CRACKING BEHAVIOR AND DETERIORATION SUPPRESSION EFFECT OF PROTECTIVE SURFACE COATINGS ON ASR-AFFECTED STRUCTURES

Koji Utsunomiya [1*], Hiroaki Uenakada[1], Kiyoshi Sakiya[2], Tsutomu Niina[2], Yukio Adachi[2]

[1]Hanshin Expressway Engineering Company Limited, Osaka, Japan

[2]Hanshin Expressway Company Limited, Osaka, Japan

Abstract

Some of piers previously repaired with protective surface coating were found to have cracks which were likely attributable to post-treatment deterioration by alkali silica reaction. The authors selected piers with different types of coating, removed the coatings from their beams, and evaluated the state of deterioration in the structures. The results revealed that crack condition varied depending on the coating type. This paper examines cracking behavior and post-treatment deterioration suppression effect of different types of coating, with the focus placed on cracks caused by deterioration after the repair due to alkali silica reaction.

Keywords: water repellent coating, waterproof coating, mitigation, surface crack

1 INTRODUCTION

Coatings are applied to the surfaces of structures on the Hanshin Expressway for repair or prevention of damage from alkali silica reaction (hereinafter referred to as “ASR”) and other deterioration in accordance with the in-house standard procedures for concrete structure surface protection [1]. Structures treated with protective surface coating are carefully checked for any recurrence of damage during periodic inspections which are performed mainly visually. In addition, follow-up inspection is conducted on those considered affected by ASR on the items and subjects determined for individual cases for monitoring the change over time.

During these inspections some of the piers previously treated with protective surface coating were found to have cracks attributable to post-treatment deterioration by advanced ASR. For accurate evaluation of the state of deterioration in these structures, it was needed to investigate the cracks generated in the pier structures, not those appearing in the coatings. The authors selected a pier with water repellent surface protection system (hereinafter referred to as “water repellent coating”) and a pier with waterproof surface protection system (hereinafter referred to as “waterproof coating”) from those found to have post-treatment deterioration and investigated the crack condition in the beams of these pier structures, with the existing coatings removed.

The water repellent coated pier and waterproof coated pier exhibited different tendencies in crack development. Difference was also found in the amount of crack propagation after the repair between the two piers. These results suggested that suppression effect on crack development might be different between the water repellent and waterproof coatings.

* Correspondence to: koji-utsunomiya@hex-eng.co.jp

This paper examines cracking behavior and post-treatment ASR deterioration suppression effect of different types of surface protection systems, with the focus placed on crack condition and amount of crack propagation attributable to deterioration after the repair.

2 SAMPLE PIERS AND EVALUATION METHODS

2.1 Outline of the sample piers

Structure types and years of completion

A T-shaped prestressed concrete (PC) pier shown in Figure 1 (hereinafter referred to as "Pier I") and a T-shaped reinforced concrete (RC) pier shown in Figure 2 (hereinafter referred to as "Pier II") were examined in the present investigation. Piers I and II were built in the same age, completed in 1969 and 1972, respectively. In-house manual of the Hanshin Expressway defines ASR-affected piers as those with a beam containing gel and showing a total crack extension (crack width: 0.3 mm or above for RC piers or 0.2 mm or above for PC piers) of over 100 m [2]. Piers I and II were found to meet this definition and have been handled as ASR-affected piers in maintenance management.

Repair and inspection histories

Table 1 shows repair histories of the sample piers. Pier I was treated with water repellent coating in 1990. Pier II was treated with waterproof coating in 1994 after previous repairs in 1980 and 1983.

Pier I received detailed inspection in 1999, and follow-up inspection in 2008 revealed post-treatment deterioration. Investigation of its pier structure was carried out in 2009. Post-treatment deterioration in Pier II was found during periodic inspection in 2006. Detailed inspection was carried out in 2007, and its pier structure was investigated in 2009.

Detailed inspection results

Table 2 shows the detailed inspection results. Effects of ASR were obvious in both piers, with alkali silica gel detected and a drastic decrease noted in static modulus of elasticity for the compressive strength levels. The two piers exhibited similar values in mechanical properties of concrete and chloride ion concentration, and total expansion ratio determined by the JCI-DD2 method (method of determination of expansion rate of AAR-damaged structure using concrete core by Japan Concrete Institute) was also at similar levels around 0.05%. These results suggested no significant difference between the two piers in the quality of the structure concrete and expansion potential by ASR.

