method used in japan, this paper will describe two kinds of surface treatment: barrier coatings and penetrating sealer.

Figure 1. Fracture of rebars and surface cracking on the footing of a bridge.

2.1 Barrier Coatings

There are at least three surface coatings materials that are actively applied in Japan: acrylic, urethane, and epoxy. In the case of low-ASR potential, Nomura *et al.* (2013) reported that acrylic fiber-sheet coating was effective, while urethane continuous-fiber sheet performed well in the case of high ASR potential. These field investigation results are in agreement with laboratory studies conducted by Hamada *et al.* (2004). Based on the Hamada experiment study, an efficient acrylic fiber-sheet coating, protective against ASR expansion, can significantly enhance the structural behavior of ASR-affected beams undergoing sustained loading. This coating is also believed to give protection against chloride attack. In contrast, the applicability of epoxy-based surface coating was difficult for repairing ASR-affected structures. Daidai *et al.* (2012) investigated ASR-affected bridge piers in Toyama Prefecture that had been repaired using epoxy coating. It was observed that the repaired sections were more damaged and fully covered with cracks than the unrepaired ones, indicating that the repairs actually promoted ASR. There is concern that this surface treatment will trap residual water, thus triggering ASR. In addition, as shown by Figure 2, water trapped inside the epoxy coating will freeze during the winter season, and easily break the coating.

2.2 Penetrating Sealer

Surface treatments using penetrating sealers are less susceptible to physical damage and weathering than barrier coatings. Thus, penetrating sealer may need less maintenance compared with barrier coating to remain effective and to retain the appearance of the surface (NZ Transport Agency 2010).

Figure 2. Breaking of the epoxy coating due to trapped residual water.

In Japan, usually cracks that are less than 0.5 mm are treated with silicon- and silicate-based compounds. The main reason is that by using this method the extension of cracks can be easily monitored. Torii *et al.* (2012) suggested that silicon-based compounds are effective for repairing concrete structures with a low risk of corrosion. In addition, as reported by Nomura *et al.* (2013), the use of sodium silicate was not effective for suppressing ASR progress in ASR-affected bridge piers. Moreover, it was found out that the bridge pier was re-damaged due to ASR.

3 STRENGTHENING METHOD OF DETERIORATED CONCRETE BRIDGES

Severe deterioration, due to natural disasters, ASR, or chloride attack, will cause structural degradation, such as loss of load-bearing capacity. Thus, the deteriorated bridge structures cannot be repaired with the surface-treatment method. As shown by Figure 3, the structure must be partially or even fully reconstructed. In addition, in some cases, the strengthening method should also be applied to restore or even increase its load-bearing capacity. The strengthening methods commonly used in Japan include CFRP sheet bonding, concrete jacketing, and PC-confined methods.

3.1 CFRP Sheet Bonding

The use of CFRP sheet bonding in Japan has dramatically increased since the Kobe Earthquake in 1995. CFRP is mainly used for seismic rehabilitation or strengthening. Besides increasing concrete strength, CFRP is also characterized as having high corrosion resistance. Thus, as reported by Torii *et al.* (2012), the CFRP sheet bonding was also applied to ASR-affected post-PC girders with fractures of prestressing steel strands (PS) due to chloride attack. However, its bond strength is still questionable if applied to structures with severe environmental conditions.

3.2 Concrete Jacketing and Steel Plate Jacketing Methods

Figure 3. Partial reconstruction of bridge footing with fracture of rebars.

Figure 4. Strengthening of column by steel plate jacketing.

In Toyama Prefecture, two PC structures repaired with concrete jacketing were showing different results (Nomura *et al.* 2013). In structures with high residual expansivity, at repair time the concrete-jacketing method was effective enough in suppressing ASR expansion. On the other hand, in structures where residual expansivity has been constant, cracks still occurred after repair. In this case, since ASR was not trending toward convergence, it was considered that concrete jacketing was not that effective in ASR suppression. However, one way to effectively suppress the ASR using this method is by increasing the margin of the reinforcement-steel diameter. As shown by Figure 4, in addition to the ordinary concrete jacketing, the steel-plate jacketing method is also being used. However, this method is more complicated and considered to be more costly than ordinary concrete jacketing.

