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STUDY ON PIPE FLOW OF GROUT
(Reprint from Transactions of JSCE, No. 354/V-2, 1985)

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SYNOPSIS

This study has the objective of rationalization of pressure grouting and rheologically examines flow of grout in pipes. It is confirmed by pressure grouting experiments using pipelines up to 80-m lengths in straight lines and lines with horizontal and vertical bends that grout roughly conforms to Bingham flow under ordinary piping conditions. Based on the above, a method of predicting flow volume during pumping of grout, or the pressure load of the pump is described, and data useful for setting up piping plans and selecting the type of pump to be used are furnished. Further, an inclined pipe testing method is proposed as a way of readily measuring viscosity of grout in the field, and the usefulness of the method is described,

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1. INTRODUCTION

Planning and execution of pumping of grouts for prepacked and prestressed concretes have often depended on experience gained in construction and trial pumping runs, there being hardly any data from analytical studies available.

The study reported here had the objective of rationalizing and systematizing pumping of grout. Pipe flow of grout was examined rheologically and application was studied. With grout for prepacked concrete as the object of study, pumping experiments were conducted with straight horizontal pipelines up to 80 m in length, and with horizontal and vertical bent pipelines. It was shown that grout for prepacked concrete conforms roughly to Bingham flow under ordinary piping conditions. Methods of predicting pumping volumes and pressure loads of pumps are described, and data useful for planning pipeline layouts for pumping grout and for selecting pump types are presented. An inclined pipe testing method was also proposed as a simple way to measure viscosity of grout in the field, and the usefulness of the method is discussed.

2. METHODS OF TESTING CONSISTENCY OF GROUT

The flow-cone method, the rotating viscometer method, and the inclined pipe method were used as methods of testing consistency of grout. The flow-cone method is not used for analysis of flow since it does not give physical constants of grout, but it is used widely as a yardstick for grout consistency, and being convenient for practical purposes, and also being established as a standard, it was used for measurements.

The physical property values of grout were measured by double-cylinder rotation visometer, but since this method is difficult to use in practice in the field, the inclined pipe testing method was proposed as a simplified testing method.

(1) Flow Cone Method

The P-type flow cone prescribed in the Japan Society of Civil Engineers Standard, "Method of Testing Consistency of Injection Mortar for Prepacked Concrete," was used. However, the J-type flow cone prescribed in the proposed JSCE Standard I-III, "Method of Testing Consistency (Draft)," was used in part.

(2) Rotation Viscometer Method

A double-cylinder rotation viscometer of outer cylinder radius 2.5 cm, inner cylinder radius 1.25 cm, and cylinder length 7.0 cm, with a cone of base angle 11.6 deg at the end of the cylinder was employed.

After sample was filled between the outer and inner cylinders the rotating speed of the outer cylinder was gradually increased and torque was read off every 10 rpm from 30 rpm. The velocity gradient V and shear stress P were calculated by Eq. (1), and the consistency curve was plotted with V on the ordinate and P on the abscissa. Plastic viscosity was obtained as the reverse gradient of the straight-line portion of the consistency curve, and yield value was calculated by Eq. (2) using the shear stress τ_a at the intersection between the extension of the straight-line portion and the abscissa.

$$\left.\begin{aligned} V &= 2\dot{\Omega}/\{1 - (R_i/R_o)^2\} \\ P &= M/2\pi R_i^2 h_c \end{aligned}\right\} \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (1)$$

where, R_i: inner cylinder radius (cm), R_o: outer cylinder radius (cm), $\dot{\Omega}$: angular velocity of outer cylinder (rad/s), M: torque (gf·cm), h_c: effective length of inner cylinder (cm)

$$\tau_f = \frac{1 - (R_i/R_o)^2}{2 \ln (R_o/R_i)} \tau_a \quad \cdots\cdots (2)$$

where, τ_f: yield value (gf/cm^2), τ_a: shear stress at intersection of straight-line portion of consistency curve and abscissa (gf/cm^2)

