- Technical Paper -

BONDING CHARACTERISTICS OF CPC AND RC UNDER UNIAXIAL TENSION

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ABSTRACT

Bond of RC and CPC under tension were tested. Effects of cross section's size and amount of expansive agent were also investigated. The strain distribution of rebar was measured from strain gages attached with 20mm interval. Local bond, slip and average bond stress were then calculated. The results show that bond of CPC near loading end is higher than that of RC, although the average bond is almost same. The effects of cross section and coarse aggregate are significant. The results partly explain the higher tension stiffening effect and smaller crack width of CPC.
Keywords: chemical prestress, chemical prestrain, expansive agent, bond, slip, strain distribution, tension

1. INTRODUCTION

Chemically prestressed concrete (CPC) have been extensively applied to relieve cracking problem and improve structural properties at the same time. When CPC is employed as flexural member, it can reduce crack width and minimize number of cracks [1]. On the other hand, deflection can be considerably reduced because of its enhanced tension stiffening effect [2]. Cracking properties and tension stiffening effect are highly related with bonding characteristics. Based on aforementioned properties of CPC, it is likely that its bond characteristics differ from those of reinforced concrete (RC). Information about bonding characteristics of CPC is required to make an explanation about its behaviors. Nevertheless, there has been no investigation on bond of CPC under tension.

This study is hence an attempt to investigate the bonding characteristics of CPC by measuring strain distribution of rebar in tensioned RC and CPC prisms and derive bond and slip from these strain distributions.

2. TEST PROGRAMS

2.1 Specimens

Nine RC and CPC prisms were prepared. The parameters varied were cross sectional area, type of materials, and amount of expansive agent (30, 45, and 60 kg/m^3). List of all specimens is given in Table 1. Specimens in the first series, which were composed of RC, CPC, reinforced mortar (RM) and chemically prestressed mortar (CPM), had a cross section of 100x100 mm^2.

Table 1 List of specimens

Series	Name	Type of Material	Expansive Agent (kg/m^3)
1st	N-10	RC	-
	E60-10-1	CPC	60
	E60-10-2	CPC	60
	NM-10	RM	-
	EM90-10	CPM	90
2nd	N-20	RC	-
	E30-20	CPC	30
	E45-20	CPC	45
	E60-20	CPC	60

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Series 2 consisted of RC and CPC specimens with different amount of expansive agent and a cross-section of 200x200 mm^2. Profile of specimens is illustrated in Fig. 1. An unbonded zone of 100 mm and spiral reinforcement were provided to avoid free ends of prisms from acting as pre-cracks. 30-mm thick plates and nuts were used to restrain the expansion of all specimens. Five holes were provided in these plates. The middle hole is for the reinforcement and the other four are for the bolts which are used to fix acrylic plates to specimens.

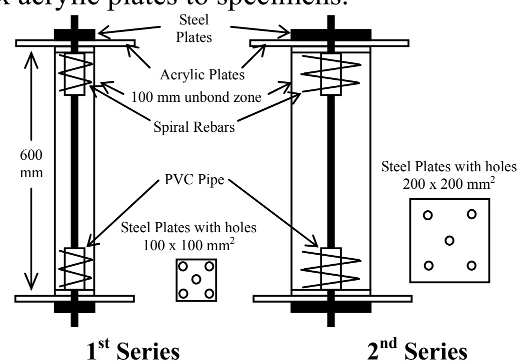

Fig.1 Profile of specimens

2.2 Materials

(1) Concrete and mortar

The mix proportions and 28-day compressive strengths are given in Table 2. Water to cement ratio was 0.5 and sand to aggregates ratio was 0.48 for all mixes.

Table 2 Mix Proportions and Strengths

	Unit Content (kg/m^3)					Strength
	W	C	E	S	G	(MPa)
N	165	330	0	860	956	37.20
E30	165	299	30	860	956	49.63
E45	164	283	45	860	956	52.44
E60	164	268	60	860	956	35.33
NM	254	507	0	1346	-	38.51
EM	252	411	90	1346	-	33.96

The compressive strengths of E30 and E45 were larger than those of N and E60. This might be because the casting date of N and E60 is different from that of E30 and E45 so that the strength was affected by the mixing temperature. Here it should be noted that the compressive strengths were measured from unrestrained cylinder specimens whose condition is different from the restrained ones. Therefore it is not used to represent the strength of the restrained prism specimens in this study.

