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Studies on Prestressed Concrete Pile with High Torsional Strength

Etude des pieux en béton précontraint ayant une grande résistance à la torsion

Untersuchungen an Spannbetonpfählen mit hoher Torsionsfestigkeit

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1. Introduction

Precast concrete piles used for pile-bent structures and torsional-motion driving methods require high torsion resistance. Since the rigidities of concrete members subjected to torsion are greatly reduced on development of cracking, it is thought important for cracking strength to be increased. The studies described herein aimed for increase of torsion resistance of precast concrete piles through introduction of mechanical prestress in the axial direction and chemical prestress. The methods of introducing large chemical prestress, the effect of mechanical prestress or chemical prestress, and the torsional properties were examined.

As a result of the experiments, the torsional strengths of mechanically and chemically prestressed piles were found to be approximately 4 times those of reinforced concrete piles and approximately 1.5 times those of piles with only mechanical prestress.

2. Manufacture and Testing

The testing was performed divided into the 4 steps described below:

Step 1. Examination of effect of chemical prestress using model piles.
Step 2. Examination using full-sized piles.
Step 3. Study of method for developing adequate chemical prestress.
Step 4. Study of effect of combining mechanical prestress and chemical prestress.

2.1 Manufacture of Test Specimens

The shapes and dimensions of the specimens used at the respective steps are as indicated in Fig. 1 and Fig. 2. It should be noted that the hollow cylindrical specimens used for internal pressure tests were of outer diameter of 200 mm (inner diameter, 106 mm) and length of 200 mm, and were provided with 2.6-mm spiral reinforcement.

Mix Proportions

With concrete of w/c = 0.37, s/a = 40%, cement content of 420 kg/m^3, using water-reducing admixture for slump of 12 cm as a basis, expansive components were used at rates of replacement of 42 kg/m^3 for Step 2, 55 kg/m^3 for Step 3, and additions of 35 kg/m^3 and 45 kg/m^3 for Step 4.

Specimen Molding and Curing

In the first step, reinforcing steel cages were fitted into molds after which concrete was placed and consolidated by vibration. On stripping the next day, curing was performed in water at 20±1°C.

At Steps 2, 3 and 4, reinforcing bar cages were fitted inside molds and centrifugal consolidation was performed after placing of concrete. Curing was by steam at a maximum temperature of 65°C, with curing in water carried out after stripping of molds. Further, at the 4th step, in order to preclude mold restraint during curing, paraffin was coated on the inner surfaces of molds to a thickness of 2 mm. Piles at the 3rd and 4th steps in which mechanical prestress was introduced were manufactured by a pretensioning method.

2.2 Methods of Testing

Torsion tests were carried out in all cases for pure torsion with one end fixed and the other subjected to torque. Loading was done in fixed increments until cracking was produced upon which the load was removed and then reapplied up to failure. Rotation angles of members were measured by dial gauge at the middle 20-cm portions in the axial direction for model piles and 90-cm portions for full-sized piles.

Internal pressure tests were performed by linear loading on inserting two small specially made jacks into the hollow cylinders. By applying internal pressure, specimens failed due to cracks produced from their exterior surfaces.

The uniaxially restrained expansion tests used in Steps 1 and 2 were performed on specimens with reinforcement ratio of 0.64%, and length changes of axial reinforcement were measured with dial gauges at Step 1, while at Step 2, the distances between gauge marks at three points on cover plates at each of the specimen ends were measured with contact-type gauges. Lengths prior to concrete placement were taken as bases in both cases.

3. Results and Deliberations

3.1 Method of Attaining Adequate Chemical Prestress

With expansive concrete the strength must not be allowed to be reduced by increased volume of expansive materials to result in offsetting chemical prestress. Almost all of the chemical prestress is transferred during steam curing and part of it is lost later on stripping of molds. In order to prevent this from happening, it is advantageous to cause the reaction to expansion to be carried by spiral reinforcement and the spiral reinforcement to be arranged as much as possible toward the outside. According to the results given in Table 3, effects of 6 to 8% were seen when curing was performed eliminating the influence of the mold, and 12 to 14% when spiral reinforcement was expanded outward.

