CRACK-CONTROLLING PROPERTIES OF CHEMICALLY PRESTRESSED REINFORCED CONCRETE

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ABSTRACT

In order to control the cracking of structure, careful design with appropriate selection of material at the construction stage is important. The chemically prestressed reinforced concrete (hereinafter, CPRC) which is made from restrained expansive concrete is regarded as the efficient crack-proofing material. CPRC shows higher cracking resistance than normal RC; it owns smaller crack width and less cracks in bending structure. The application of CPRC is therefore a promising way to improve the appearance and deformability of the infrastructure. The cracking resistance can be related to the chemical prestress and chemical prestrain.

1. INTRODUCTION

Due the natural weakness of concrete under tension, cracks can easily take place in the structure if the tensile stress exerted on the concrete part exceeds the tensile strength. These cracks can cause not only the durability problem but also the aesthetic problem. In order to limit the degree of problems to the acceptable limits, the maximum crack width and number of cracks in the structure should be controlled carefully.

In general, the rehabilitation after cracking is complicated and cost consuming. It is therefore preferable if the deterioration from cracking can be diminished in advance and the application of the chemical prestressed reinforced concrete (also known as CPRC) is recognized as one of the promising methods to achieve that objective.

The CPRC have been investigated by many researchers and it has been found out that CPRC has the better structural performance than normal RC. As Okamura (1979) showed, CPRC can increase the bending cracking resisting capacity and retard the increase of rebar's strain even after the occurrence of bending cracks. In addition, it have been suggested that the restrained expansive concrete in CPRC has distinguished nonlinearity especially during its early age (Hosoda, 2000).

Even though the merits of CPRC have been pointed out so far, the application of CPRC has still been ignored by engineers due to lack of support data and design criteria. Therefore, this study aims to investigate the cracking resistant properties of CPRC and its key parameters in order to establish the design method of CPRC.

2. BACKGROUND

In CPRC, the prestressing effect is mainly induced by the expansion of expansive concrete; when expansion takes place, rebars are then pulled and compressive stress is gradually developed in concrete at the same time. If the cross-section of the member is symmetric and there is no slip between the concrete and rebars. The total compressive force in concrete is equal to the summation of the tension force in all rebars.

$$\sum E_s A_s \varepsilon_{s,pre} = A_c \sigma_{c,pre} \quad (1)$$

According to above equation, $\varepsilon_{s,pre}$ is the so-called 'chemical prestrain' or the initial strain for rebars caused by the volume change of the member and $\sigma_{c.pre}$ is the so-called 'chemical prestress' which is the corresponding stress exerted on concrete. Both chemical prestrain and chemical prestress are important to describe the cracking resistance of CPRC.

3. EXPERIMENTAL PROGRAM

Totally 15 chemically prestressed reinforced beams were tested in this study. The specimens were mainly separated into two groups; group A which was composed of three beams made from ordinary mortars and six beams made from expansive mortar and group B which was composed of two beams made from normal concrete and four beams made from expansive concrete. Sizes and reinforcement profiles of group A and B are shown in *Figure 1*.

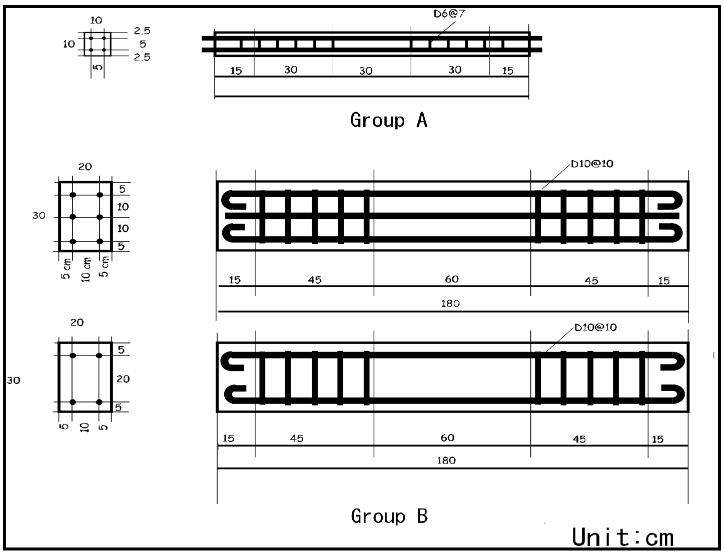

Figure 1: Geometric details of the specimens

To vary the restraining level in each specimen, the steel bar sizes and the number of longitudinal reinforcing bars were different 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 were 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 *Table 1.*

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 rebars

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

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

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.

4. EXPERIMENTAL RESULTS

4.1 Enhanced cracking load of CPRC

Table 4 shows the cracking load (F_{cr}) of each specimen observed during loading. It is clear that the cracking loads of CPRCs were much better than those of RC with same geometry. The chemical prestress (hereinafter CPS), chemical prestrain (hereinafter, CPN), and the load that diminishes the effect of chemical prestress (Fo) are also given.

