論文

THE EFFECT OF RESTRAINED LEVEL ON CRACKING RESISTANCE FOR CHEMICALLY PRESTRESSED REINFORCED CONCRETE

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ABSTRACT: The cracking resistance of CPRC beams was investigated by considering mainly cracking load, average crack width, and average crack spacing. The cracking resistance of CPRC was compared with RC with same reinforcement. The influence of restraining level on the cracking behaviors of CPRC was inspected by varying the reinforcing bar size. The effect of restraining level on the cracking load, average crack width, and average crack spacing can be interpreted by the chemical prestress and chemical prestrain of each specimen.

KEYWORDS: restraining level, chemical prestress (CPS), chemical prestrain (CPN), cracking load, crack width, crack spacing, deformability

1. INTRODUCTION

Crack in reinforced concrete structure is an unwanted property and can greatly downgrade the durability of the structure. Therefore, reducing the number of cracks and minimizing the crack width can enhance the durability and extend the service life span of the structure. Recently, there has been an interest in applying expansive agent to control the cracking of the structure. M.Tanimura et al. [1] reported that the expansive agent is remarkably effective in improving flexural performance and can reduce the average crack width of high-strength RC structures.

Chemically prestressed reinforced concrete (hereinafter, CPRC) is the reinforced concrete into which expansive agent is used to induce prestress effect. The CPRC can provide the better structural performances than that of normal RC. Okamura et al. [2] pointed out that the CPRC can increase the bending crack resisting capacity and can also retard the increase in strains of tensile reinforcement even after the occurrence of bending cracks. Furthermore, Ishimura et al. [3] reported the tension stiffening characteristic of CPRC under axial tension force and suggested that CPRC has high cracking resistance under tension.

In addition, the expansive concrete under restrained condition has the nonlinear behavior before cracking [4, 5]. However, the cracking mechanism of CPRC has been poorly known so far. The knowledge on the cracking load, crack width and crack spacing is limited and the effect by the restraining level is still not clear. Therefore, this study is aimed to investigate the cracking behaviors of CPRC by considering the restraining level and the environmental effect.

2. EXPERIMENTAL PROGRAM

Totally 15 chemically prestressed reinforced beams were tested in this study. The specimens are mainly separated into two groups; group A which is composed of three beams made from ordinary mortars and six beams made from expansive mortar and group B which is

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composed of two beams made from normal concrete and four beams made from expansive concrete. Sizes and reinforcement profiles of both group A and B are shown in **Fig. 1**.

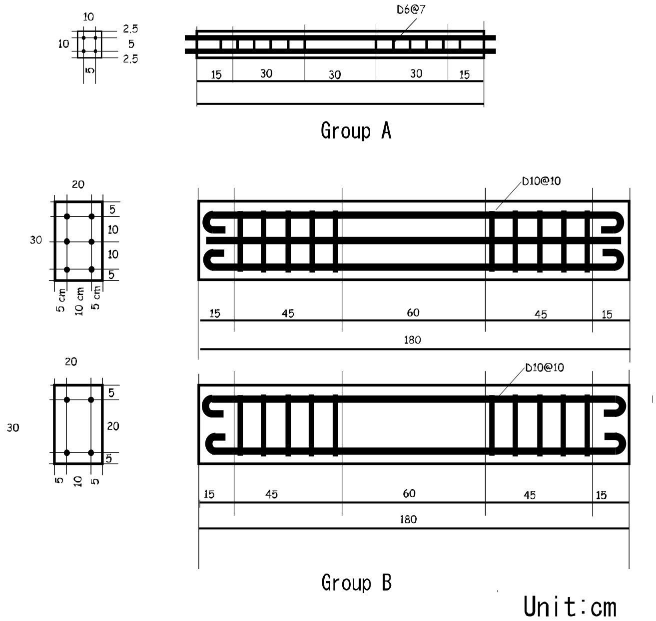

Fig.1 Details of test beams

To vary the restraining level in each specimen, the steel bar sizes and the number of longitudinal reinforcing bars were differed for each specimen. In group A, three sizes of steel bars; D6, D10, and D13 were applied, while only two sizes of steel bar; D13, D16 were used for beams in group B.

Besides the size of steel bars, the beams in group A were cured in different conditions. Half of CPRC in group A was cured under dry condition after 7 days while the others were cured under wet condition until loading at 14 days.