Natural environment

Difference in natural environment between the two piers was examined from their locations and orientations. No difference was estimated in temperature and weather influences on the two piers which were located approximately six kilometers apart by straight line distance within Osaka City. Although sunlight conditions might vary to some extent between Pier I facing north and south and Pier II facing east and west, no major difference was assumed with the presence of decks on top of them and the similarity in their heights taken into account.

Water exposure conditions

There can be two major sources of moisture supply for bridge piers: exposure to rain and leakage from expansion joints. From the natural environment conditions of the sites, moisture supply from rain was not considered to differ between the two piers. According to the inspection history records, water leakage from expansion joints had been detected in both piers at similar times. Therefore, the sample piers were considered to have been subjected to similar water exposure conditions.

2.2 Specifications of surface protection systems

General

Surface protection systems are applied to concrete structure surfaces for the purposes of damage repair, long-term corrosion prevention, preventive maintenance and landscaping as a means to improve durability and suppress or repair deterioration of concrete structures [1].

The Hanshin Expressway has a set of in-house coating specifications established and applies proper ones to individual cases, depending on the cause of damage and purpose of use. There are two major categories in the specifications for ASR control: water repellent coating and waterproof coating. Both are water control measures, but water repellent coating uses silane penetrant which allows moisture vapor permeation, while waterproof coating shields water. Table 3 shows the water repellent coating applied to Pier I, and Table 4 shows the waterproof coating applied to Pier II.

Japan Society of Civil Engineers classifies surface protection systems into surface coating, penetrant application and patch repair in the "Recommendations for Design and Application of Surface Protection Systems (Draft)" [3]. According to the recommendations, waterproof coating is a type of surface coating, and water repellent coating has unique specifications with combined features of surface coating and penetrant application.

Surface coating is a technique of providing coats of organic or inorganic materials to the surface of concrete structures to control or prevent penetration of deteriorating substances for improved durability of structures or suppressed progress of deterioration [3]. Penetrant application is a technique in which surface penetrant applied to the surface of concrete penetrates into it, controlling penetration of deteriorating substances or providing additional features to the impregnated concrete [3].

2.3 Analysis items and methods

Figure 3 shows a flow of the investigation and analysis items, and Table 5 shows the analysis methods used. In this investigation protective surface coatings were removed, and crack extension in the pier structures (hereinafter referred to as "post-removal crack extension") was determined for accurate evaluation of the state of deterioration in the pier structures. Prior to this, extension of cracks appearing in the protective surface coatings (hereinafter referred to as "pre-removal crack extension") was also determined. Analysis was made based on these results, with the focus placed on the difference in the surface protection type.

In Analysis 1 amount of crack propagation generated after the last application of protective surface coating (hereinafter referred to as "crack propagation amount") was determined by subtracting previously injected crack extension from post-removal crack extension, and then ratio of crack propagation amount to pre-removal crack extension was calculated. This ratio is a factor to estimate crack propagation amount from pre-removal crack extension and presents the difference in cracking behavior of the water repellent and waterproof coatings quantitatively.

In Analysis 2 crack propagation amount obtained in Analysis 1 was divided by beam area size and the number of years from repair, to obtain annual crack propagation density ($m/m^2 \cdot y$). Post-treatment ASR deterioration suppression effect of each surface protection type was evaluated based on the calculation results.

3 INVESTIGATION RESULTS

3.1 Crack drawings

Crack development in Pier I

Figures 4 and 5 show drawings of cracks found in the coating and those found in the pier structure of Pier I.

Crack development in Pier II

Figures 6 and 7 show drawings of cracks found in the coating and those found in the pier structure of Pier II.

3.2 Crack extensions and other results

Table 6 shows crack extensions and other results from the investigation. Pier I had a pre-removal crack extension of about 60 m and a post-removal crack extension of about 180 m. Crack injection was conducted in 1990 for a length of about 140 m prior to application of water repellent coating. Crack propagation amount after 19 years from the repair was therefore about 40 m. Pier II had a pre-removal crack extension of about 50 m and a post-removal crack extension of about 570 m. Crack injection was conducted in 1980 and 1983 for a total length of about 360 m in combination with protective surface coating, and crack injection was again conducted in 1994 for a length of about 30 m prior to the application of waterproof coating. As a result, total injected crack extension amounted to about 390 m, and crack propagation amount after 15 years from the last repair was about 180 m.