(2) Rebar

Specially grooved screw-shaped D19 bars were used as a reinforcement of all specimens. The Groove was 4mm wide and 2.5mm deep. Net area of reinforcement was 246.5 mm^2. Yield strength and Young's Modulus were 730 N/mm^2 and 183200 N/mm^2, respectively. Yielding took place when strain approximately reached 4000 μ.

2.3 Measurement, Curing, and Loading

38 strain gages were attached to each bar in the groove with an interval of 20 mm. Special strain gages with thin cable (diameter of 0.18 mm) were used. The cables of these strain gages were placed inside the grooves along the reinforcing bar. The grooves were then filled with paraffin to coat the strain gages and cables. Strains during curing were also measured by these strain gages. All specimens were covered by wet clothes until 12 hrs before loading. Uniaxial tensile loading was conducted at the age of 28 day. The restraining steel plates were removed before loading.

3. EXPERIMENTAL RESULTS

3.1 Chemical Prestress and Chemical Prestrain

The distribution of expansive strain was measured during the curing period and the chemical prestrain (CPN) was determined by averaging the strain of reinforcing bar before loading and chemical prestress (CPS) was then calculated based on the equilibrium of the section. CPS and CPN of each specimen are given in Table 3.

Table 3 CPS and CPN

Series	Name	Chemical Prestrain (μ)	Chemical Prestress (N/mm^2)
1st	N-10	0.2	0.001
	E60-10-1	230.0	1.070
	E60-10-2	199.0	0.925
	NM-10	-3.3	-0.153
	EM90-10	400.7	1.863
2nd	N-20	0.5	0.001
	E30-20	66.2	0.152
	E45-20	187.9	0.430
	E60-20	392.0	0.898

3.2 Strain Distribution of Rebar

In this section, the strain distribution of reinforcement caused by loading is shown. The strains of all points are thus set to zero initially. The strain distribution of rebar in each specimen at different load levels is given in Fig.2-Fig.5. In the case of small cross section, the slope of strain distribution in CPC was steeper near the end and become more flat at inner part. Although the shape of strain distribution is different, the strain at middle of specimen is almost the same (Fig.2).

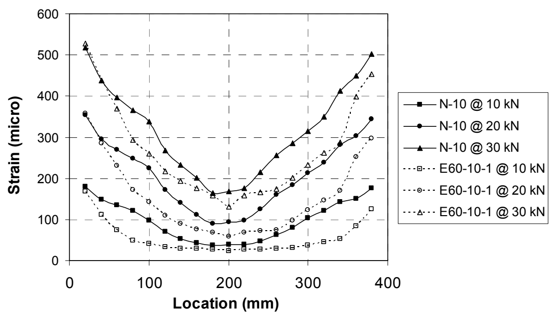

Fig.2 Strain distribution of RC and CPC (expansive agent of 60 kg/m^3) with 100x100 mm^2 cross section

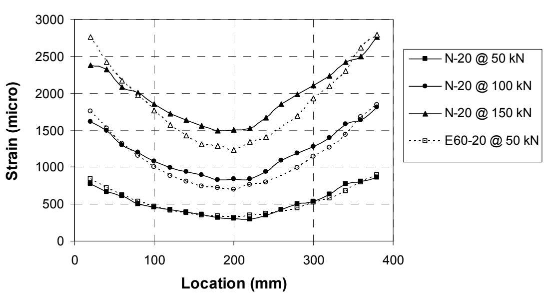

Fig.3 Strain distribution of RC and CPC (expansive agent of 60 kg/m^3) with 200x200 mm^2 cross section

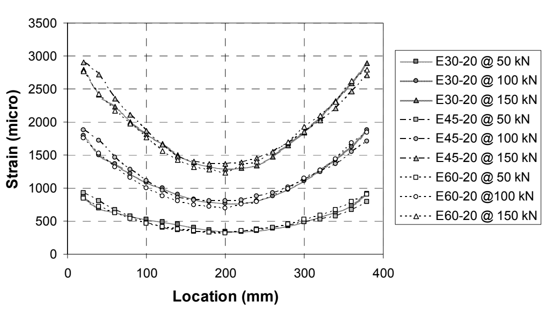

Fig.4 Strain distribution of RC and CPC with different amounts of expansive agent