The effective length h_c of the inner cylinder in Eq. (1) was obtained adding to the cylindrical portion length the conical portion converted to cylinder length assuming the sample to be a Newtonian body for the sake of simplicity. In effect, since the tip of the cone contacts the bottom of the container, the torque between the conical surface and the bottom surface of the container is

$$M = \int_o^{R_i} 2\pi r^2 dr \left(\frac{\dot{\Omega}}{\tan \phi} \eta\right) = \frac{2}{3} \pi R_i^2 \eta \frac{\dot{\Omega}}{\tan \phi} \quad \cdots\cdots (3)$$

where, ϕ: bottom angle of cone (deg), $\dot{\Omega}$: angular velocity of cylinder (rad/s), η: viscosity coefficient (gf·s/cm^2)

Putting converted length of cylinder as h_c

$$\eta \cdot \dot{\Omega} = \frac{M}{4\pi h_s} \left(\frac{1}{R_i^2} - \frac{1}{R_o^2}\right) \quad \cdots\cdots (4)$$

$$h_s = \frac{R_i^3}{6 \tan \phi} \left(\frac{1}{R_i^2} - \frac{1}{R_o^2}\right) \quad \cdots\cdots (5)$$

$$h_c = h_o + h_s \quad \cdots\cdots (6)$$

where, h_o: length of cylindrical portion (cm), h_s: conical portion converted to cylindrical length (cm)

Eq. (1) was used for calculation of velocity gradient and shear stress because it had been ascertained in advance that in case of grout for prepacked concrete of normal consistency of P-type flow cone flow time of about 20 s and under, all of the sample between the outer and inner cylinders flows, and that slipping between cylinder walls and sample is of sufficiently small degree that it can be ignored. Fig. 1 is an example of the results of measurements on flow velocities at various points on the sample surface using an outer cylinder rotating type viscometer with radius of 5.0 cm, and is a case of a grout of flow time of 18.6 s with the P-type flow cone. The width of flow of the sample increases with increased number of revolutions, and becomes more or less constant at speed of 60 rpm and higher, the value being approximately 15.3 mm. As for slipping of sample and inner cylinder wall, it is not more than 3 percent of angular velocity of the cylinder. However, when P-type flow cone flow time exceeded approximately 20 s, a viscometer of outer cylinder radius 5.0 cm was used to measure flow velocities at six points on the surface of the sample between the outer and inner cylinders to obtain the range of flow (R_n) of the sample, and the rheological constant was calculated with R_i = 1.45 cm, $\dot{\Omega} = \dot{\Omega}_i$, and $R_o = R_n$ in Eq. (1) using the measured value of angular velocity ($\dot{\Omega}_i$) at a point 0.2 cm from the inner cylinder wall[1].

(3) Inclined Pipe Testing Method[2]

The inclined pipe testing method was devised as an improvement on the flow cone

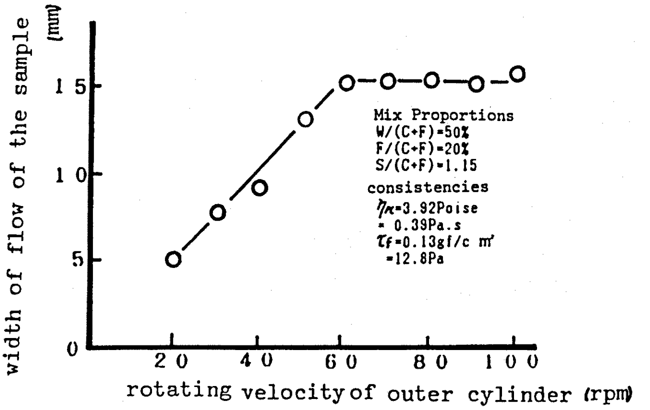

Fig. 1 relationship of rotating velocity of outer cylinder and width of flow of the sample

