APPLICATION TO A PROTOTYPE STRUCTURE

Construction Outline

High-strength concrete of specified design strength of 60N/mm^2 was used to fill tubular steel columns in an eleven story office building. The location of the 15 columns is shown in Fig.11. Twelve columns were filled continuously by pumping the concrete from the inlet port of the lower end up to roof height (approximately 40m). The remaining 3 columns were first filled to the fourth floor (approximately 12m). The section above the fourth floor was subsequently filled at the same time when other columns were filled.

The cross sections of the tubular steel columns were either 55cm square or 45cm square. The wall thickness of the steel was 22mm up to the second floor, 19mm from the third floor to the sixth floor,16mm above the sixth floor. The columns have several diaphragms. The size of the central opening in the diaphragm for passage of concrete was ϕ 22cm, and four holes to let air through were opened at 4 corners. The volume of concrete in the column was 10.5m^3, and a piston type concrete pump with a maximum discharge pressure of 7.2N/mm^2 was used for pumping.

During construction, the following data which were not determined in the previous experiments with short model columns, were obtained.

1) Slump flow loss as the concrete rises inside the column
2) Pressure of concrete and distortion of the column
3) Subsidence of concrete at the top of the column
4) Change of strength and coarse aggregate volume as the concrete rises inside the column

Mixture Proportions of Concrete

Materials and mixture proportions of the concrete are shown in Tables 4 and 5, respectively. The specified slump flow value was 65cm and the specified air content was 2.0%. The ready-mixed concrete plant was located near the construction site and the concrete pump was set up close to the columns. Because of these easy execution conditions, belite rich cement (L2 of Table 1) was used as the cement of the filling concrete.

Trial mixing was performed to determine mixture proportions for the high-strength concrete. The strength was controlled using the standard curing strength at 56 days. Concretes were produced of using water:cementitious ratios of 25%, 28%, and 32%; model columns were made for investigating the strength of concrete in structures, and core strength was investigated before the actual construction was initiated. The standard cylinder strength at 56 days and the core strength at 91 days are shown in Fig.12.

Recently in Japan, strength of concrete in structures of 60N/mm^2 class is controlled by standard curing strength. In this case, a modified value called "S" needed to be determined for the difference between standard curing strength and core strength at the design age. Mixture proportions are determined based on the standard curing strength which showed not less than the sum of the specified design strength and the modified value "S". This is shown with the following expression.

$$F56 \geqq Fc + S + K\sigma \quad (N/mm^2)$$
$$F56 \geqq 0.9\,(Fc + S) + 3\sigma \quad (N/mm^2)$$

where, F56: Proportioning strength of concrete (N/mm^2). It is expressed as the standard curing strength at 56 days.

Fc : Specified design strength of concrete (N/mm^2).

S : The difference between the standard curing strength at 56 days and the strength of concrete in structures (core strength from structure model at 91 days). (N/mm^2)

σ : Standard deviation of concrete strength of the plant producing concrete (N/mm^2).

K : The normal deviation according to permitted defectiveness, percent of compressive strength.

$8.8N/mm^2$ was adopted as modified value "S" from the results of the trial mixing for this construction. From past findings, "σ" and "K" were $3.6N/mm^2$ and 3.28, respectively. As a result, the proportioning strength became $80.6N/mm^2$. The standard curing strength at 56 days of the concrete with the water:cementitious ratio of 32% was $96.2N/mm^2$ in the trial mixing, which exceeded the proportioning strength. Although the water:cementitious ratio of 32% was acceptable from trial mixes, the actual water:cementitious ratio used for this construction was 30%. This was due to consideration being given to possible large dispersions in the concrete strength at the upper part of the column and in the vicinity of the diaphragms.

Results and Discussion

Properties of Fresh Concrete--The results of slump flow tests at the unloading point are shown in Fig.13, and the plastic viscosity of the concrete calculated from the time taken for it to discharge from a inverted slump cone is shown in Fig.14. These results pertain to the concrete transported by 24 agitator trucks for filling 12 columns from the lower end to the roof at the same time. The average for slump flow was 66.8cm, and the standard deviation was 3.7cm, reflecting that the change in fluidity of fresh concrete was small and that the production of concrete had been stable. The calculated plastic viscosity became smaller than that obtained in the pumping experiment. This is probably due to the different type of aggregate used and the shortening of the transportation time by agitator truck.

The concrete that had overflowed from the top of three columns was examined to determine the change of slump flow when the concrete had risen inside the column. The results are shown in Table 6. The slump flow loss of concrete which was kept aside without agitation for the period required to fill the column was 7.8-11.4cm, that in the pipeline from the concrete pump to the inlet port of the column was 3.5-7.0cm, and that from unloading point to the column top was 17.7-22.2cm. Since slump flow at the top of the column was more than 45cm in every column, it was concluded that the filling performance was satisfactory.

