THE FEATURE OF CRACKING IN PRESTRESSED CONCRETE BRIDGE GIRDERS DETERIORATED BY ALKALI-SILICA REACTION

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Abstract

There exist large numbers of ASR-affected prestressed concrete bridge girders (PC) in the Hokuriku district in Japan. In some cases of serious ASR, the PC girders show a significant cracking and/or a large deformation due to the strong longitudinal confinement by prestressing steel strand (PS) and the relatively low steel reinforcement ratio by other supplementary steel reinforcement. This paper describes the deterioration characteristics of cracking and/or deformation in ASR-affected PC girders based on the recent survey of about 30 bridges. In the laboratory test of cores, both the type of reactive aggregate used in concrete and the damage level of concrete caused by ASR are examined. Furthermore, the repair and strengthing methods applied to them are discussed in the relation to their effectiveness of controlling ASR expantion for a long term especially in a severe environment influenced by the sea water or deicing salt.

Keywords: ASR, cracking, PC girder, repair and strengthening method, cathodic protection

1 INTRODUCTION

Recently, large numbers of ASR-affected PC girders produced in the construction site or in the concrete factory have been discovered all over the nation by the recent survey of the JCI committee on ASR mitigation [1,2], although in the usual case using a normal-strength concrete around 24 N/mm^2, the occurrence of ASR was reduced to a significant degree since 1989 when the preventive measures for ASR mitigation had been adopted to the specification of JIS A5308 for the ready-mixed concrete. Concerning ASR in PC girders using a high-strength concrete of 40 N/mm^2 or 50 N/mm^2, it is recognized that there are both negative and positive effects on the occurrence of ASR and thereafter the successive extension of ASR cracking ; one is the accelerating effect due to the relatively large amounts of cement or alkalies used in concrete, and the other is the mitigating one due to the low water to cement ratio of 30% to 35 % since the water and alkalies do not easily diffuse and move in the concrete. Moreover, in concrete factories, the steam curing of concrete is also often applied mainly to the pretensioned PC girders so as to ensure the higher compressive strength at the early ages of de-moulding. It has been also pointed out by some researchers that the steam curing of pretensioned PC girders may increase a risk of cracking due to ASR and/or DEF [3,4].

In the Hokuriku district in Japan, in 1990s, PC girders have been actively treated by the surface coating of epoxy-resin or acrylic rubber materials in order to prevent PS from corroding, but it was hardly effective in controlling the expansion of concrete itself due to ASR, resulting in breaking of these surface coating within 5 years after repairing [5]. On the other hand, in the severe saline condion, some wires of PS

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were found out to be actually fractured, where the strengthening by the outside cable with PS or the bonding method with CFRP sheet was carried out from the veiw-point of restoring the load-bearing capacity of PC girders. Furthermore, the electro-chemical repair method such as cathodic protection has recently been applied even to the ASR-affected PC girders in PC bridges which are located on the seashore in the Noto peninsula in Ishiawa Prefecture. In such a case of combined deterioration of ASR and chloride induced steel corrosion, there are very few studies investigating the influence the direct electric current given in cathodic protection on the expansion of concrete in ASR-affected PC bridge, although some results in laboratory tests reveal that the application of cathodic protection possibly increases in the extensive ASR cracking [6]. The acceleration of ASR when the cathodic protection was applied may be mainly due to the elctro-migration of alkali ions from the surrounding cement paste towards the steel reinforcement, but its mechanisms is not fully understood.

In the first part of the paper, the characteristic feature of deterioration such as cracking and deformation occurred in ASR-deteriorated PC girders is introduced in their relation to the type of reactive aggregates used in concrete and the mechanical properties of cores taken from PC girders. In the second part, the effectiveness of surface coating and cathodic protection applied to them is discussed based on the results of a visual inspection and monitoring after the repair and strengthening.