In group B, the numbers of longitudinal reinforcing bars were varied to investigate the effect of the restraining level. The details about the loading condition and curing condition are given in **Table1**.

Table 1 Details about loading and curing condition

Specimen	Shear Span (mm)	Constant Moment Span (mm)	Number of Bars	Curing Condition
A-4NW-6	300	300	4	14 days wet
A-4NW-10	300	300	4	14 days wet
A-4NW-13	300	300	4	14 days wet
A-4ED-6	300	300	4	7 days wet and 7 days dry
A-4ED-10	300	300	4	7 days wet and 7 days dry
A-4ED-13	300	300	4	7 days wet and 7 days dry
A-4EW-6	300	300	4	14 days wet
A-4EW-10	300	300	4	14 days wet
A-4EW-13	300	300	4	14 days wet
B-6N-13	450	600	6	14 days wet and 14 days dry
B-6N-16	450	600	6	14 days wet and 14 days dry
B-6E-13	450	600	6	14 days wet and 14 days dry
B-6E-16	450	600	6	14 days wet and 14 days dry
B-4E-13	450	600	4	14 days wet and 14 days dry
B-4E-16	450	600	4	14 days wet and 14 days dry

*The group of specimens is indicated by the first capital letter followed by the number indicating number of reinforcing bars, type of concrete; normal (N) or expansive (E), and curing condition; wet(W) or dry (D). The number at the end of each specimen's name means the size of reinforcing bar.

Table 2 Compressive strength of concretes and mortars

Type	Compressive Strength
Normal Mortar	49.5 MPa
Expansive Mortar	37.7 MPa
Normal Concrete	53.3 MPa
Expansive Concrete	65.7 MPa

Table 3 Yielding strength and Young's modulus of steel bars

Steel Size	Yielding Strength (MPa)	E_s (MPa)
D6	335	1.78×10^5
D10	370	1.93×10^5
D13	365	1.88×10^5
D16	378	1.86×10^5

The water to cement ratio of the mortars were 0.5 and those of concretes were 0.4. For both expansive concrete and expansive mortar, expansive agent 15% of total binder content was applied as the replacement of cement. **Table 2** and **Table 3** show the properties of mortar, concrete and steel bars in this experiment.

During the curing period, the tensile reinforcing bars' strains of each specimen were measured in order to obtain the prestrain. The 4-point loading was conducted at the age of 14 days for group A and at the age of 28 days for group B. To measure crack width during the loading, a series of 50-mm pie-gages was attached continuously in the constant moment span. Load was applied monotonically until failure of the beams, while crack initiation and propagation were monitored by visual inspection during testing.

3. EXPERIMENTAL RESULT

3.1 CHEMICAL PRESTRESS, CHEMICAL PRESTRAIN, AND CRACKING LOAD

The chemical prestrain (CPN) of each specimen was determined by measuring the strain of reinforcing bar. Since the distance between each bar is not so large, these CPNs can represent the deformation of concrete which can be assumed as uniform. The chemical prestress (CPS) is then calculated from the CPN by considering force equilibrium in the section.