Pressure--Pressure gauges were installed in the pipe at the concrete inlet port of the column, and the pressure was measured for all columns. Examples of the result are shown in Fig.15 and 16. The pressure pulsates corresponding to the movement of the piston. The value at the bottom of pulsation is equal to the head pressure that is obtained by multiplying the unit weight of concrete by the filling height. The value of pressure at the upper part of pulsation is around 1.2 times the head pressure. The pressure became larger at the diaphragm passage and when pumping was re-started after an interruption. Fig.16 shows that speed of filling influences pulsation.

When the filling height is high, control of filling speed and continuous pumping without interruption are important. From the results, obtaining a discharge volume below $20m^3/h$ will reduce the upper part of the pulsation pressure to less than 1.2 times the head pressure, causing the filling speed in the columns to fell below 1m / minute. The maximum pressure in the pipe at the inlet port of the column is 1.17 times the head pressure on average and 1.31 times the head pressure at maximum.

Strain in Steel Column--Strains of the tubular steel column during filling with concrete were measured by electric strain gauges attached to the column surfaces at 3 points located at the first floor (FL+2m), fourth floor (FL+1.9m) and seventh floor (FL+1.9m) as shown in Fig.17. The strains in the column are subjected to the influence of pump pulsation. The strain at the bottom period of pulsation is almost equal to the value calculated from the head pressure. The column shown in Fig.17 is the same as the column shown in Fig.15. The strain in the column was 1.1 times the head pressure, and pressure in the pipe was 1.2 times the head pressure. Since the cross-section of the column is larger than that of the pipe at the inlet port, the influence of pulsation is smaller in the steel column than in the pipe. The results measured for 24 hours is shown in Fig.18. The strains decrease with time and residual strains were below 250 μ .

Compressive Strength--The compressive strengths of concrete sampled at the unloading points are shown in Fig.19. The standard curing compressive strength at 56 days was $91.9N/mm^2$, exceeding the required value of $68.8N/mm^2$ ("Fc+S").

To investigate the compressive strength of cores at the column top, a dummy columns (50cm square mold) was set at the top of the column, and it was filled to 1.5m height following filling of the column itself. For comparison, concrete was also placed into a dummy columns on the ground floor. Comparison of strength of cores drilled from these dummy columns with standard curing strength of test pieces sampled at the unloading point is shown in Fig.20. "S", the difference between standard curing strength at 56 days and core strength at the top of column at 91days, was $3.9N/mm^2$. "S", the difference between standard curing strength at 56 days and core strength at the ground, was $1.1N/mm^2$. The 91-day core strength is larger than the 28-day standard curing strength, and smaller than the 56-days standard curing strength. Accordingly it may be said that the control of strength at 56 days was proper.

The standard curing strength at 56 days of the test pieces sampled at the column top and sampled at unloading point are shown in Fig.21. Strength shows a tendency to decrease slightly when the concrete has risen inside the column. However the decrease is only about 5 %, which can be compensated for easily by increasing the mixture proportions strength.

Amount of Coarse Aggregate--The area of coarse aggregate of the concrete in the dummy column on the ground was 29.7%, and that of column top was 32.1%. The amount of coarse aggregate shows a tendency to increase slightly when the concrete has a riser inside the column. This is caused by adherence of the mortar in concrete to the inner wall of the column. However, it is thought that this phenomenon is not a problem since it does not affect strength and flowability to any significant extent.

CONCLUDING REMARKS

The following results were obtained from experiments on filling tubular steel columns with high-strength concrete and the application to an actual construction.

1) Pumpability of concrete is greatly affected by the type of cementitious material used; using silica fume in the cementitious materials results in better pumpability.
2) The pressure loss shows good correlation to the plastic viscosity of the concrete calculated from the slump flow value and the time taken for it to discharge from an inverted slump cone.
3) When the high-fluidity concrete and the silica fume concrete used in the tests were pumped into tubular columns, the cavity area under the diaphragm plates was less than 10% and the core strength obtained at 91 days was over 80 N/mm^2.
4) If the slump flow of concrete at the top of the column is more than 45cm, it can be expected that the column will be well filled.
5) The pressure of concrete at the bottom of the column is approximately 1.2 times the head pressure(maximum is 1.3times), and the strain of a steel tube is approximately 1.1 times of the value calculated from the head pressure.
6) When filling height is high, control of the speed of filling and continuous filling without interruption are important.
7) Strength shows a tendency to decrease slightly when the concrete has risen inside the column. However the decrease is only about 5 %, which can be compensated for easily by increasing the mixture proportions strength.