Table 4: Chemical Prestress, Chemical Prestrain, and Cracking Load

Specimen	CPN (micron)	CPS (MPa)	Fo(MPa)	Fcr (MPa)	Enhancement of cracking capacity (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

The chemical prestrain was measured directly from the strain gages during the curing period and the corresponding chemical prestress was then calculated according to *Equation 1*.

The “Fo” was calculated as the load that release all prestressing stress at the bottom fiber of the member as illustrated in *Figure 2*.

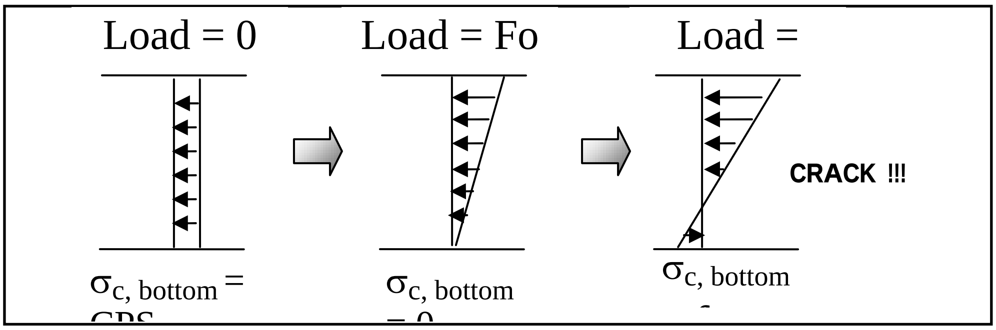

Figure 2: The meaning of Fo and Fcr

The comparison of the cracking capacity between CPRC and RC was made by comparing the different between cracking load and “Fo” in order to exclude the effect from prestress. The calculation was made as shown in *Equation 2* and the comparison is shown in the last column of *Table 4*.

$$\text{Enhancement of Cracking Capacity} = \left(F_{cr} - F_o\right)_{CPRC} - \left(F_{cr} - F_o\right)_{RC} \qquad (2)$$

This additional enhancement of cracking capacity is considered as the result of large non-linear deformation under tension of restrained expansive concrete that can not be explained by a conventional cross section analysis.

4.2 Crack width

Figure 3 and *Figure 4* are the examples of load-average crack width relationship obtained from the experiment. The average crack width of CPRC is much smaller to that of normal RC at the same load. For instance, in case of beams with D6 bars, the crack width of 0.2 mm can be reduced to 0.05 mm. However, it is valuable to noted that drying condition has a significant effect on the crack width of CPRC.

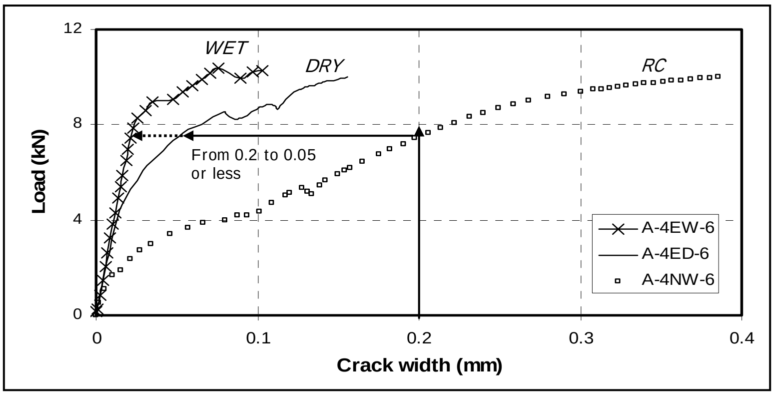

Figure 3: Load-average crack width relationship of group A’s beam with D6 bars

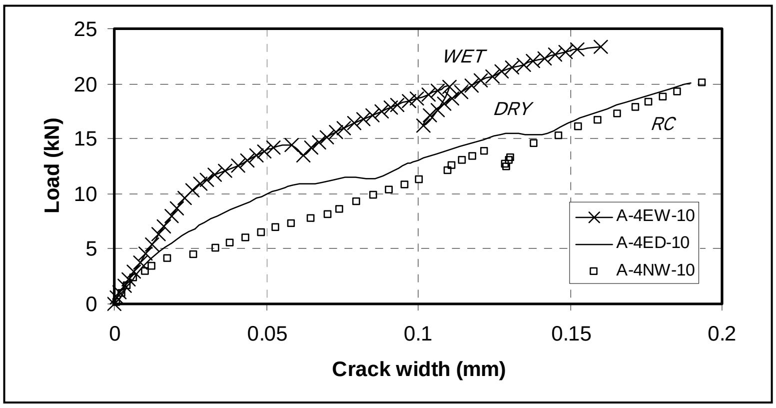

Figure 4: Load-average crack width relationship of group A's beam with D10 bars

In order to compare the CPRC with different reinforcement ratios, the normalized load, e.g., the ratio of load (F) to yielding load (F_y) is calculated. The example of the relationship between average crack width and normalized load is given in *Figure 5*. 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. These results (*Figure 3-5*) suggest that the reduction of crack width is better when the chemical prestrain is larger.

