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THE MAINTENANCE AND REHABILITATION TECHNIQUES FOR ASR-AFFECTED BRIDGE PIERS WITH FRACTURE OF STEEL BARS

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Abstract

The brittle fracture of steel bars in ASR-affected bridge piers has recently been reported in many places in Japan. At present, the development of rehabilitation and maintenance techniques for severely deteriorated bridge piers due to ASR is an important subject to concrete engineers. In the case study of the Arisawa Bridge in Toyama Prefecture, the authors carried out a series of investigations on both, the reduction in mechanical properties of concrete and the degree of fracture of steel bars in RC piers in which a severe deterioration again occurred after the surface coating had been applied. This paper describes the process of re-deterioration of ASR-affected bridge piers after the repair and the new countermeasures for them. Based on the survey results, the maintenance procedure for ASR-deteriorated bridge piers is proposed.

Keywords: ASR, Cracking, Fracture of steel bars, Rehabilitation, Maintenance

1 INTRODUCTION

In Toyama Prefecture, Japan, deterioration due to alkali silica reaction was observed in bridge structures built from the 60's to the 70's. The use of river sand and river gravel aggregates concrete is the main cause associated to that phenomenon [1]. From about 20 years ago, extensive repair works have been undertaken, but presently, after almost 30 years in service, severe ASR re-deterioration has been occurring after the repair was had been concluded [2]. In addition, fracture of main steel bars and shear reinforcement bars has recently been detected in bridge piers of structures with excessive expansion due to ASR, thus significantly affecting the load-bearing capacity of those structural elements [3]. During the demolition of these concrete piers with fracture of steel bars, it was found that the concrete itself was severely damaged and completely brittle. Neither the extent of the actual ASR deterioration condition of the structures nor the causes were sufficiently understood in the previous survey. Therefore, the relationship between concrete brittleness and fracture of steel reinforcing bars, as a combined effect of severe ASR deterioration, has become an important research topic for practicing engineers involved in the recent bridge maintenance efforts in Toyama Prefecture.

In the first part of the paper, the investigation on ASR-affected bridge piers, which were severely deteriorated again immediately after the coating on surface and the injection into cracks had been applied, is described. In the second part of the paper, both the rehabilitation technique and the execution process for such bridge piers across the Jinzu River are introduced.

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2 GEOGRAPHICAL DISTRIBUTION OF ASR-AFFECTED BRIDGES AND GEOLOGICAL FEATURES

The map of ASR-affected bridges in Toyama Prefecture is shown in Figure 1. The Prefecture is crossed by two important roads: the Hokuriku Expressway and the National Route 8. All bridges constructed in the 70's, along the by-pass sections in both roadways are severely damaged by ASR, because local reactive aggregates were supplied for concrete in the whole construction works. Figure 2 shows the main rivers and the geological map of reactive aggregates in Toyama Prefecture. Mineral deposits with reactive components cover most of the prefectural area and mainly originated from marine volcanic eruptions followed by hydrothermal alteration process, which led to the formation of a green tuff's stratum. Andesite sub-layers cover all the east to the southwest regions and rhyolite sub-stratums are generally found in southwest region. The concentration of these deposits is high along the main rivers, where most of coarse and fine aggregates are usually extracted, and there is a high probability that they are mixed with concrete aggregates in the Prefecture. The proportions of rock types along the main rivers in the Prefecture are shown in Table 1 [4]. In Jouganji river the reactive andesite content is the highest and exceeds 40%. As for Shou river the contents of andesite and rhyolite in aggregates range from 13 to 17%. On the other hand, in Hayatsuki and Kurobe rivers neither andesite nor rhyolite deposits were found. These findings show that the varying content of reactive aggregates from river to river is a major geological feature in the Prefecture. The ASR-affected bridges mainly occurred in the Jouganji and Shou river basins, where the deposits with the highest contents of andesite aggregates were found. This clearly indicates a connection pattern with the flow aggregates in the region.