2 OUTLINES OF INVESTIGATION IN PC GIRDERS

In the site of investigation, the deterioration level by ASR is basically examined based on the results of a visual inspection such as the intensity of cracking, the discoloration of surface concrete, the extrusion of ASR gel through cracks, the deformation of PC girder, the corrosion and/or fracture of PS and other supplementary steel reinforcement [7]. Also, the mixture proportions of concrete, the type of reactive aggregates and the environmental condition around PC bridge are documented as far as possible through the interview to the owners. Furthermore, by taking the cores from PC girders, the mechanical properties such as the compressive strength, the modulus of elasticity and the residual expansion capacity were examined in the laboratory. The regional map of ASR-affected PC girders in the Hokuriku district is shown in Figure 1. The structure type and environmental condition of the selected 6 PC bridges, in which the laboratory test using the cores was carried out, are presented in Table 1. The cores, which is 55 mm in diameter and 110 mm long, were used in all tests. The cores for residual expansion capacity test were stored both in 1N NaOH solution at 80 ^{0}C for 4 weeks and in saturated NaCl solution at 50 ^{0}C for 13 weeks. Futhermore, the petrographic observation such as the rock type of reactive aggregate and the intensity of microcracks around them were also conducted by means of a polarizing microscope for thin section samples of cores.

As mentioned above, there are two types of ASR-afffected PC girders : one is the pre-tentioned girder (pre-PC) with the span of less than 25 m which is produced mostly in the concrete factory in Nanao city, where the river gravel containing both reactive andesite and rhyolite particles supplied from the river in Toyama Prefecture was mainly used, and the other the post-tensioned girder (post-PC) with the long span of more than 30 m where the very reactive crushed andesite stone (As) or reactive river gravel (Rg) was respectively used in each area, because the concrete used in post-PC is supplied from the ready-mixed concrete plant near the construction site. Especially, the andesite stone produced in the northen area of Noto peninsula is well known to contain the very reactive cristobalite and large amounts of volcanic glass. In the alkali silica reactivity test for the aggregate in concrete, the former is assessed as “innocuous” according to the chemical test of JIS A1145 and the mortar bar test of JIS A1146, but assessed as “deleterious” according to the mortar bar test of ASTM C1260, although the latter is assessed as “deleterious” according to all tests of JIS A1145, JIS A1146 and ASTM C1260.

3 THE FEATURE OF DETERIORATION OF ASR-AFFECTED PC GIRDERS

3.1 The Cracking of Pre-PC Girders

The pre-PC girders prevailng in the Hokuriku district are classified into 3 types by the shape of girder: I type, T type and hollow-core type. The typical deterioration cases of pre-PC girders are shown in Figures 2, 3 and 4. In 1980s and 1990s, the hollow-core type with the rectangular section of 60 cm to 80 cm was popularly adopted in PC bridges across the small river in the town or city. It is apparent by our research work that the cracking due to ASR is more serious in this hollow-core type one with the central vacant section compared with T-shaped or I-shaped ones. In this type girder, the reflection cracking often extended from the upper flange of girder extended to the surface of asphalt pavement. The load-bearing capacity test was carried out for the hollow-core type girders removed in Kanazawa city in 2006. From the results of test, both the bending strength and deformation were enough in the common use if the PS in them did not corrode or fracture, although the horizontal cracks of girder were observed to be very serious. So, in the rehabilitation work, it is proposed to prevent the rainfall water or deicing salt from penetrating into the interior of girder by the execution of water-proofing membrane under the asphalt pavement by the improvement of finger joint.

3.2 The Cracking of Post-PC Girders

The typical deterioration cases of post-PC girders are shown in Figures 5 and 6. The large horizontal cracks along the execution joint which occurrs at the time of placing the concrete as the initial defect were often observed in the hollow-core box slab type post-PC girderes. The expansion of concrete due to ASR widened these cracks and large amounts of ASR gel extruded from them. The reactive crushed andesite stone was used in this girder. This type bridge is considered to easily allow the penetration of the rainfall water into the interior of vacant portion, leading to the more serious deterioration. On the contrary, in the T-shaped post-PC bridge, the cracks along the sheath of PS of web and lower flange occurred, which was more significant at the end portion of girder and in the outside girder, because the rainfall may mainly influence these portions. In this type of bridge, the surface coating after the injection of epoxy-resin into large cracks was carried out so as to prevent PS from corroding because the deicing salt was spread out. In the maintenance work of ASR-affected post-PC girders with the long span, it should be noted that the large deformation of girder may sometimes bring about the partial collapse of concrete at the expansion joint and near bridge shoes by colliding it to the edge of abutment. So, in the daily inspection, the clearance between the girder and the abutment should be also carefully observed and checked.