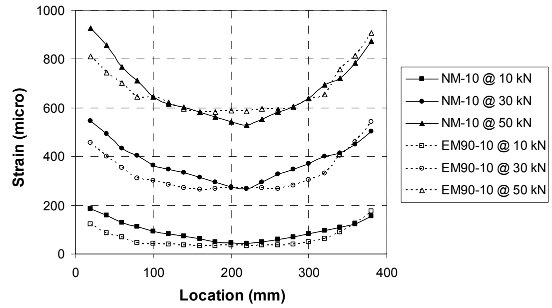

Fig.5 Strain distribution of RM and CPM

On the other hand, in the case of larger cross section, there is no significant difference in strain distribution when the load is low. However, strain distribution became dissimilar when load increased (Fig.3). In addition, the strain at middle of CPC with larger cross section was remarkably reduced.

Fig.4 shows the effect of expansive agent's dosage. The results indicate that CPC with 30-60 kg/m^3 of expansive agent possessed almost same strain distribution. Hence, it is concluded here that the effect of chemical prestress as well as chemical prestrain on bond can be simply ignored.

Fig. 5 shows the strain distribution of specimens made from mortars which is unique. Initially, mortar specimens showed similar behaviors with concrete specimens. Nevertheless, CPM (EM90-10) maintained its flat strain distribution even under comparatively higher load (above 50 kN). Its strain at middle was finally larger than that of RM (NM-10). This implies that the presence of coarse aggregate considerably influences properties of expansive concrete.

3.3 Calculation of Local Bond and Slip

Since local bond is defined as the change in stress of reinforcement at any point, it can be determined as a slope of strain distribution at any point. In this study, 2nd polynomial function was created by fitting three adjacent data points and the local bond can then be determined by Eq 1.

$$\bar{\tau}_x = \frac{E_s D}{4}\frac{d\varepsilon_x}{dx} \qquad (1)$$

where,

$\bar{\tau}_x$: bond stress at any point x (N/mm^2)

ε_x : strain at any location x

E_s : Young's modulus of rebar (N/mm^2)
D : rebar's diameter (mm)

Since it is impossible to measure strain of concrete around reinforcement, the slip in this study is defined as a displacement of the rebar at the point concerned from the fixed point which has no slip in concrete instead of the a relative displacement between bars and concrete. In addition, slip at the middle of rebar is assumed to be zero. Therefore, the slip of any point x can be calculated as follows.

$$S_x = \int_{l/2}^{x} \varepsilon_x dx \qquad (2)$$

$$S_{x=l/2} = 0 \qquad (3)$$

where,
S_x : slip (mm)

3.4 Local Bond

Fig.6 shows the comparison of bond distribution between N-10 and E60-10-1. It can be seen that bond of N-10 is larger at the middle part of specimen while smaller at the end of specimen. Fig.7 shows same comparison of N-20 and E60-20. Bond of N-20 is lower at the middle part of the specimen. Although the calculated bond is not perfectly balanced because a small fluctuation in strain distribution can greatly affect the bond stress, these results indicate the different shape of bond distribution between RC and CPC. Besides, they imply that change in cover depth can drastically influence the bond distribution of RC and CPC under direct tension. This effect of cover depth is likely to relate with the length of specimen. In authors' opinion, there is a good possibility that specimen with 100x100 mm^2 cross section will give similar bond distribution with 200x200 mm^2 if length is sufficiently shortened. This behavior is related with the boundary condition as reported by Shima [3].

In case of EM90-10 (Fig. 8), the bond distribution at each end is not same. This might be caused by an unexpected local damage at the ends. However, bond stress at the middle part (from 150 mm to 300 mm) was almost zero. It is possible that the expansive mortar could distribute the deformation in this range. In short, the restrained mortar may be weaker in terms of bond strength but allow reinforcement to deform more before cracking.