3 ASR-RELATED CRACK DISTRIBUTION AND DETERIORATION LEVEL AFTER REPAIRING WORKS

The ASR-related crack distribution in P4 pier pillow-beam after 17 years in service is shown in Figure 3. It was observed that cracking occurred in the whole bottom side of the pillow-beam and a white free-lime powder exuded from the cracks. Figure 4 shows the condition of crack distribution in P4 pier in 2004, i.e. 15 years after being repaired with crack injection and surface waterproof coating. The repair works were carried out in accordance with the Japanese specifications for soft-tick type of coating materials, which were applied for ASR-affected structures at the time. The materials mainly consisted of soft epoxi resins capable of further penetrating the cracks. The deterioration occurred several years later, because the expansion of concrete due to ASR continued.

This phenomenon can be explained with two main reasons:

(1) After crack injection and surface coating, residual water was trapped inside the concrete structure, which enabled continuous expansion due to ASR. Crack enlargement followed and damaging of surface coating occurred.

(2) Drainage water and lots of deicing salts (NaCl) penetrating the structure from the upper side of the bridge piers, especially through the expansion joints, caused ASR acceleration and consequently, the cracking rapidly extended to all coated surfaces.

Even though, cutting off the water and alkali external supply is accomplished, if the absorbed amount of these substances in concrete has reached a certain threshold to be considered sufficient enough before the repairing works have been carried out, then it becomes virtually impossible to stop ASR progress. In the case of Toyama Prefecture, waterproof coating was applied as ASR countermeasure, but this repair method has failed and played a major role on the escalation of ASR-related deformations due to crack propagation and fracture of steel reinforcement bars, thus becoming an embarassment to maintenance management professionals. For this reason, in those structures where ASR progressed for over 30 years, it was decided to remove all the surface coating executed in the previous repair works, in order to assess the causes of ongoing damage. Figure 5 shows the boundary between the repaired and unrepaired sections of one pier. At the time, surface coating was executed only above ground and nothing was done for the underground sections. But it was later observed that the repaired sections were more damaged and fully covered with cracks than the unrepaired ones, which may indicate that the repairing choices actually promoted ASR progress. In addition, there is a strong possibility that surface coating could be trapping water inside the concrete for longer periods, thus enabling a steady ASR process. Figure 6 and Table 2 show the crack condition of P4 pier in Jinzu river. In the underwater section of P4 pier, the crack width and crack density were higher than that above ground and it is believed that inside the river ASR advances at faster pace due to the regular moisture supply. As for pier footing, since cracks have a direct effect on the earthquake resistance capacity of the structure, a special attention was paid during the field survey. Figure 7 shows the crack distribution in P4 pier underwater section at Jinzu river. On the pillow beam sections, 1mm cracks covered the entire area and penetrated the surface coating but especially the propagation of 1~2mm cracks in the horizontal direction was remarkable. However, on the lateral and bottom sides the crack width difference was about 5mm and in both cases fracture of steel reinforcing bars has occurred. On the lateral pier sections parallel to the river flow and below water level, cracking mainly occurred in the vertical direction. On the beam stirrup bending lining and pier ending points, cracking generally developed on the horizontal direction. It was concluded from the layout that the relating cause was the different ratios of steel reinforcement bars, especially on the transition zone.