4 THE REPAIR AND STRENGTHENING OF ASR-AFFECTED PC GIRDER

4.1 The Surface Coating and CFRP Sheet Bonding for ASR-affected PC Girders

In the I-shaped and T-shaped pre-PC girders, the surface coating is not always required since the width of cracks due to ASR is as small as 0.5 mm. More importantly in the visual inspection for ASR-affected PC bridge, the surface coating is not desirable to check the extention of cracks, so the treatment with the silane or silicone materials, in which the surface of concrete can be easily checked, is presently more preferable to the bridge maintenance engineers. However, in the hollow-core box slab type pre-PC girders, the width of longitudinal cracks is often estimated to be more than 1mm, where the central vacant portion of girder is partially fulfilled with the rain water penetrating through reflection cracks on the surface of Asphalt pavement. So, it is presently recommended that first of all, the water kept inside should be flowed out by drilling from the lower flange of girder. As shown in Figure 7, the tranverse prestressing bar confining all girders was accidentally fractured and flied out by the combined effect of partial steel corrosion and expansion pressure induced by ASR. Only in such a severe case, the surface coating associated with the epoxy-resin injection will be required in the maintenance work of PC bridge. On the other hand, in post-PC girders in the severe saline environment, the surface coating has been conducted, however, which is not satisfied especially in its elongation and bonding strength ability.

The CFRP sheet bonding was also applied as one of the strengthening methods for ASR-afffected post-PC girders with the fracture of PS due to chloride induced corrosion, as shown in Figure 8. However, the adoption of this method becomes questionable whether or not how many years it can guarantee enough bond strength in the severe environment influenced by the rainfall and ultra-violet ray. Suprisingly, as shown in Figure 9, the 3 layers of CFRP sheet was easily broken out by the accident of contact with the boom of crane car.

4.2 The Cathodic Protection for ASR-affected PC Girders

The ASR-affected pre-PC girders electro-chemically repaired by cathodic protection with electrical conductive paint containing the carbon fibers coated with an highly oxidation resistant metal layer is shown in Figure 10. This bridge passed about 35 years after construction, where the river gravel containing the reactive andesite and rhyolite particles from the Toyama Prefecture was used in the T-type pre-PC girders and the filling concrete between them. The actual average direct electric current in cathodic protection was 5 mA/m^2 to 10 mA/m^2, which is considered to be smaller than those applied in the previous laboratory test [6]. During the period of about three years, the electric potential was relatively stable although it shifted toward noble direction in the summer and less noble direction in the winter depending on the temperature of concrete. Judging from the fact that all values monitored are well controlled in the noble state of more than -1000 mV, there is no risk in the hydrogen embrittlement of PS. Furthermore, the recovery in electric potential at the instant-off shows over the value of more than 100 mV, as shown in Figure 11. These monitaring data indicate that the catodic protection is working well even in the ASR-affected PC girders. On the other hand, the crack width on the surface of lower flange in PC girders was periodically measured by means of contact strain meter. As shown in Figure 12, the results of measurement also show that the direct electric current in cathodic protection does not accellerate ASR expansion and lead to the further difficult problem. It is considered that in the old PC bridge, the alkalies in the pore solution in concrete are almost consumed by fixing them into CSH and ASR gel, which becomes very low possibly compared with the threshold value in which ASR will occur again. This monitoring is stil going on other 2 PC bridges.