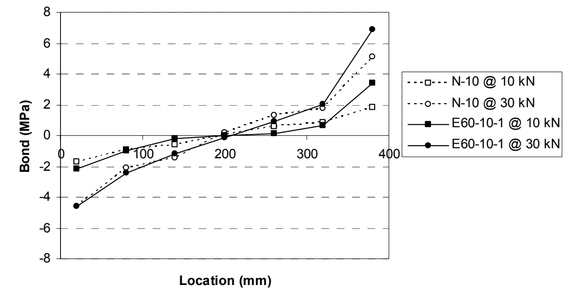

Fig.6 Bond distribution of RC and CPC (expansive agent of 60 kg/m^3) with 100x100 mm^2 cross section

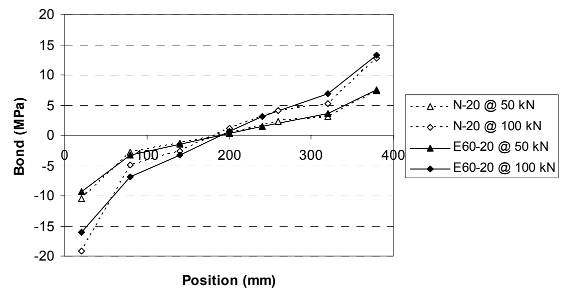

Fig.7 Bond distribution of RC and CPC (expansive agent of 60 kg/m^3) with 200x200 mm^2 cross section

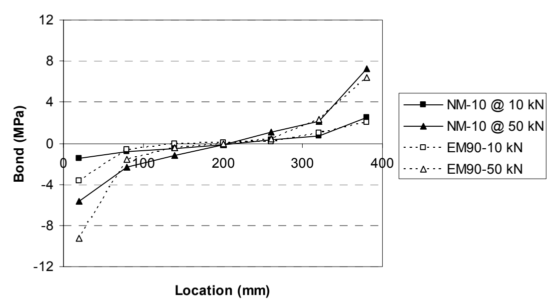

Fig.8 Bond distribution of RM and CPM

3.5 Slip

Fig. 9 and Fig. 10 compare slip of RC and CPC. The slip of CPC is appreciably smaller than that of RC especially at higher load. Fig 11 shows the relationship between load and slip of RC and CPC with small cross section. The relationship of RC is linear while CPC shows some non-linearity at beginning then follows by linear relationship when load is higher than 20 kN. The relationships between load and slip of RC and CPC are almost parallel to each other for loads above

20 kN. However, the difference of slip between RC and CPC with larger cross section gets larger when the load increases.In case of N-10 and E60-10, the difference in slip is approximately 0.01 mm at 30 kN. While, in the case of N-20 and E60-20, the difference in slip is approximately 0.0003 mm, 0.017 mm, and 0.024 mm at 50 kN, 100 kN, and 150 kN, respectively.

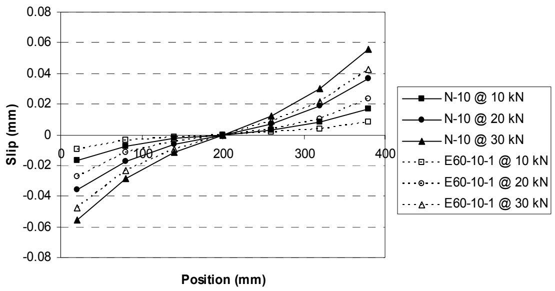

Fig.9 Slip distribution of RC and CPC (expansive agent of 60 kg/m^3) with 100x100 mm^2 cross section

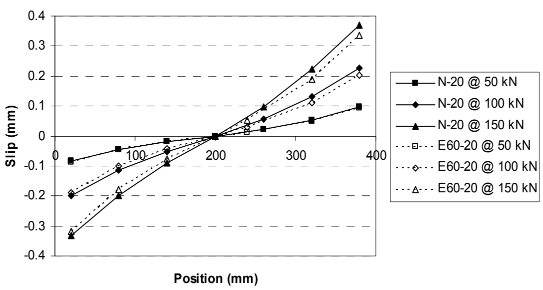

Fig.10 Slip distribution of RC and CPC (expansive agent of 60 kg/m^3) with 200x200 mm^2 cross section

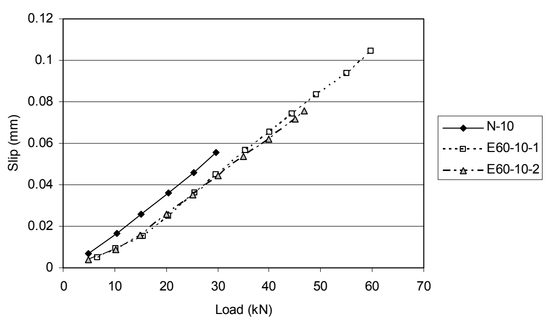

Fig.11 Load-slip relationship of RC and CPC (expansive agent of 60 kg/m^3) with 100x100 mm^2 cross section

This reduction in slip can be related to the smaller crack width of CPC because the crack width is the difference between elongation of reinforcement and concrete. Therefore crack width is smaller if the slip is smaller.