4 PROPERTIES OF CONCRETE CORES FROM BRIDGE PIERS

4.1 Mechanical Properties of Concrete

Figure 8 shows the relationship between the compressive strength and the static modulus of elasticity in cores drilled from the pillow beam, column and caisson of bridge piers. As shown in Figure 8, the reduction in the elastic modulus of cores taken from ASR-deteriorated piers was more significant compared with that in the compressive strength, all values obtained being under the theoretical curve estimated for the sound concrete specified in the Standard Specifications for Road Bridges. In particular, the elastic modulus of cores in the hammerhead beam was particularly lower than those of columns, presumably because of the low steel reinforcement ratio for confinement and the high water supply from the superstructure. Figure 9 shows the results of compressive strength and Young's modulus of concrete cores drilled from the surface and inside of the beam section. Surface cores were drilled up to 500mm depth and inside cores were drilled from 1300mm up to 2000mm depths. ASR damage degree in concrete was compared at those set depths. Figure 10 shows an external overview of a concrete core drilled at P6 bridge beam section. The compressive strength of cover concrete was below design strength and considerably decreased due to cracking. On the other hand, the compressive strength of inside concrete was within design values and far higher if compared with the surface concrete values.

4.2 Visual Observation of Concrete Cores

Figure 11 shows the XRD pattern of andesite stone in concrete aggregates. Observed peaks confirmed the presence of cristobalite and volcanic glass as the main reactive components. The percentage of colored area, i.e. ASR-gel observed in thin sections by uranyl acetate fluorescence method is shown in Table 3 and the images of ASR-gel formation in concrete cores observed by the same method are shown in Figure 12. ASR gel was observed around both, coarse river gravel and fine river sand aggregates. This observation of light green and yellow fluorescent areas around the andesite particles refers to ASR gel formation and confirms that it has broadly reacted to a wide extent. The ratio of colored area was higher in cores from beams than footings. Because the beams are subjected to dryness and moisture cycles as well as temperature variation, it is believed that the hygroscopic swelling of ASR gel repeatedly occurs, thus causing a remarkable ASR deterioration.

4.3 Residual expansivity of concrete cores

Figures 13 and 14 show the results of accelerated expansion tests conducted in accordance to JCI-DD2 method and Danish method, respectively. In the Danish test, the specimens were immersed in a saturated NaCl solution for over 35 days. The results revealed a linear expansion in cores from bridge piers, so a "residual expansivity exists". As for beams and caisson, the assessment indicates that a "residual expansivity doesn't exist". It can be explained with the fact that the regular moisture supply to beams and caisson could accelerate ASR from the early stages, to the extent that the ASR process was almost completed at the time this investigation was conducted. On the other hand, JCI-DD2 test results showed a stable or decreasing tendency of expansivity in all concrete cores immersed for more than 70 days, indicating that a "residual expansivity doesn't exist". In this method, due to moisture curing atmosphere, alkalis liquate out prompting the reduction of alkali concentration in the concrete cores. Consequently, ASR stagnates or even stops, which for structures in service for longer period of time, almost no expansion occurs. The Danish method is effective for assessment of volcanic rock types which contain cristobalite and volcanic glass as the reactive minerals. These are the common type of aggregates in Toyama Prefecture, with highly reactive silica minerals, so applying this method is believed to be an appropriate measure.

4.4 Rock mineralogical composition and ASR gel formation in Concrete

The results of rock composition in aggregates from cores drilled in beams and bridge piers are shown in Figure 15. In river sands and gravels from Toyama Prefecture, various other type of rocks are mixed all together, but, because in each river basin the content of reactive aggregates is fairly known, it is possible to determine the origin of certain aggregate by assessing the contents of andesite and rhyolite in concrete cores. The main reactive rock types in river gravels were volcanic rocks such as andesite and rhyolite, but sedimentary rocks were almost inexistent. The andesite content in river gravel was about 20~40% and, since this ratio is high, the origin of these aggregates in concrete was considered to be Jouganji river. In addition, this andesite content reaches pessimum values for Jouganji river aggregates, which may be the presumably cause of continuous expansion and considerable ASR deterioration over the course of long periods of time.

5 MINERALOGICAL CHARACTERISTICS AND ALKALI-SILICA REACTIVITY OF AGGREGATES

5.1 Degree of Deterioration in Concrete

Crushed fragments and concrete rubble resulting from the demolition of P4 pier are shown in Figure 16. Reaction rims were observed around andesite particles in fine and coarse aggregates in concrete and ASR gel covered the whole entire area in thin sections. The extent of concrete deterioration was such that it became brittle and fragmented into 5cm pieces during the demolition process. The actual condition of this concrete largely differed from the compressive strength results on concrete cores.