3.2 Cracking Moment

Fig. 3 is a summarization of cracking strengths in the results of torsion tests performed at Steps 1 and 2. It can be seen that shear stress at the time of crack production is increased in correspondence with restraining reinforcement ratio. The shear stresses at crack production of piles not using expansive additives were 29.8 and 21.6 kg/cm^2 respectively for Specimens N01 and N3.

In restrained expansion of concrete, it can be considered that Eq. (1) is applicable for age of t and reinforcement ratio of p_i.

$$K_t = \sigma_{cpit} \cdot \varepsilon_{pit} = E_s \cdot p_i \cdot \varepsilon^2_{pit} = \text{constant} \quad \dots\dots (1)$$

where ε_{pit} : expansion strain at age t and reinforcement ratio p_i

σ_{pit} : chemical prestress at age t and reinforcement ratio p_i

E_s : modulus of elasticity of restraining steel

The chemical prestress transferred to a member with reinforcement ratio of p_i is according to Eq. (2) when K_t is determined for restrained expansion specimens.

$$\sigma_{cpit} = \sqrt{K_t \cdot E_s \cdot p_i} \quad \dots\dots (2)$$

For the sake of simplicity in this case, the reinforcement ratios in the axial direction and the circumferential direction of the pile were converted to a 45-degree direction, and the chemical prestress transferred to the 45-degree direction of the pile at this reinforcement ratio was estimated. With the concretes used in the piles at Steps 1 and 2, the chemical prestresses estimated from K are 14.1 kg/cm^2 in the 45-degree direction of the pile E4 and 12.1 kg/cm^2 for E3.

It is seen from Fig. 3 that by superimposing cracking strength of concrete not using expansive additive on the estimated value of chemical prestress the result approximates the stress intensity at the time of crack production of an expansive concrete pile. In effect, the torsional strength of the expansive concrete pile was approximately 1.7 times greater at spiral reinforcement ratio of 0.73% for the full-sized piles in Step 2.

Assuming that cracking due to torsion of a member prestressed in two directions follows the maximum stress theory, Eq. (3) is obtained.

$$M_{tpc} = M_{tc}\sqrt{1 + \frac{\sigma_{cpv} + \sigma_{cpl}}{\sigma_{ct}} + \frac{\sigma_{cpv} \cdot \sigma_{cpl}}{\sigma_{ct}^2}} \quad \dots\dots (3)$$

where σ_{cpv}, σ_{cpl} : prestresses in circumferential and axial directions

σ_{ct} : tensile strength of concrete

M_{tc}, M_{tpc} : cracking moments of non-reinforced and prestressed concretes

Eq. (3) coincides with Cowan's equation when prestress in the circumferential direction is taken to be zero. The cracking moment of S0 with mechanical prestress only was 2.56 tm. Assuming that tensile strength of concrete is about 1/13 of compressive strength, the estimated value according to Eq. (3) becomes 2.69 tm and the ratio of 1.05 indicates a good approximation. The cracking strength of W45 handled in a manner for chemical prestress to be sufficiently introduced was 3.80 tm, approximately 1.5 times that for a pile with mechanical prestress only.

3.3 Torsional Rigidity and Ultimate Yield Strength

Fig. 4 indicates the relationships between torsional moments and torsional angles of S0 and W45. There were no great differences in torsional rigidities until production of cracks, while stiffnesses after production of cracks were extremely reduced. The precast concrete piles being marketed in Japan at present have small quantities of spiral reinforcement, and with yield strengths reduced accompanying crack production, it is thought they would be hazardous used as structural members subjected to torsion. The pile W45 had an increased quantity of spiral reinforcement for the purpose of introducing strong prestress, and as a result there was no reduction in yield strength accompanying crack production at an ultimate yield strength of 4.35 tm; an increase of approximately 15% from the cracking strength of 3.80 tm was indicated. For piles to be used in pile-bent structures, there should be a necessity for determination of spiral reinforcement quantity of an extent that cracking strength can be maintained at the least.

With S0, to which only mechanical prestress was introduced, a single continuous crack developed in a direction at an angle of $30^\circ \sim 35^\circ$ to the axis. Piles to which chemical prestress and mechanical prestress were transferred showed numerous cracks at 45° or at angles close to 45°. This is an indication of good stress dispersion after crack production because of the increase in the quantity of spiral reinforcement.