4 ANALYSIS EVALUATION AND DISCUSSION

4.1 Cracking behavior factor

Cracking behavior factor (ratio of crack propagation amount to pre-removal crack extension) was calculated from the investigation results shown in Section 3 in the manner described in Section 2.3 as Analysis 1. Table 7 shows the calculation results. Crack propagation amount in Pier I was 40 m, while pre-removal crack extension was 60 m. That is, extension of cracks generated in the pier structure after the last application of protective surface coating (= crack propagation amount) was smaller than that of those appearing in the coating (= pre-removal crack extension), resulting in a cracking behavior factor of 0.7. In contrast to this, crack propagation amount in Pier II was 180 m and was larger than pre-removal crack extension which was 50 m, resulting in a cracking behavior factor of 3.6.

These analysis results suggest that the amount of cracks generated in the water repellent coated pier structure would be slightly smaller than or almost equal to that appearing in the coating. In contrast, the amount of cracks generated in the waterproof coated pier structure would be larger than that appearing in the coating.

The difference in cracking behavior of water repellent and waterproof coatings was considered to be mainly related to crack bridging capacity of the materials used. Waterproof coating uses materials with a high elongation factor such as polybutadiene resin and flexible polyurethane resin which were used on Pier II, to meet higher crack bridging performance requirements.

One of the major problems in maintenance management of protective surface coated concrete structures is the difficulty of accurately determining the state of deterioration in the pier structure due to the presence of the coating. The present investigation revealed that crack propagation amount in the waterproof coated Pier II could be very different from its pre-removal crack extension due to the high crack bridging properties of the coating materials. This suggests that pre-removal crack extension cannot be used as a sole basis for the evaluation of deterioration generated in waterproof coated structures. No such difference was found in the water repellent coated Pier I, suggesting that there would be no major errors in the evaluation of deterioration in waterproof coated structures based on the observation from above the coating.

4.2 Post-treatment ASR deterioration suppression effect

Annual crack propagation density ($m/m^2 \cdot y$) was calculated from the investigation results shown in Section 3 in the manner described in Section 2.3 as Analysis 2 for determination of post-treatment ASR deterioration suppression effect (crack propagation amount divided by beam area size and the number of years from repair). Table 8 shows the calculation results. The state of post-treatment deterioration was about 0.02 $m/m^2 \cdot y$ in the water repellent coated Pier I and about 0.09 $m/m^2 \cdot y$ in Pier II.

The analysis results suggested that progress of ASR deterioration would be relatively minor in water repellent coated piers as compared to waterproof coated piers. Annual crack propagation density in the water repellent coated pier was about one-fourth that in the waterproof coated pier.

The difference found in post-treatment ASR deterioration suppression effect between the water repellent and waterproof coatings was most likely caused by the water absorption prevention effect and moisture vapor permeability of silane which was used in the water repellent coating. The assumption is that waterproof coated structures may not exhibit obvious cracks in the coating due to the high crack bridging properties of the coating materials, even when cracks are generated in the structure surface by ASR. However, once cracks appear in the coating even in a slight amount, water which is a deteriorating factor will penetrate through them into the structure and promote the progress of ASR. It is also possible that the waterproof coating traps moisture. Water repellent coated structures will behave differently. When cracks are generated in the structure surface by ASR, cracks will also appear in the coating to the similar degree, possibly allowing water to penetrate. However, silane penetrating into the structure surface has a water absorption prevention effect which likely contributes to controlling water penetration and suppressing the progress of ASR. It is also possible that its moisture vapor permeability allows moisture to escape to the outside.

Since the sample piers of this investigation had similar ASR expansion potential and similar natural environment, alkali silica gel must have been generated in both piers. It was assumed that the water repellent coating which contained silane prevented water penetration and reduced alkali silica gel expansion in Pier I. This process is demonstrated in Figure 8 which shows change in crack development and cumulative crack density together with total expansion ratios measured during detailed inspections.

4.3 Proposals

As shown in the investigation results, pre-removal crack extension and crack propagation amount tend to vary depending on the surface protection type. The authors propose to calculate cracking behavior factor using the same method to that used in this investigation at every replacement of surface protection system on ASR-affected structures. Accumulation of data on cracking behavior factor of each surface protection type will enable accurate estimation of crack propagation amount from pre-removal crack extension values.