5.2 Concrete Observation by Fluorescence Microscope and Polarizing Microscope

The images of polished core surfaces observed by fluorescence microscope are shown in Figure 17. A considerable large number of 10~100μm width microcracks were observed in andesite particles from river gravel, but places also where they partially melted. In addition, cracks penetrated andesite particles with grain size around 1~2mm. Furthermore, cracks developing from the aggregates connected with cracks inside the cement paste and advanced in straight or radial pattern, thus forming a continuous cracking net. We infer that is this wide crack net formation in aggregates and cement paste that causes the massive concrete deterioration and brittleness. The micrographs of andesite particles in coarse and fine aggregates observed by polizing microscope are shown in Figure 18. As for coarse aggregates, cracks developed inside the andesite particles and were filled up with ASR gel. In fine aggregates cracks also penetrated the andesite particles and a kind of ASR gel similar to that of coarse aggregates formed and filled up the cracks.

6 THE RECONSTRUCTION OF PILLOW BEAM AND STRENGTHENING OF PIER No.4 AT ARISAWA BRIDGE

Figure 19 shows the temporary warren-truss supporting bent and all the old concrete demolished from the pillow beam was by jackhammer. The rehabilitation work of Arisawa Bridge consisted of the complete demolition and reconstruction of the pillow beam because the majority of stirrups were fractured at the bending point and the degree of deterioration in concrete due to ASR was such, that it became brittle. The bridge piers were earthquake strengthened with precast prestressed concrete confinement method. This construction technique is unique for seismic retrofitting of bridge piers and was applied on the grounds that the confinement effect by the surrounding PC steel ring could effectively control crack development and ASR expansion on the deteriorated pier [5]. Figure 20 shows an overview of pillow beam after reconstruction and bridge pier P4 after being retrofitted with PC confinement method.

7 CONCLUSIONS

The severely deteriorated bridge piers due to ASR, Arisawa Bridge, were precisely investigated. Based on the results of a survey on the fracture of steel bars in bridge piers, the beams were completely reconstructed. The main results obtained in this survey are summarized as follows:

(1) There is a strong possibility that surface coating could be trapping water inside the concrete for longer periods, thus enabling a steady ASR process even after repairing.

(2) The Danish method is effective for assessment of the reactivity aggregate which contain cristobalite and volcanic glass in Toyama prefecture.

(3) The content of andesite particles in the river sand and river gravel from the Jouganji River ranged from 30 % to 40 %, which was considered to be around its pessimum content.

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Table 1: Rock composition of aggregates Toyama prefecture rivers(%)

	Andesite	Rhyolite	Granite	Diabase	Sandstone	Others
Oyabe river	14.9	12.6	9.9	0	36.9	25.7
Shou river	16.8	16.8	21.7	4.2	27.5	13
Jinzu river	8.4	0	15	46.7	29.9	0
Jouganji river	40.7	5.5	46.9	6.9	0	0
Hayatsuki river	0	0	76	22	0	2
Katakai river	0	0	59.8	23.6	12	4.6
Kurobe river	1.7	0	33.2	13.1	42.6	9.4

Table 2: Crack distribution in P4 pier

	0.1〜0.5 (mm)	0.5〜1.0 (mm)	1.0〜2.0 (mm)	2.0〜 (mm)	Total (mm)
West face	7,779	3,906	11,591	2,637	25,913
East face	9,333	5,739	8,935	2,707	26,714
side surface(upstream)	2,922	3,246	6,184	2,722	15,074
side surface(downstream)	1,078	4,324	5,770	2,105	13,277
Beam subordinate surface	39	607	673	194	1,513
Total(cm)	21,151	17,822	33,153	10,365	82,491