REFERENCES

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[2] S Kuroiwa, Y Matsuoka, M Hayakawa and T Shindoh "Application of Super-Workable Concrete to Construction of an 20-Story Building" ; SP 140, American Concrete Institute,1993, pp.147-161
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TABLE 1—PROPERTIES OF MATERIALS (PUMPING EXPERIMENTS)

Material	Symbol	Kind
Cementitious Material	L1	Belite Rich Cement containing 55% C2S (Specific gravity 3.22、Specific surface area = 3460cm^2/g)
	L2	Belite Rich Cement containing 46% C2S (Specific gravity = 3.20、Specific surface area = 4160cm^2/g)
	OPC	Normal Portland Cement (Specific gravity = 3.16、Specific surface area = 3260cm^2/g)
	BG	Blast-furnace slag gypsum (Specific gravity = 2.92、Specific surface area = 7580cm^2/g)
	SF	Silica Fume (Specific gravity = 2.2、Specific surface area = 200,000cm^2/g)
Admixture	SP	Superplasticizer (Polycarbonicacid-based)
	BP	Viscosity admixture (biopolymer)
Fine Aggregate	A Plant	(Specific gravity 2.64, Fineness modulus = 2.56)
	B Plant	(Specific gravity 2.60, Fineness modulus = 2.70)
Coarse Aggregate	A Plant	(Specific gravity 2.68, Solid volume = 60.4%, Maximum size = 20 mm)
	B Plant	(Specific gravity 2.70, Solid volume = 60.0%, Maximum size = 20 mm)

TABLE 2—MIXTURE PROPORTIONS (PUMPING EXPERIMENTS)

Mix	W/C %	Air %	Slump Flow cm	Water kg/m^3	Cementitious Material kg/m^3					Coarse Aggregate Volume / Concrete m^3/m^3	Viscosity admixture kg/m^3	Superplasticizer B×%	Plant
					L1	L2	OPC	BG	SF				
LB*	30	2.0	60	168	560	-	-	-	-	0.330	0.5	2.7	A
LB	30	2.0	70	168	560	-	-	-	-	0.330	0.5	3.0	A
LN	30	2.0	60	168	560	-	-	-	-	0.330	-	2.7	A
HB	30	2.0	70	168	-	560	-	-	-	0.330	0.5	3.3	A
TN*	30	2.0	50	160	-	-	373	107	53	0.340	-	2.5	B
TN	30	2.0	60	160	-	-	373	107	53	0.340	-	2.8	B

TABLE 3—MIXTURE PROPORTIONS AND SLUMP FLOW (FILLING EXPERIMENTS)

Model Column		Concrete			
Name	Height m	Mixture Proportions of Concrete	SlumpFlow at unloading point cm	SlumpFlow at concrete inlet port cm	Slump Flow at column top cm
L-L	6.5	LB	72.0	67.5	69.0
L-S	1.5	LB*	47.0	25.8	-
T-L	6.5	TN	66.3	67.5	70.5
T-S	1.5	TN*	48.5	44.3	-

TABLE 4—PROPERTIES OF MATERIALS (APPLICATION TO PROTOTYPE STRUCTURE)

Cement	Belite Rich Cement containing 46% C2S (Specific gravity = 3.20、Specific surface area = 4160cm^2/g)
Fine Aggregate	(Specific gravity = 2.64, Fineness modulus = 2.62)
Coarse Aggregate	(Specific gravity = 2.70, Solid volume = 60.3%, Maximum size = 20 mm)
Admixture	Superplasticizer (Polycarbonicacid-based) Viscosity admixture (biopolymer)

TABLE 5—MIXTURE PROPORTIONS (APPLICATION TO PROTOTYPE STRUCTURE)

W/C %	Air %	Sand-Aggregate Ratio %	Water kg/m^3	Cement kg/m^3	Coarse Aggregate Volume / Concrete m^3/m^3	Viscosity admixture kg/m^3
30	2.0	50.2	165	550	0.32	0.5

TABLE 6—SLUMP FLOW LOSS DUE TO PUMPING AND TIME

Column No.	Slump Flow of Concrete (cm)				Period required to fill the column (minutes)
	at unloading point	at concrete inlet port	at column top	kept aside without agitation	
A	66.5	-	48.8	55.2	77
	68.8	65.0	-	-	-
B	68.8	-	47.8	61.0	89
	68.5	61.5	-	-	-
C	70.2	-	48.0	58.8	57
	72.5	69.0	-	-	-