3.6 Average Bond

Average bond ($\bar{\tau}_{avg}$) is an average of bond stress along the specimen and can be calculated according to Eq. 4.

$$\bar{\tau}_{avg} = \frac{P - E_s A_s \varepsilon_{s,middle}}{ul/2} \qquad (4)$$

where,
P : external load (kN),
$\varepsilon_{s,middle}$: strain at the middle of specimen
u : circumference of rebar (mm)
l : net length of specimen (mm)

The relationships between load and average bond are shown in Fig.12 and Fig.13. In the case of small cross section, the average bond stress of both RC and CPC is almost same. On the other hand, although the average bond stress is almost same initially, the difference in average bond becomes larger when the load is higher in the case of larger cross section.

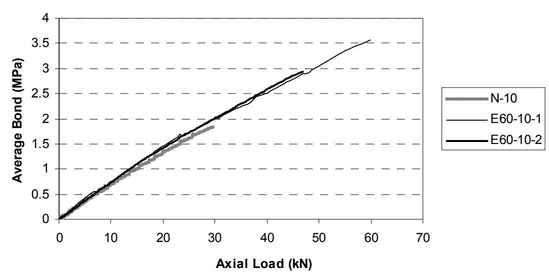

Fig.12 Average bond of RC and CPC (expansive agent of 60 kg/m^3) with 100x100 mm^2 cross section

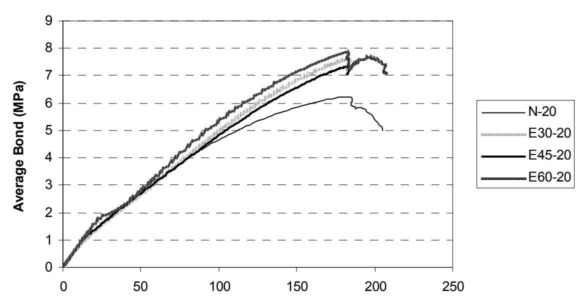

Fig.13 Average bond of RC and CPC (expansive agent of 60 kg/m^3) with 200x200 mm^2 cross section

4. DISCUSSION

4.1 Effect of Cover Thickness and Bond of CPC

The possible explanation for the different shapes of strain distribution and bond observed from specimen with different sizes is the effect of the boundary condition proposed by Shima[3]. In his research, it was illustrated that the bond and slip of RC is affected by the boundary condition which can simply be expressed by strain. However, it is possible that the strain function of CPC and RC is not same.

4.2 Effect of Improved Bond on Tension Stiffening Effect and Crack Width

The better bond of CPC proved in this study is major factor of the enhanced tension stiffening of CPC reported by many researchers [2].

It was reported that crack width of flexural CPC member is smaller than that of RC [1]. This is partially because of the prestrain as in the case of prestressed concrete (PC). However, based on the smaller slip of CPC found in this study, it can be expected that the crack width of CPC is additionally reduced because of reduced elongation of reinforcement.

4.3 Difference between Bond of CPC under Axial Tension and CPC in Pull-Out Test

Bond properties of deformed bar embedded in mass expansive concrete was not significantly different from those embedded in normal concrete although a little free slip could be observed at the beginning in some specimens [4]. The different bond characteristics of CPC in pull-out and direct tension may involve with the stress condition of the restrained expansive concrete.

4.4 Effect of Amount of Expansive Agent on Bond of CPC

Dosages of expansive agent in the range of 30 kg/m^3 to 60 kg/m^3 have no effect on bond and slip of CPC under direct tension. This means that bonds of most CPC can be assumed to be same in practice.

4.5 Bond Properties of Expansive Mortar

In the case of EM90-10 which is made from expansive mortar, unique behaviors were observed, especially the unexpected flat distribution of strain at the middle of specimen (Fig.5). This may indicate that the existence of coarse aggregate has significant effect on the mechanical properties of chemical prestressed materials.

5. CONCLUSIONS

Bond distribution of CPC is different from that of RC in tension. However, this distribution is influenced by numerous factors such as cover depth, presence of coarse aggregate but not affected by amount of expansive agent in the range of 30-60 kg/m^3.

ACKNOWLEDGEMENT

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