Table 3: Fluorescent colored area in cores and concrete prisms

<table>
<tr><th>Type of core</th><th colspan="2">Fluorescence area (%)</th></tr>
<tr><td>Beam No.1</td><td>19.5</td><td rowspan="2">Average 20.7</td></tr>
<tr><td>Beam No.2</td><td>21.9</td></tr>
<tr><td>Caison No.1</td><td>10.5</td><td rowspan="2">Average 11.3</td></tr>
<tr><td>Caison No.2</td><td>12.1</td></tr>
<tr><td>Concrete prism*</td><td colspan="2">28.9</td></tr>
</table>

*: Stored in saturated NaCl solution for 6 months

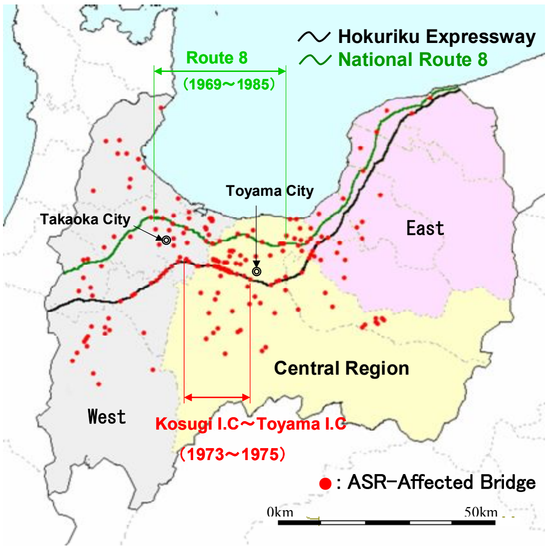

Figure 1: Location map of ASR-affected bridges in Toyama Prefecture

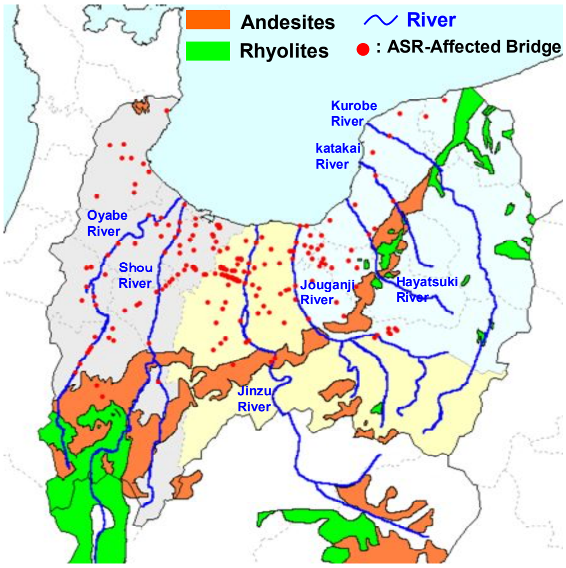

Figure 2: Geological map of reactive aggregates in Toyama Prefecture

Figure 3: Cracking in P4 pier 17 years after construction

Figure 4: Cracking in P4 pier 15 years after repairing