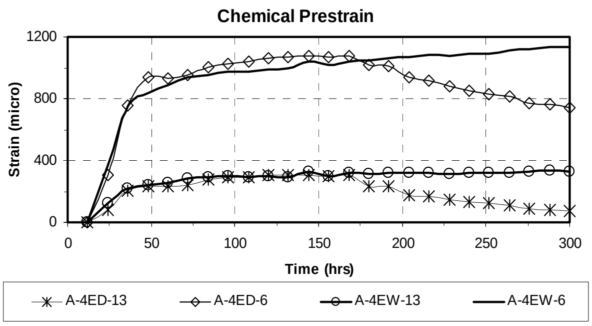

Fig.2 Example of chemical prestrain development in specimen

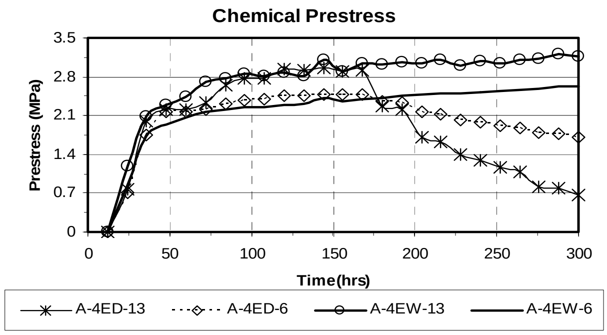

Fig.3 Example of chemical prestressing during curing

Table 4 Effect of deformability on the cracking load of CPRC

Specimen	CPN (micron)	CPS (MPa)	Fo(MPa)	Fcr (MPa)	Effect from Deformability (MPa)
A-4NW-6	small	small	0.00	0.67	-
A-4NW-10	small	small	0.00	2.45	-
A-4NW-13	small	small	0.00	2.87	-
A-4ED-6	739	1.71	2.01	4.57	1.89
A-4ED-10	210	1.11	1.41	4.98	1.12
A-4ED-13	70	0.68	0.94	4.01	0.20
A-4EW-6	1133	2.62	3.08	8.03	4.28
A-4EW-10	596	3.15	4.00	10.01	3.56
A-4EW-13	330	3.18	4.44	9.53	2.22
B-6N-13	-	-	0.00	28.20	-
B-6N-16	-	-	0.00	19.10	-
B-6E-13	274	0.65	9.17	67.88	30.51
B-6E-16	183	0.69	10.09	63.18	33.99
B-4E-13	333	0.52	7.38	68.58	32.99
B-4E-16	237	0.59	8.67	51.66	23.89

Fig.2 and **Fig.3** show the development of CPS and CPN in the CPRC. Under wet condition, the CPRC with higher reinforcement develops less chemical prestrain but is able to gain the higher prestress. However, if CPRC is subjected to drying, the loss of prestrain will be almost same regardless of the reinforcement ratio. This means that the CPRC with highest prestress will lose most of its prestress and has lowest prestress and prestrain. Therefore the curing condition and reinforcement ratio should be considered to effectively design CPRC.

Table 4 shows the CPN and CPS of each specimen. The cracking loads (F_{cr}) is also given in the same table. F_o is the load necessary to make the tensile strain of concrete at bottom fiber equal to zero or can be considered as the load to eliminate the CPS effect. F_o was calculated by considering that the concrete is in an elastic range. From the results it is clear that CPRCs can improve cracking load not only because the prestress effect but also the additional effect considered as the results of expansive concrete's deformation up to cracking.

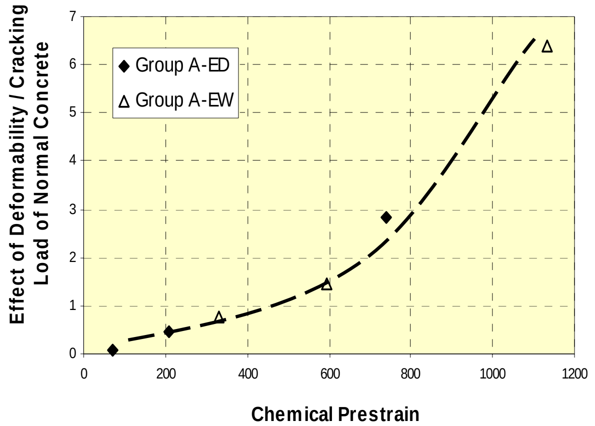

Fig.4 Relationship between the ratio of additional effect for cracking load and CPN

By normalizing these additional effects by the cracking load of normal concrete with same reinforcement, the comparison between CPRCs with different reinforcements can be made in **Fig.4** and the results show that this effect from deformability is increased when the chemical prestrain is larger and similar tendency could be obtained in different environmental conditions. This implies that the deformability of CPRC might be estimated by the CPNs in the stipulated condition.