4. Conclusions

The following results were obtained through torsion tests of piles made with expansive concrete which were mechanically prestressed:

(1) In case of manufacturing piles using expansive concrete, it was found advisable for the quantity of spiral reinforcement to be increased and at the same time to be arranged toward the outside as much as possible, and further, for restraint on concrete to be removed at an early period by stripping molds, with reaction to expansion made to be carried by spiral reinforcement. The result was that the increase in cracking strength was approximately 1.34 times greater.

(2) The torsional strength of piles with mechanical prestress of 47 kg/cm^2 was 2.56 tm, and using expansive additive at a rate of 45 kg/m^3 with spiral reinforcement ratio of 1.54%, the result was 3.80 tm, or an increase in strength of approximately 1.5 times.

(3) In the case of the pile W45, increases in cracking strength and ultimate yield strength were attained through increase in spiral reinforcement ratio. It was confirmed through this that cracks could be well dispersed.

(4) It is thought that cracking strengths of expansive concrete members can be estimated by obtaining chemical prestress by $\sigma = \sqrt{K \cdot E \cdot p}$ and by superimposing on strength of concrete not containing expansive additive.

References

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Table 1. Chemical Composition of Expansive Additive (Calcium Oxide Type)

Chemical Analysis, (%)								Specific Surface (cm^2/g)	Specific Gravity
Ig.Loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Total		
0.9	11.4	2.7	1.6	79.4	0.8	3.3	100.1	2440	3.18

Table 2. Torsional Strength Results

Step	Kind of Concrete	Pile No.	Condition of Mold	Spiral Dia.-Pitch (mm)	Spiral Ratio (%)	Torsional Moment Cracking (t·m)	Torsional Moment Ultimate (t·m)	Comp. Strength (kg/cm^2)
1	W:C:S =1:2.5:4	N01		1.8-10	1.37	5.10×10^{-2}	5.23×10^{-2}	564
	W:C:S =1:2.5:4 E_X=Cx0.1	E11	Mold restraint	1.8-10	1.37	9.19×10^{-2}	7.12×10^{-2}	455
		E12		1.8-20	0.68	6.86×10^{-2}	5.13×10^{-2}	
		E13		1.8-30	0.46	5.88×10^{-2}	4.56×10^{-2}	
		E12S		1.8-19.3 -45°	1.00	11.24×10^{-2}	10.62×10^{-2}	
2	C = 420	N3	Mold restraint	3-30	0.41	1.00	1.58	578
	C = 378 E_x = 42	E3		3-30	0.41	1.44	1.64	526
		E4		4-30	0.73	1.66	1.90	
3	C = 365 E_x = 55	D3	Mold restraint	4-30	0.73	2.84	3.05	473
		G3		(I)4-30 (O)3-50	1.06	2.96	3.73	
4	C = 420	S0		3-100	0.12	2.56	1.57	511
	C = 420 E_x = 35	U35	Paraffin coated	(I)3-50	1.06	3.00	3.81	566
			Mold restraint	(O)4-30		3.01		
		W35	Paraffin coated	(I)4-30 (O)4-30	1.54	3.42	4.53	
	C = 420 E_x = 45	U45	Paraffin coated	(I)3-50	1.06	3.27	3.88	541
			Mold restraint	(O)4-30		3.04		
		W45	Paraffin coated	(I)4-30 (O)4-30	1.54	3.80	4.35	

Test results averages of 2 specimens. Six 7-mm bars used as axial reinforcement in all cases. Mechanical prestress of 47 kg/cm^2 introduced in axial direction in Steps 3 and 4. (I): inner spiral reinforcement. (O): outer spiral reinforcement.