3.3 PC Confined Method

Restoring structural performance of ASR-affected structures in Japan has also been done by a PC-confined method with prestressing steel wire (Torii *et al.* 2000) (Figure 5). This method has been successfully applied on ASR-affected reinforced concrete piers of the Toyokawa Bridge, Ishikawa Prefecture. Two years of monitoring also have shown that the prestressing forces around the existing RC piers effectively controls the extension of ASR cracks and the expansion of concrete. In 2006, this technique was also reported to be effective in controlling crack development and ASR expansion on ASR-affected bridge piers in Toyama Prefecture (Torii and Daidai 2006).

4 EXPERIMENTS RESULTS OF MORTAR BARS IMMERSED 1N Na_2SiO_3 AND Li_2SiO_3 SOLUTIONS

Figure 5. Strengthening of column by immersed PC confined method.

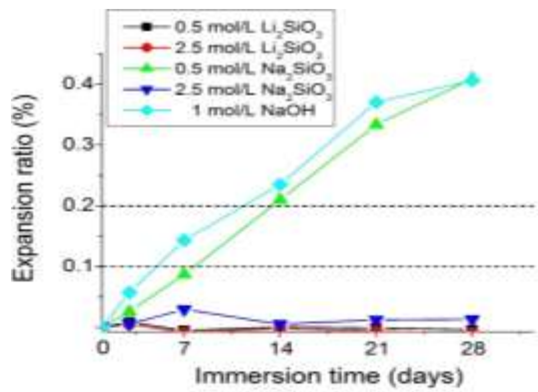

Figure 6. Expansion ratio of mortar bars in 0.5 mol/L and 2.5 mol/L Na_2SiO_3 and Li_2SiO_3 solutions (Prasetia *et al.* 2013).

Previous research was conducted to investigate the ASR mitigation effect of Na_2SiO_3 and Li_2SiO_3 solutions (Prasetia *et al.* 2013). The accelerated mortar bar test was conducted according to a modified ASTM C1260 method. As shown by Figure 6, the mortar bar specimens immersed in Li_2SiO_3 solution did not expand at all, which suggests no ASR occurrence. In contrast, in the case of Na_2SiO_3 solution, specimens immersed in 0.5 mol/L solution revealed a large expansion. This might be evidence that Na_2SiO_3 actually triggers ASR. However, in the case of the specimens immersed in 2.5 mol/L solution, an early low expansion was observed up to 7 days, but this expansion subsequently vanished. It seems that as the steady supply of highly concentrated Na_2SiO_3 from the external source continues, the reaction between Na_2SiO_3 and $Ca(OH)_2$ takes place and suppress the pace of alkali-silica reaction. Based on these results, the use of Li_2SiO_3 material as a surface treatment method can be recommended for repairing ASR deteriorated concrete structures. Moreover, although Na_2SiO_3 material possesses ASR-suppression properties, it might not be recommended for external supply application unless it is in high concentration.

5 CONCLUSIONS

- The application of acrylic fiber-sheet coating and urethane continuous fiber sheet coating are recommended for repairing ASR-affected structures. In addition, the acrylic fiber-sheet coating can also protect against chloride attack.
- When crack widths are <0.5 mm, the silicon-based penetrating sealer is recommended to repair structures with low risk of rebar corrosion.
- As strengthening methods, the application of CFRP sheet bonding, concrete jacketing, and PC-confined methods are effective in repairing and strengthening ASR-affected bridge structures. Hence, selection of the appropriate method should be based on restoring or increasing structural load-bearing capacity.
- Instead of using sodium silicate material, lithium silicate material can be more effective as a surface treatment for repairing ASR-affected concrete structures.

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