Figure 5: Cracking in underground and above ground sections of P6 pier

Figure 6: Cracking in River Section of P4 pier

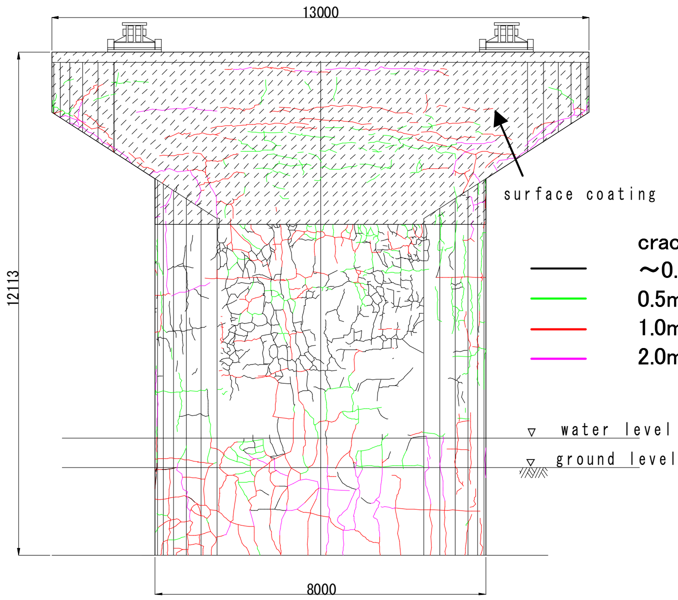

Figure 7: Cracking condition in P4 pier

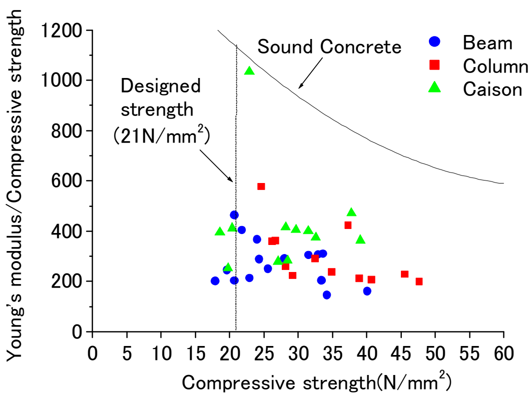

Figure 8: Relationship between compressive strength and Young's modulus of cores drilled from RC piers

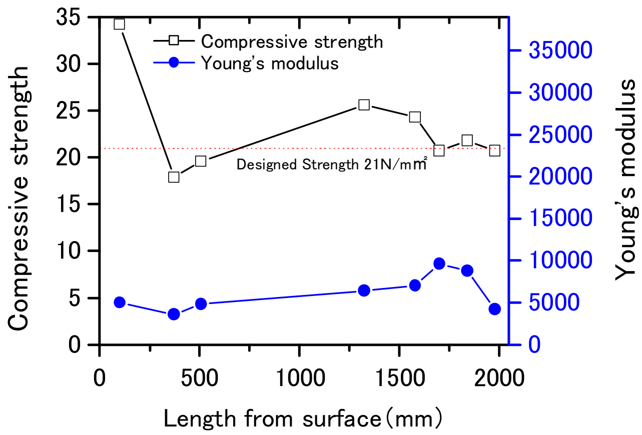

Figure 9: Compressive strength and Young's modulus of transversal cores drilled from pillow beam in P6 piers

Figure 10: External appearance of transversal core drilled from pillow beam in P6 piers（φ75×3,000mm）

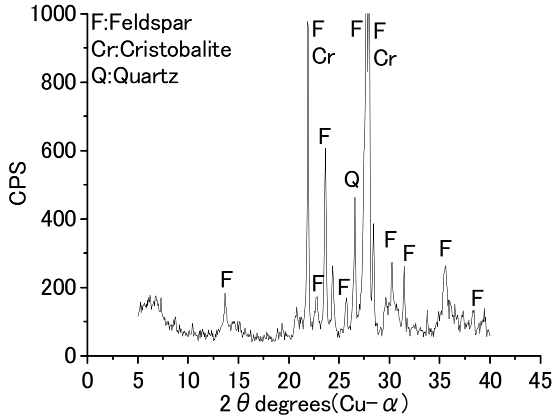

Figure 11: XRD pattern of andesitic stone contained in aggregates

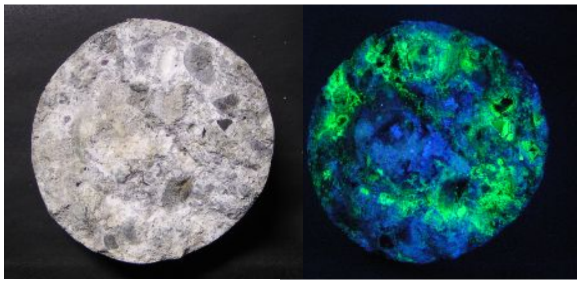

Figure 12: Core observation by uranyle-acetate fluorescence method (left: Before Test, right: After Test)