5 THE MECHANICAL AND MINERALOGICAL PROPERTIES OF CONCRETE CORES

5.1 The Mechanical Properties and Residual Expansion Capacity of Cores

The Relationship between the compressive strength and the modulus of elasticity in cores taken from 6 PC bridges is shown in Figure 13. It has been pointed out that the lower the ratio of elastic modulus to compressive strength (Ec/f'c), the higher the degree of deterioration due to ASR. For all cores tested, it is apparent that the reduction in compressive strength is more remarkable than that in modulus of elasticity. The compressive strength of cores taken from the B bridge was lower than its designed strength of 40 N/mm^2, but those from other PC bridges were satisfied with their designed strength. This may be attributable to the high reactivity of river gravel used in the B bridge and the severe environment across over the inland sea. Furthermore, in the F bridge with minor ASR cracks, the compressive strength of cores was as high as 90 N/mm^2, which is quite out of assumption for bridge engineers. It was later made clear that this 50 years old PC bridge was executed by connecting 2 PC segments with the very low water to cement ratio of 25 %, which was produced in concrete factory in Nanao city. From the result of core test, it is generally found out that the decrease in compressive strength of PC girders is not so significant. So, in the maintenance work, the degree of steel corrosion of PS caused by ASR cracks should be paid more attention to than the mechanical properties of concrete itself.

The residual expansion capacity of cores when stored in the 1N NaOH solution and in the saturated NaCl solution is shown in Figures 14 and 15, respectively. All cores expanded to a lesser extent when they were stored in the fog box specified by JCI DD-2. This may be mainly attributed to the leakage of alkalies in the moist environment. On the other hand, in the accelerated condition both in both the 1N NaOH solution and the saturated NaCl solution, some cores containing reactive river gravel significantly expanded with the period of storage, because the andesite and rhyolite particles in them began to react with the NaOH solution supplied from outside. However, in most cases of 30 years and 40 years old PC bridges, except for those using the crushed andesite stone, it is assumed that the residual expansion capacity of concrete has already become very low or negligible. Moreover, it can be pointed out that in PC girder with a low water to cement ratio, the reactive stone particles in concrete may mostly remain as it is because the moisure in concrete is always kept very low by the self-desiccation effect.

5.3 ASR Deteriolation Level Judged by Visual Inspection and Polarizing Microscope

The ASR deterioration level judging from the cracking level both in visual inspection of PC girder and in microscopic observation of thin section of cores is presented in Table 2. It is well recognized that the river gravel and river sand supplied in the Hokuriku district usually contains the volcanic rock stones of the andesite and the ryolite, and the sedimentary rock stones of melted tuff, chert and sand stone as the reactive ones. The most reactive stone in them is likely to be the andesite stone, where the reactivity of river gravel is proportional to the content of andesite stone in their geological compositions. The content of reactive andesite stone in the concrete examined in the petrographic work increased in the following order of the Kurobe river, the Kuzuryu river, the Sho river and the Joganji river. As shown in Figure 16, it is observed from the thin section sample of ASR-deteriorated cores that the andesite stone particles in the river gravel react very well compared with the rhyolite and melted tuff ones, where microcracks filled with ASR gel around them extensively develop to the cement paste, resulting in a formation of continuous microcrack net. It can be concluded that the evaluation of ASR deterioration level by the polarizing microscope is very useful for the diagnosis of concrete core, which is also almost consistent well with that obtained from the visual inspection for PC bridge.

6 CONCLUDING REMARKS

The ASR-affected 30 PC bridges located in the Hokuriku district were investigated, where their cracking caused by ASR significantly varied depending on the structure type of PC girder and the environmental condition around PC bridge. Concerning the pre-PC girders, the PC girders produced in the concrete factory in Tsuruga city, in which the crushed sand stone was used, showed little ASR, but those produced in the concrete factory in Nanao city in 1970s and 1980s, in which the reactive river gravel from Toyama Prefecture was used, often showed the serious ASR cracking especially in the halo-box type giirder. This is attributed to the rainfall water penetrated into the vacant portion of this type girder. On the other hand, the cracking level in post-PC girders was basically related to the locality of the aggregate used in the ready-mixed concrete plant, where the crushed andesite aggregate in the Noto peninsula in Ishikawa Prefecture was the most reactive and dangerous one, resulting in the serious cracking especially in the hollow-core box type and T-shaped ones.