The other proposal is the application of water repellent coating as an effective repair on ASR-affected structures. The effectiveness of this repair was demonstrated in the results of annual crack propagation density calculation. Although it is most preferred to apply the coating during the initiation stage of ASR deterioration, application during the propagation stage of ASR deterioration is expected to be still effective in deterioration suppression. The investigation results on Pier I revealed successful suppression of post-treatment ASR deterioration in it after the application of water repellent coating which was implemented when crack extension was 140 m (crack density: 1.43 m/m^2).

4.4 Future work

The focus of this study was placed on cracking behavior and post-treatment ASR deterioration suppression effect of different surface protection systems. Since the presented investigation results are from only one waterproof coated pier and one water repellent coated pier, more data based on the same investigation method need to be accumulated to verify and enhance the discussion in this report. It is preferred to select existing structures of the same types as those used in this study, i.e., PC and RC beams, for future investigations on cracking behavior and deterioration suppression effect of the water repellent and waterproof coatings in practical application.

5 CONCLUSIONS

- Cracking behavior factor was proposed as a representation or index of the state of deterioration in the surface of ASR-affected structures for estimation by the observation from above the protective surface coating.
- Annual crack propagation density was presented as a basis for the evaluation of deterioration suppression effect of surface protection system applied to ASR-affected structures.
- Cracking behavior factor calculation results suggested that pre-removal crack extension and crack propagation amount varied depending on the surface protection type.
- Annual crack propagation density calculation results revealed that water repellent coating had better deterioration suppression effect than that of waterproof coating.
- It was proposed to determine cracking behavior factor at every replacement of surface protection system on ASR-affected structures, using the proposed investigation method, for accumulation of data.
- Water repellent coating is expected to be effective in suppression of deterioration even when it is applied during the propagation stage of ASR deterioration.

6 REFERENCES

[1] Hanshin Expressway Company Limited (2007): Concrete Structure Surface Protection System Procedures. (in Japanese)

[2] Hanshin Expressway Company Limited (2007): Maintenance Management Manual for ASR-Affected Structures. (in Japanese)

[3] Japan Society of Civil Engineers Concrete Committee (2005): Recommendations for Design and Application of Surface Protection Systems (Draft). (in Japanese)

TABLE 1: Repair histories of sample piers				
Year	*Pier I*		*Pier II*	
1969	Completed	Prestressed concrete structure, T-shaped		
1972			Completed	Reinforced concrete structure, T-shaped
1980			Repaired	Crack injection (160 m*1) + surface protection*2
1983			Repaired	Crack injection (200 m*1) + surface protection*2
1990	Repaired	Crack injection (140 m) + surface protection (water repellent)		
1994			Repaired	Crack injection (30 m) + surface protection (waterproof)

*1: Width of repaired cracks is unknown.
*2: Surface protection type is unknown.

TABLE 2: Detailed inspection results					
Evaluation items		*Design value or threshold*	*Unit*	*Pier I Inspection in 1999*	*Pier II Inspection in 2007*
Mechanical properties	Compressive strength	27	N/mm^2	31.2	30.0
	Static modulus of elasticity	26.5	kN/mm^2	7.0	9.6
Chloride ion concentration	JCI-SC4	1.2	kg/m^3	1.28	1.09
Total expansion ratio	JCI-DD2	0.1	%	0.059	0.046
Alkali silica gel	Present/absent	--	--	Present	Present
Maximum crack density per inspection		--	m/m^2	1.25 (1990)	0.97 (1983)

TABLE 3: Water repellent coating specifications				
Process	*Tools and materials*	*Target film thickness (μm)*	*Standard dosage (kg/m²)*	*Applying tools*
Surface preparation	Disk sander or wire brush			
Undercoat (1-2 layers)	Reactive silane penetrant	--	0.20~0.24	Brush or roller
Intermediate coat (2-3 layers)	Flexible polymer cement mortar	1050~1200	2.10~2.30	Brush or roller
Topcoat (2 layers)	Acrylic emulsion paint	60~80	0.2	Brush or roller

TABLE 4: Waterproof coating specifications					
Process		*Tools and materials*	*Target film thickness (μm)*	*Standard dosage (kg/m²)*	*Applying tools*
Surface preparation	Primer	Epoxy resin primer	--	0.1	Brush or roller
	Putty	Epoxy resin putty	--	0.5	Spatula or trowel
Intermediate coat 1		Polybutadiene resin paint	500	0.75	Spatula or trowel
Intermediate coat 2		Polybutadiene resin paint	500	0.75	Spatula or trowel
Topcoat 1		Flexible polyurethane resin paint	30	0.12	Brush or roller
Topcoat 2		Flexible polyurethane resin paint	30	0.12	Brush or roller