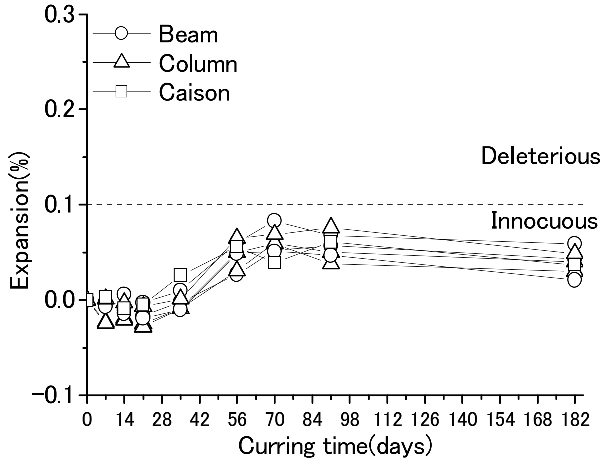

Figure 13: Expansion behavior of cores stored in fog box (JCI-DD2 method)

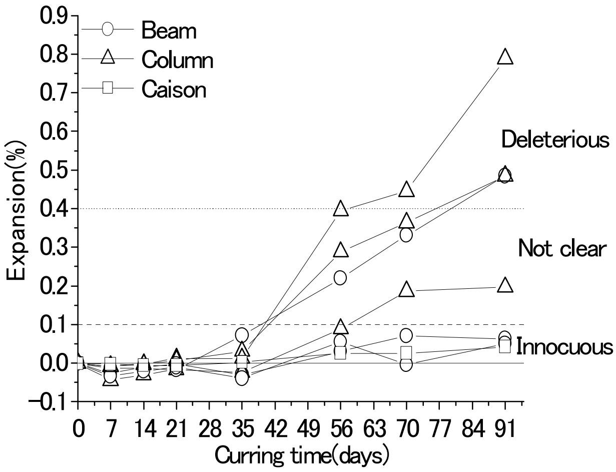

Figure 14: Expansion behavior of cores stored in saturated NaCl solution (Danish method)