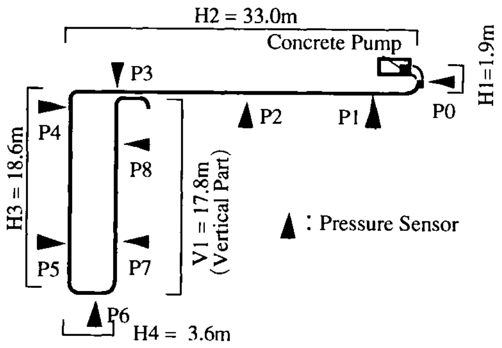

Fig. 1—Layout of pipeline on pumping test

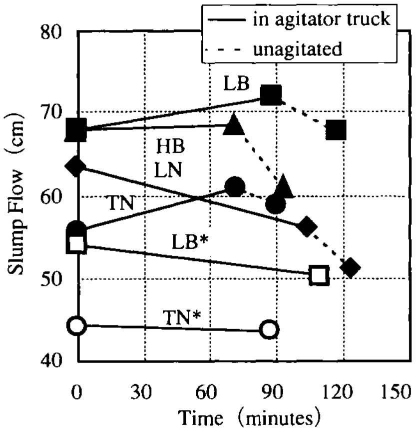

Fig. 2—Time dependent change of slump flow

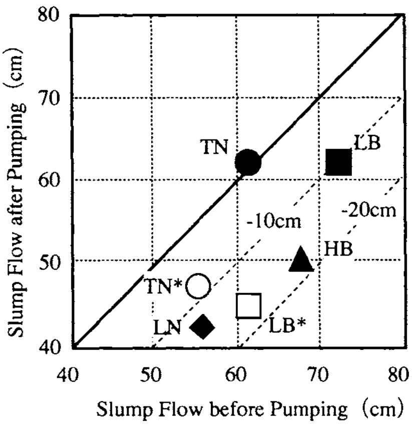

Fig. 3—Change of slump fl$_0$w due to pumping

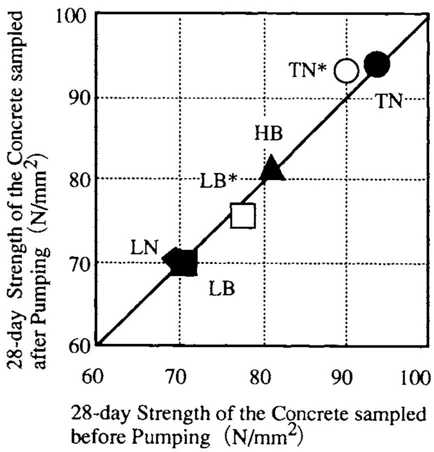

Fig. 4—Change of compressive strength due to pumping

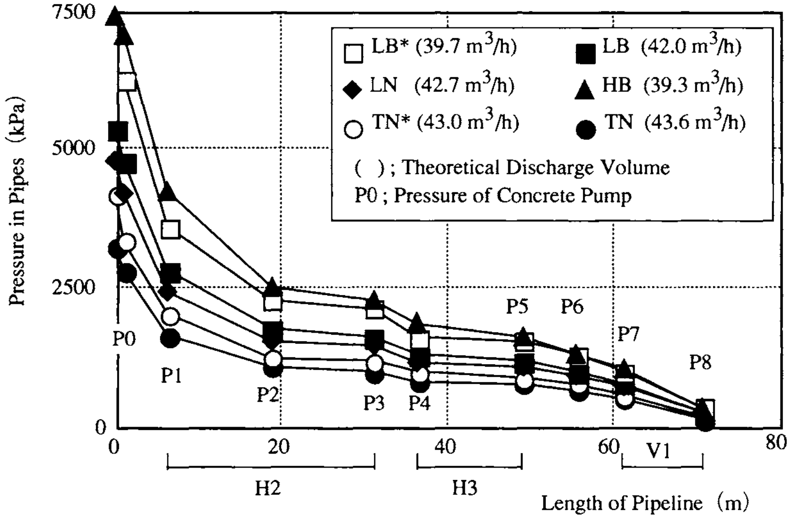

Fig. 5—Distribution of pressure in pipes

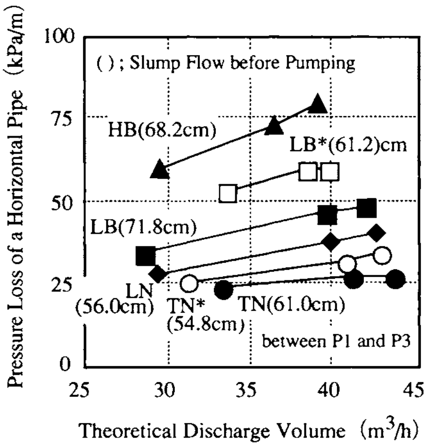

Fig. 6—Pressure loss of horizontal pipeline