3.2 LOAD-AVERAGE CRACK WIDTH RELATIONSHIP

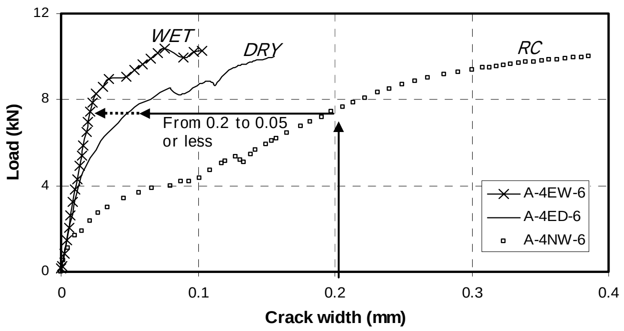

Fig.5 Load-average crack width of group A's beam with D6 bars

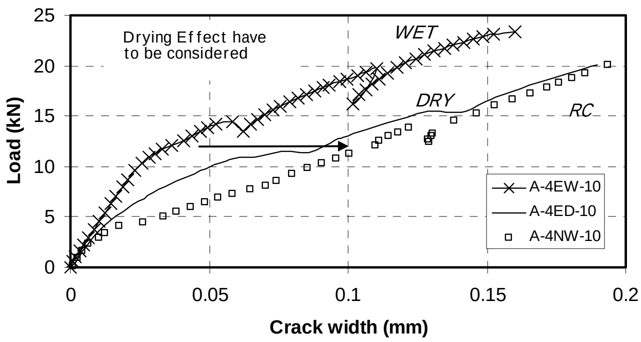

Fig.6 Load-average crack width of group A's beam with D10 bars

The example of load-average crack width relationship is given in **Fig.5** and **Fig.6**. It is clear that the average crack width of CPRC is much smaller at the same load level and crack width of 0.2 mm can be reduced to 0.05 mm in case of beams with D6 bars. However, the drying condition has significant effect on the crack width of CPRC in the relatively higher restrained condition (**Fig.6**).

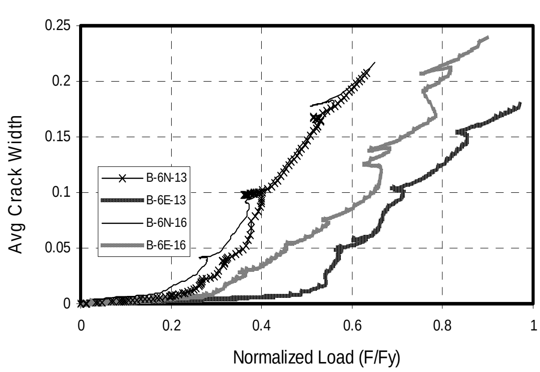

Fig.7 Example of an average crack width-normalized load relationship

To compare the CPRC with different reinforcement ratios, the normalized load, e.g., the ratio of load (F) to yielding load (F_y) is determined. The example of the relationship between average crack width and normalized load is given in **Fig.7**. The relationship of RC is almost same even though reinforcement ratios are different. However, the CPRC with lower reinforcement ratio and therefore larger prestrain shows lower crack width at the same load level. The results suggest that the reduction of crack width is better when the chemical prestrain is larger.

3.3 CRACK PATTERNS

Table 5 Crack spacing

Specimen	Average Crack Spacing	Ratio to Crack spacing of RC with same reinforcement
A-4NW-6	6.5 cm	1.00
A-4ED-6	8.0 cm	1.22
A-4EW-6	7.7 cm	1.18
A-4NW-10	6.0 cm	1.00
A-4ED-10	6.9 cm	1.15
A-4EW-10	7.2 cm	1.20
A-4NW-13	6.7 cm	1.00
A-4ED-13	8.1 cm	1.22
A-4EW-13	8.5 cm	1.28
B-6N-13	17.9 cm	1.00
B-6E-13	24.8 cm	1.38
B-6N-16	10.7 cm	1.00
B-6E-16	13.0 cm	1.21
B-4E-13	26.8 cm	-
B-4E-16	15.6 cm	-

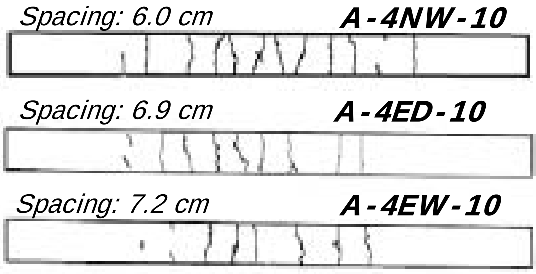

Fig.8 Example of crack profile of beams in A group

Table 5 shows the average crack spacing of each beam after the crack spacing becomes stable (no additional crack form afterwards). The crack spacing of CPRC is clearly larger than the crack spacing of RC with same reinforcement. The crack spacing is approximately increased of 15% to 30% in this experiment.

Fig.8 shows the crack profiles of the bottom surface of A-4NW-10, A4ED-10, and A-4EW-10. The effect of environmental condition is unclear and can be neglected in this structural condition.