Table 3 Internal Pressure Test Results of Hollow Cylinders

Steel Ratio (%)	0.71				0.83	
Covering of Spiral R. (mm)	10		1		1	
Condition of Mold	Mold	Demold	Mold	Demold	Mold	Demold
Cracking Load (t)	2.38	2.56	2.71	2.88	3.07	3.27

The value is the average of two measurements

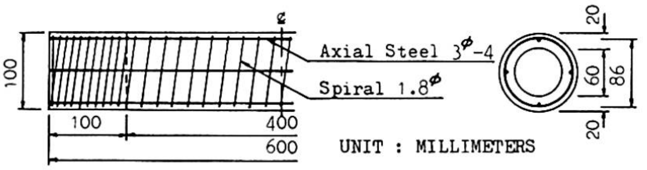

Fig. 1 Details of Model Pile

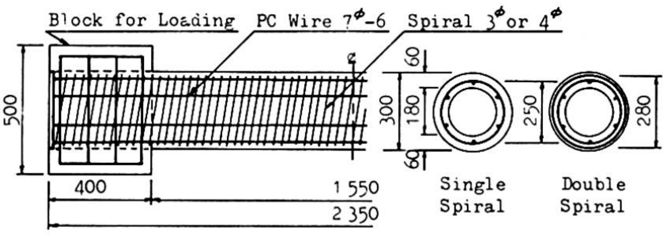

Fig. 2 Details of Full-sized Pile

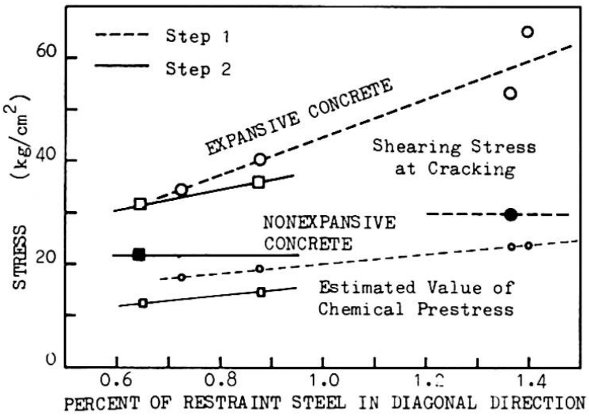

Fig. 3 Cracking Stress and Chemical Prestress

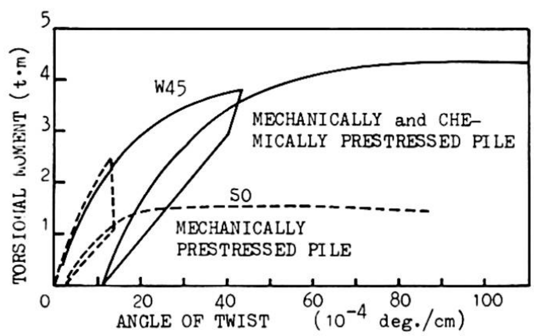

Fig. 4 Torsional Moment-Twist Curve

SUMMARY

Precast concrete piles used for pile-bent structures and torsional-motion pile-driving methods require high torsion resistance. In the experiments described here, mechanical prestress is introduced in the axial direction, added to which a considerable chemical prestress is introduced through increase in spiral reinforcement steel and release of mold restraint during curing, and torsional moments approximately 4 times those of reinforced concrete piles and approximately 1.5 times those of prestressed concrete piles are obtained.

RESUME

Un pieu préfabriqué mis en place par torsion requiert une haute résistance à la torsion. Dans les essais présentés ici, on a réalisé d'une part une précontrainte axiale introduite mécaniquement et d'autre part une précontrainte chimique obtenue par renforcement spiral et démoulage pendant le durcissement du béton. La résistance à la torsion de ces pieux est 4 fois, resp. 1,5 fois plus grande que celle de pieux en béton armé, resp. en béton précontraint normal.

ZUSAMMENFASSUNG

Spannbetonpfähle in biegebeanspruchten Konstruktionen, oder solche, die durch Eindrehen abgesenkt werden, erfordern eine hohe Torsionsfestigkeit. In den hier vorgelegten Versuchen wurde die Vorspannung in axialer Richtung einerseits mechanisch, andererseits auf chemischem Wege durch Verstärken der Spiralbewegung und Ausschalen während der Erhärtung des Betons eingetragen. Hiermit wird eine Torsionsfestigkeit erreicht, die 4 mal bezw. 1,5 mal so hoch ist wie diejenige von Stahlbetonpfählen bezw. normalen Spannbetonpfählen.