In the repair and strengthening work for ASR-affected PC girders, if there is little or low risk of steel corrosion of PS itself, the authors strongly recommend to treat them with the silane or silicone materials so as to enable the daily visual observation on the surface of concrete structures. However, in a saline environment where PS in PC girder is severely corroded or partially fractured, the authors actively applied the CFRP sheet bonding method or the cathodic protection method in them. In such cases, it is more important to select the most appropriate repair and strengthening method, taking into considerations that the restore in the load-bearing capacity of PC giirder is most critical in the verification of the safety of PC bridge. Fortunately, in our trials, the applicaion of cathodic protection in ASR-affected girders did not accelerate ASR cracking at all. However, a long-term monitoring and further research will be needed to clarify the influence of cathodic protection on ASR.

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TABLE 1: The structure type and environmental condition of 6 PC bridges examined.

	Date (years)	Structure Type	Enviromental Conditions
A Bridge (Toyama)	1980 (30)	Post-PC T-type	Plain field (expressway) , de-icing salts
B-1Bridge (Ishikawa)	1982 (29)	Post-PC T-type	Sea area, deicing salts
B-2 Bridge (Ishikawa)	1982 (29)	Post-PC Box-type	Sea area, deicing salts
C Bridge (Ishikawa)	1971 (40)	Pre-PC Box-type	Plain field, de-icing salts
D Bridge (Ishikawa)	1975 (36)	Pre-PC T-type	Plain field, de-icing salts
E Bridge (Ishikawa)	1973 (38)	Post-PC Box-type	Sea area (expressway)
F Bridge (Ishikawa)	1961 (50)	Post-PC T-type	Plain field

TABLE 2: The ASR deterioration level of 6 PC bridges judged from surface cracking in visual inspection and microcracks in polarlizing microscope observation.

	River (Prefecture)	Cracking of PC Girders	Microcracks and ASR gel of Cores
A Bridge	Joganji-R (Toyama)	Very Low	Minor
B-1Bridge	Sho-R (Toyama)	Low	Moderate
B-2 Bridge	Sho-R (Toyama	Middle	Moderate
C Bridge	Sho-R (Toyama)	High	Severe
D Bridge	Sho-R (Toyama)	Middle	Severe
E Bridge	Kuzuryu-R (Fukui)	Middle	Moderate
F Bridge	Kurobe-R (Toyama)	Very Low	Minor

* River gravel usually contains the andesite, the ryolite and the melted tuff particles as reactive stone.

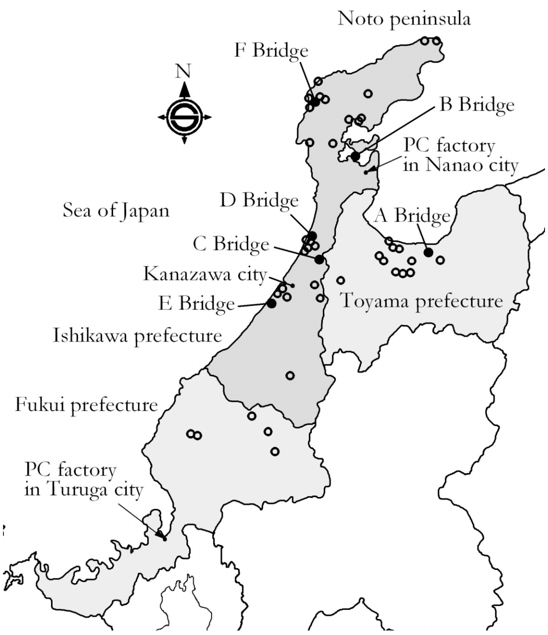

FIGURE 1: The regional map of ASR-affected PC girders investigated in Hokuriku district.

FIGURE 2: The cracking of hollo-core type pre-PC girder (Rg).

FIGURE 3: The reflection cracking on asphalt pavement.

FIGURE 4: The cracking of T-shaped pre-PC girder (Rg).