TABLE 5: Analysis methods		
Analysis	*Analysis items*	*Analysis methods*
1	Cracking behavior factor	Crack propagation amount / pre-removal crack extension
2	ASR re-deterioration suppression effect	Crack propagation amount / beam area size /number of years from repair

Note: Crack propagation amount = post-removal crack extension – previously injected crack extension

TABLE 6: Crack extensions and other results from the investigation							
Pier and surface protection types	*A. Beam area size (m²)*	*Items*	*a. Pre-removal crack extension*	*b. Post-removal crack extension*	*c. Previously injected crack extension*	*d. Crack propagation amount (b-c)*	*t. Years from repair*
Pier I: PC beam, water repellent coating	97.8	Crack extension (m)	60.00	180.00	140.00	40.00	19
		Crack density (m/m²)	0.61	1.84	1.43	0.41	
Pier II: RC beam, waterproof coating	138.5	Crack extension (m)	50.00	570.00	390.00	180.00	15
		Crack density (m/m²)	0.36	4.12	2.82	1.30	

TABLE 7: Cracking behavior factor calculation results						
Pier and surface protection types	*Items*	*a. Pre-removal crack extension*	*b. Post-removal crack extension*	*c. Previously injected crack extension*	*d. Crack propagation amount (b-c)*	*Cracking behavior factor (d/a)*
Pier I: PC beam, water repellent coating	Crack extension (m)	60.00	180.00	140.00	40.00	0.7
Pier II: RC beam, waterproof coating	Crack extension (m)	50.00	570.00	390.00	180.00	3.6

TABLE 8: ASR re-deterioration suppression effect (annual crack propagation density calculation results)						
Pier and surface protection types	*A. Beam area size (m²)*	*b. Post-removal crack extension (m)*	*c. Previously injected crack extension (m)*	*d. Crack propagation amount (b-c)*	*t. Years from repair*	*Annual crack propagation density, d/A/t (m/m²/y)*
Pier I: PC beam, water repellent coating	97.80	180.00	140.00	40.00	19	0.02
Pier II: RC beam, waterproof coating	138.50	570.00	390.00	180.00	15	0.09