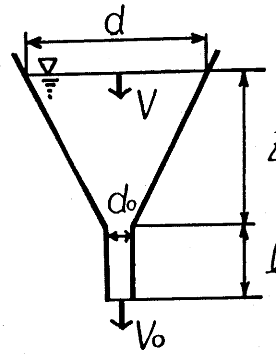

Fig. 2 shape of flow cone

method. Using Fig. 2 as a reference and applying the equation of energy to the liquid surface of the sample in the flow cone and the outlet of the discharge tube[3],

$$\frac{V^2}{2g} + Z + l = \frac{V_o^2}{2g} + f_m \frac{V_o^2}{2g} + h_l \qquad \cdots\cdots (7)$$

where, V: flow velocity of liquid surface in flow cone (cm/s), V_o: flow velocity at discharge tube outlet (cm/s), Z: height of liquid surface (cm), l: length of discharge tube, $f_m\ (V_o^2/2g)$: energy loss in flow to discharge tube from flow cone (cm), h_l: energy loss at discharge tube (cm)

Substituting $V = (d_o/d)^2 V_o$ and $h_l = \frac{l}{K} V_o$ in $V = (d_o/d)^2 V_o$, and solving for V_o, Eq. (8) is obtained.

$$V_o = \frac{2}{\frac{l}{K(Z+l)} + \sqrt{\frac{l^2}{K^2(Z+l)^2} + \frac{2}{g(Z-l)}\{1 + f_m - (\frac{d_o}{d})^4\}}} \qquad \cdots\cdots (8)$$

provided that

$$K = \frac{\rho g R^2}{8\eta_{pl}} \{1 - \frac{4}{3}(\frac{2\tau_f}{\rho g I R}) + \frac{1}{3}(\frac{2\tau_f}{\rho g I R})^4\}$$

where, R: radius of pipe (cm), ρ: unit weight of grout (g/cm^3), I = energy gradient, g: gravitational acceleration (cm/s^2), f_m: loss factor

In Eq. (8), in case of $l = 0$,

$$V_o = \sqrt{\frac{2gZ}{1 + f_m - (d_o/d)^4}} \qquad \cdots\cdots (9)$$

and the outflow velocity is related to the configuration of the flow cone and there is practically no relationship with the physical properties of the grout.

In contrast, in case l is sufficiently long,

$$V_O = \frac{K(Z + l)}{l} \qquad \text{.........................} \quad (10)$$

Consequently, measurements having closer relationships to physical property values are obtained the longer that the discharge tube length is made. The discharge tube lengths of P- and J-type flow cones are 3.8 and 3.0 cm, respectively, and fairly small compared with the depths of the flow cones.

Photo. 1 shows an inclined pipe testing apparatus for prepacked concrete grout.

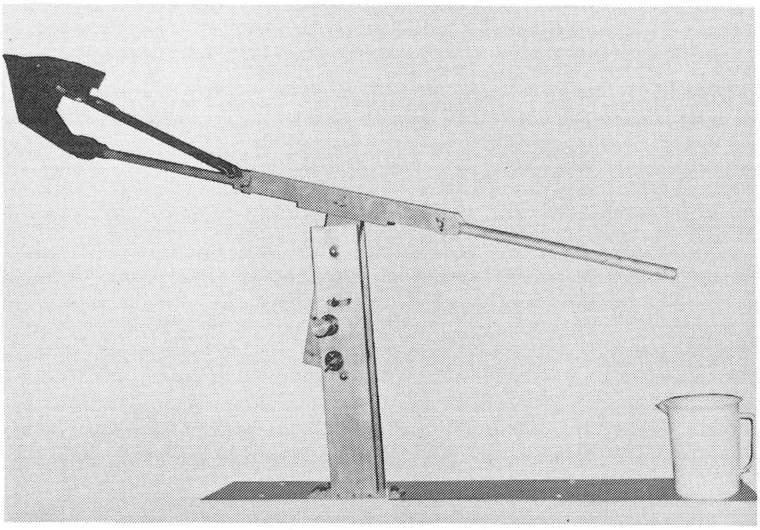

Photo. 1 inclined pipe testing apparatus

As a result of study concerning the specifications of the apparatus[4], the discharge tube was made a stainless steel tube of diameter of 20 mm and length of 70 cm and this was set close to horizontal. This was in consideration of decreasing the hydraulic gradient so that slippage would not occur between tube wall and sample. The shape of the funned was made a bell-mouth (morning glory) form of top-edge diameter 20 cm, and height of 15 cm so that the flow velocity of the liquid surface would be adequately low (1/100) compared with that inside the tube, while an overflow section was provided at the top edge as a consideration of steady flow of the sample to be obtained.