FIGURE 5: The cracking of hollow-core box type post-PC girder (As).

FIGURE 6: The cracking of hollow-core box type post-PC girder (Rg).

FIGURE 7: The tranverse prestressing bar fractured.

FIGURE 8: The strengthening of PC girders by CFRP sheet bonding method.

FIGURE 9: The CFRP sheet and girder broken.

FIGURE 10: The repair of PC girders by cathodic protection method.

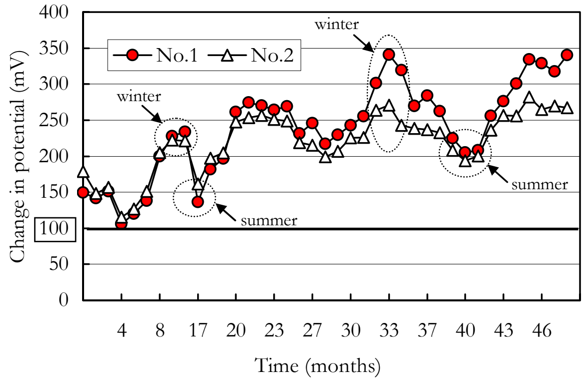

FIGURE 11: The change in potential at instant-off.

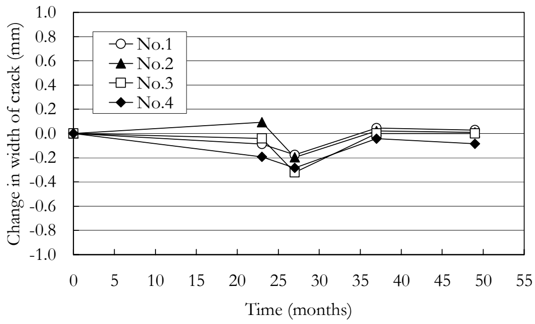

FIGURE 12: The change in width of cracks.

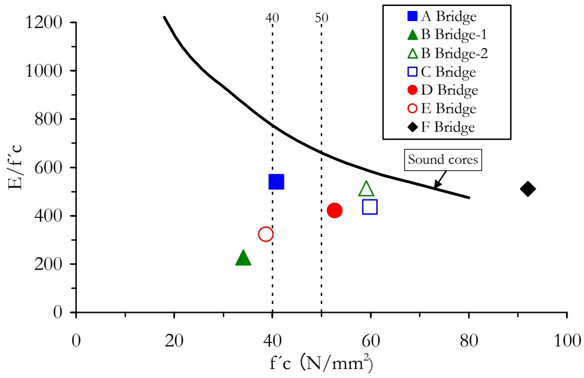

FIGURE 13: The Relationship between compressive strength (f'c) and modulus of elasticity (Ec) in cores.

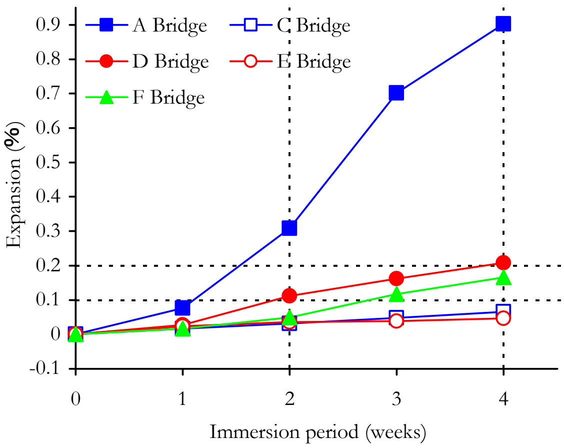

Figure 14: The expansion of cores stored in NaOH solution.