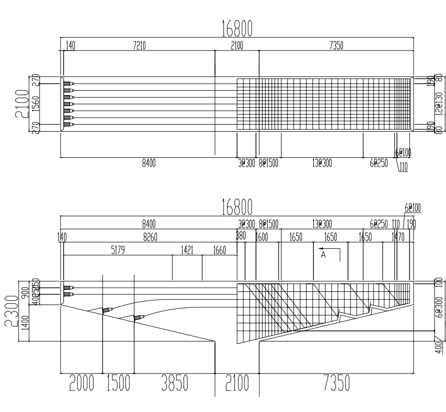

FIGURE 1: Structural drawings of Pier I

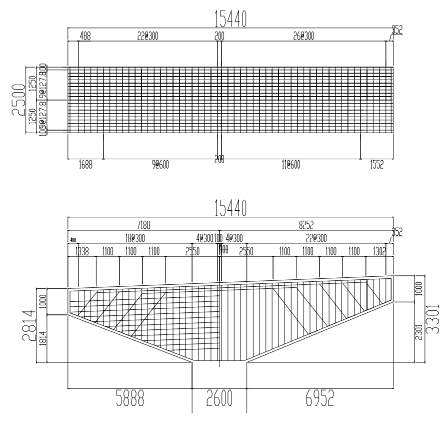

FIGURE 2: Structural drawings of Pier II

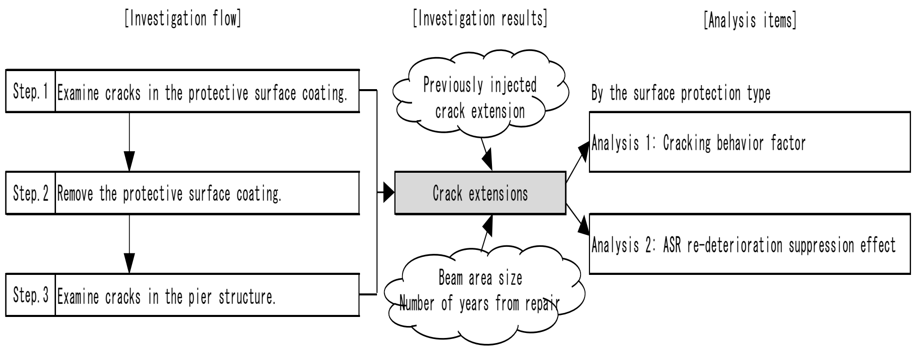

FIGURE 3: Investigation flow and analysis items

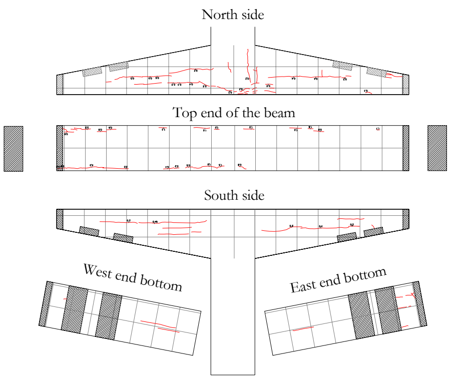

FIGURE 4: Cracks in the coating on Pier I

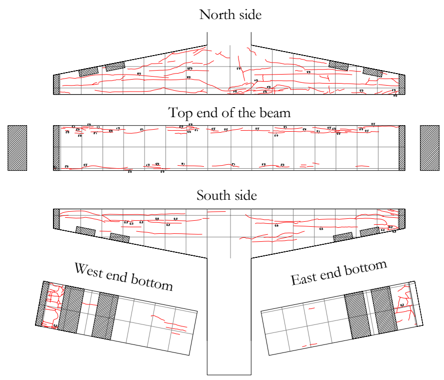

FIGURE 5: Cracks in the structure of Pier I

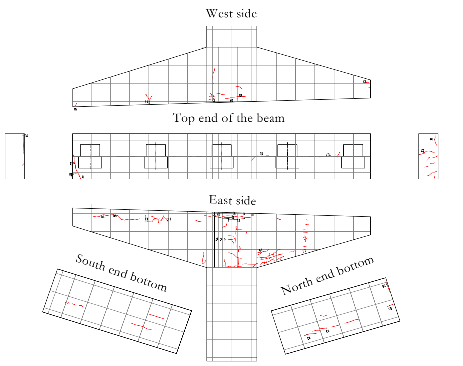

FIGURE 6: Cracks in the coating on Pier II

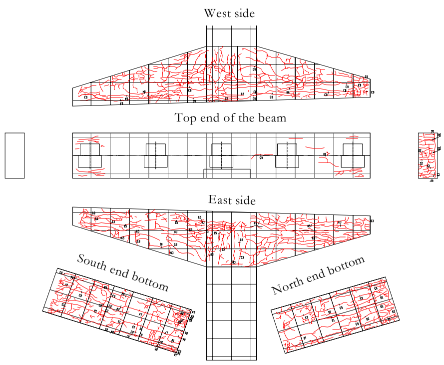

FIGURE 7: Cracks in the structure of Pier II

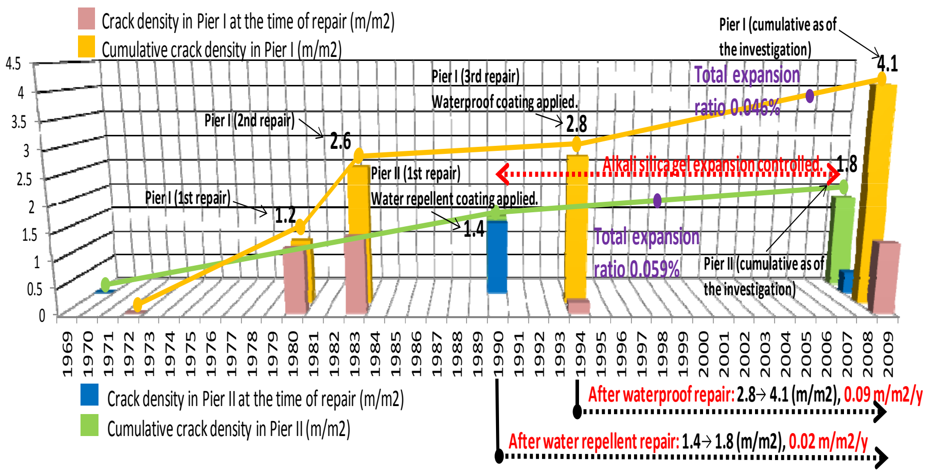

FIGURE 8: Changes in crack development and cumulative crack density