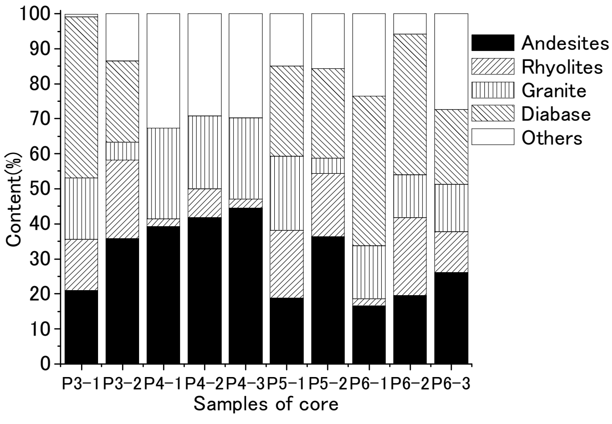

Figure 15: Composition of stones contained in aggregates

Figure 16: Crushed fragments of concrete rubbles

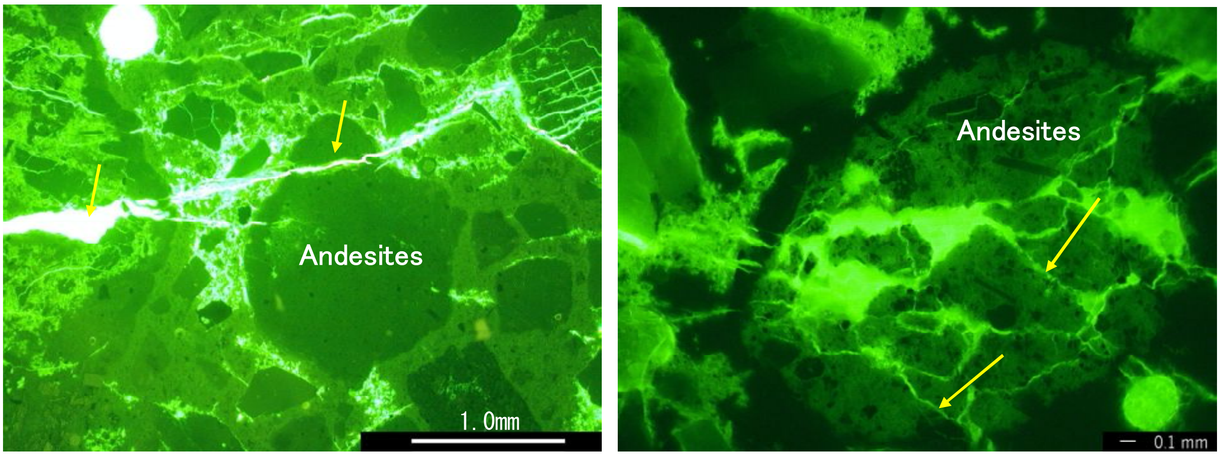

Figure 17: Visible fine cracks across fine particles on polished core surfaces（left: fine aggregate, right: coarse aggregate）

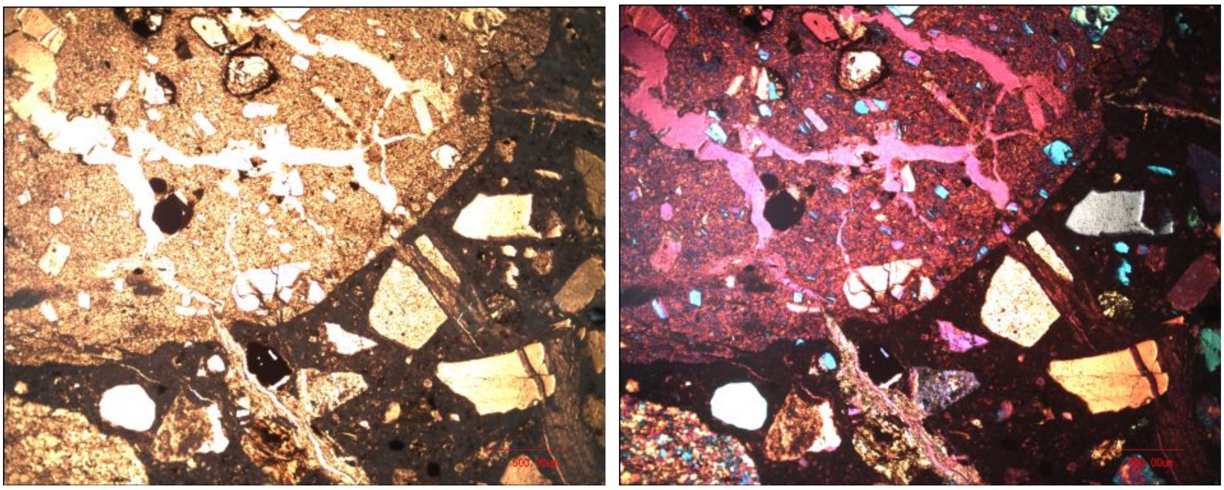

Figure 18: Optical microscopic observations of thin section of core samples（left: with plane polarized right , right: with crossed polars (gypsum filter)）

Figure 19: Temporary Supporting and Demolition of Beam

Figure 20: General over view of P4 pier after repairing with precast PC confinement method