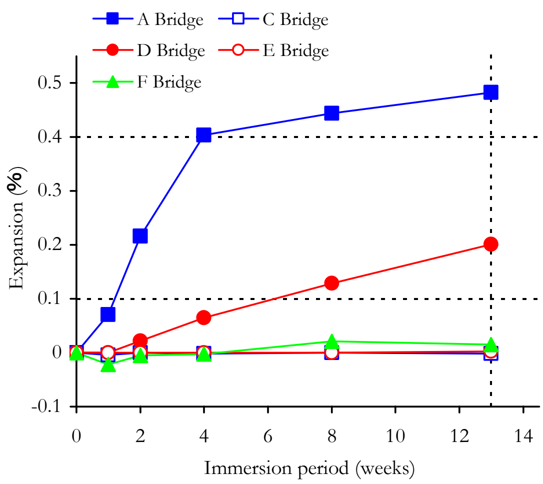

Figure 15: The expansion of cores stored in NaCl solution.

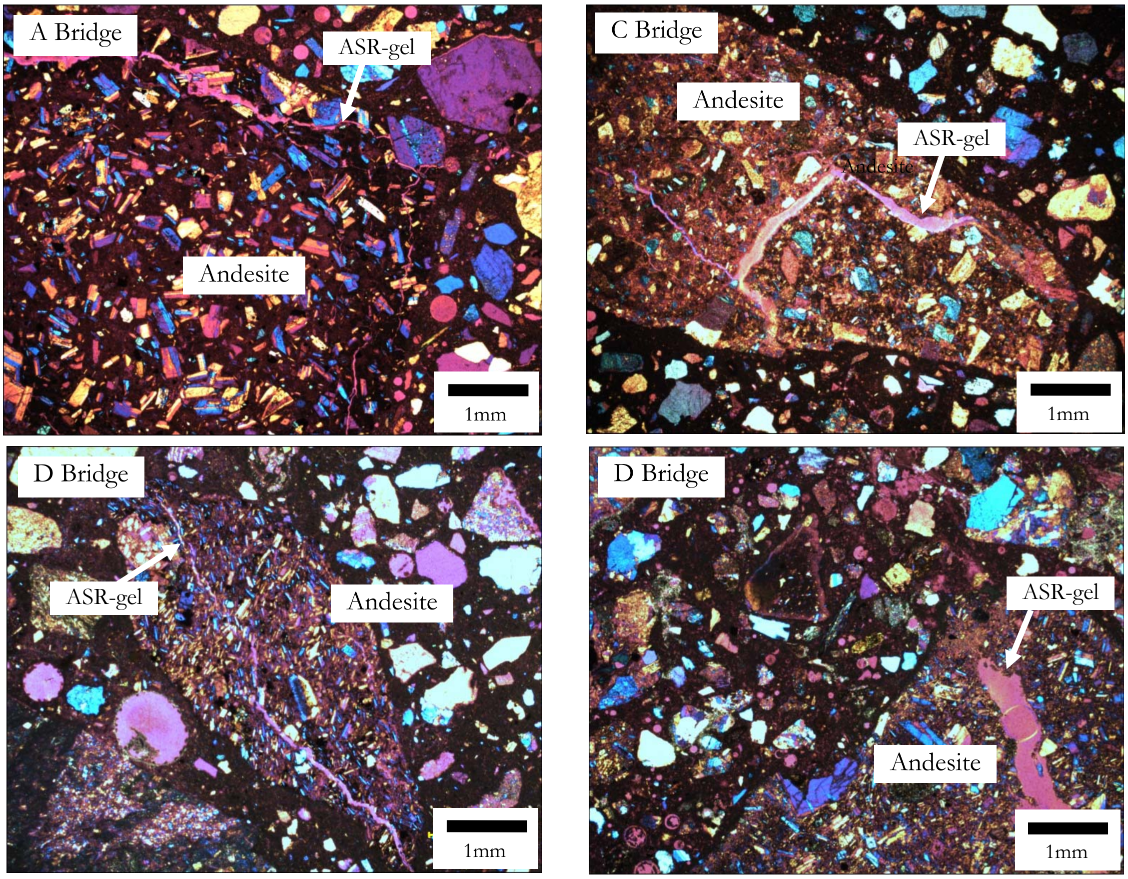

Figure 16: The petrographic observations for thin section of cores by porlizing microscope (crossed nicol with gypsum filter).