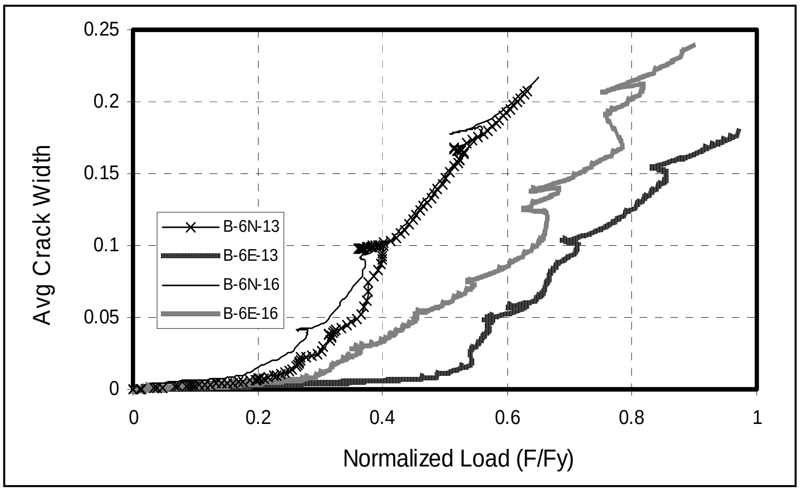

Figure 5: Example of average crack width-normalized load

4.3 Crack Patterns

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 from 15% to 30% in this experiment. It is valuable to note that the crack spacing of CPRC observed in this experiment have no clear relationship with chemical prestress or chemical prestrain.

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	-

Additionally, *Figure 6* 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 secondary crack takes place as soon as bonding stress overcome the strength of concrete portion. Therefore, several secondary cracks appear in RC. However, these secondary cracks were rarely seen in CPRC. This may be due to two main reasons. Firstly, in CPRC, the shrinkage effect can be perfectly eliminated; therefore the tensile stress capacity of CPRC is not reduced by the volume change. Secondly, the occurrence of secondary cracks in CPRC is partly prevented by the deformability of CPRC which relieves the tensile stress in concrete during the elongation.

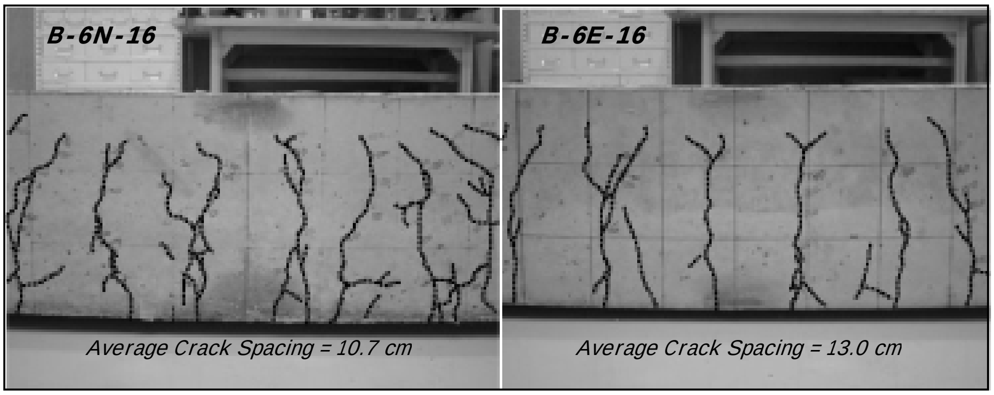

Figure 6: Difference between the crack patterns between RC and CPRC after loading

5. DISCUSSIONS

Generally, the crack width has the close relationship with the stress of the rebars at crack section and this concept has been adopted in current design equation for the crack width of RC. However, according to the experimental results, the current design equation is clearly not sufficient for prediction of crack width of CPRC.

Additionally the crack width and crack spacing of RC is 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 design equation of CPRC that satisfy aforementioned property of CPRC should be established in order to safely and cost-effectively apply the CPRC to control the crackings.

6. CONCLUSIONS

1. The CPRC can bring notably high cracking load compared with RC. This enhancement of cracking load is not only because of the prestressing effect but also due to the deformability of CPRC.
2. Crack width is reduced in CPRC. This reduction is affected by the environmental condition.
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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