Fig. 9 illustrates the comparison of crack patterns between RC and CPRC in B group. In general, for RC beams, the primary cracks take place when the concrete's stress at any point reaches the modulus of rupture and is followed by the generation of some primary cracks. When the load is increased, the cracked concrete portion will be pulled by bond with reinforcing bars and new secondary crack takes place when bonding stress overcome the strength of concrete portion [6]. Therefore, several secondary cracks appear in RC. However, these secondary cracks were rarely seen in CPRC due to two main reasons. Firstly, in CPRC, the shrinkage effect is most of the times eliminated. Secondly, the occurrence of secondary cracks in CPRC is prevented by the deformability of CPRC which relieves the tensile stress in concrete during the elongation.

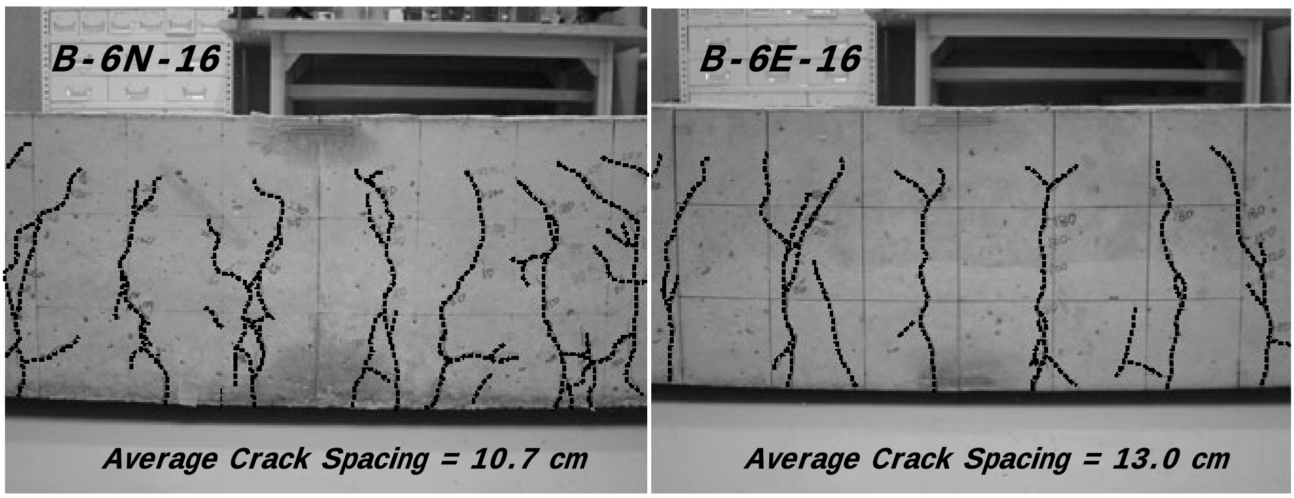

Fig. 9 Difference between the crack patterns between RC and CPRC after loading

4. DISCUSSIONS

The average crack width and average crack spacing of RC is essentially related by the bond-slip relationship and the longer crack spacing always lead to the larger crack width. In the other words, to reduce the crack width in RC, engineers usually have to compensate by increasing number of cracks. However, according to the results regarding cracking load, average crack width, and crack spacing, it is the interesting feature of CPRC that can reduce the crack width and minimize number of cracks at the same time.

The possible determinants are the deformability of the expansive concrete under restrained condition and the bonding between concrete and reinforcing bar in CPRC. To date, there is no clear evidence about the bond-slip properties of CPRC. However, the deformability of expansive concrete under restrained condition has been pointed out by previous researches [4,5] and this study suggests that the deformability is related to the prestrain or the deformation of CPRC before loading. However, the numerical method to effectively predict the deformability of expansive concrete has not been established yet.

5. CONCLUSIONS

1. The CPRC can bring notably high cracking load compared with RC and this enhancement of cracking load is not only because of the prestress effect but also due to the deformability of CPRC.
2. Crack width is reduced in CPRC. Further, this reduction is affected by the environmental condition and related to the deformability of CPRC. However, this phenomenon also involves of bond-slip of CPRC which is still not well-understood.
3. The CPRC's resistance to the secondary crack results leads to the larger crack spacing. This resistance is due to the absent of shrinkage and the deformability of expansive concrete.

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