Normally, flow volume is measured with the inclination angle of the discharge tube 10 deg as standard, and this is made the yardstick for consistency. Since this apparatus is a kind of slender tube type viscometer, it is also possible to determine the rheological constants of the sample, In effect, the flow volumes at inclination angles of 10 deg, 5 deg and 15 deg were measured, and the following procedure was taken;

i) After setting the inclination angle of the discharge tube at 15 deg, grout is filled in the hopper and is made to flow down the tube while causing overflow to occur at all times.

ii) Approximately 5 s after grout begins to flow out from the tube, the grout flowing out is collected for 10 s in a sample container.

iii) The mass of the sample collected is accurately measured, and using the unit mass of the sample, the flow volume per unit length of time is computed.

iv) The operations from i) and ii) are repeated for inclination angles of 10 and 5 deg.

The flow volume of a Bingham body inside a round pipe is given by the Buckingham equation (see Fig. 11).

$$Q = \frac{\pi R^4 \Delta P}{8 l \eta_{pl}} \{1 - \frac{4}{3}(\frac{r_f}{R}) + \frac{1}{3}(\frac{r_f}{R})^4\} \qquad \text{(11)}$$

where, Q: flow volume (cm^3/s), ΔP: pressure differential (gf/cm^2) = $\rho g I l$, l: pipe length (cm), η_{pl}: plastic viscosity ($gf{\cdot}s/cm^2$), r_f: plug flow radius (cm) = $2l\tau_f/\Delta P$

Rewriting Eq. (11),

$$Q = A\rho g I + \frac{B}{(\rho g I)^3} - C \qquad \text{(12)}$$

where, $A = \pi R^4/8\rho_{pl}$, $B = 2\pi\tau_f^{\,4}/3\eta_{pl}$, $C = \pi R^3\tau_f/3\eta_{pl}$, I: energy gradient = $(l \sin\theta + h_p \cos\theta)/l$, h_p: height of hopper (cm), θ: inclination angle of tube (deg)

Plastic viscosity and yield value are calculated by Eq. (13).

$$\left.\begin{aligned} \eta_{pl} &= \frac{\pi R^4}{8A} \\ \tau_f &= \frac{3RC}{8A} \end{aligned}\right\} \qquad \text{(13)}$$

Ordinarily, it would be desirable to vary the inclination angle at many levels to measure flow volumes and determine the surest values of rheological constants applying the method of least squares, but test values of ample reliability can be obtained even with the abovementioned simplified method. That is, the rheological constants for prepacked concrete grout possessing normal consistency obtained by the simplified method using the inclined pipe and by rotation viscometer roughly coincide, the ratios of the two being 0.91 to 1.13 for plastic viscosity and 0.94 to 1.15 for yield value. As for the coefficients of variation of the measurements, they are 1.9 to 7.6 percent for plastic viscosity, and 5.1 to 8.2 percent for yield value, which are comparatively low[2].
It is when slippage does not occur between sample and pipe wall that satisfactory results such as mentioned above are obtained with the inclined pipe testing method. Fig. 3 shows examples of the relationship of hydraulic gradient and inclined pipe flow volume in case of varying the inclination angle of the inclined pipe between 5 to 60 deg from among results of tests on 650 cases, and this relationship roughly coincides with values calculated by Eq. (11) in the range of hydraulic gradients approximately 0.4 to 1.0. However, when hydraulic gradient exceeds 1.0, the measured flow volume gradually becomes larger than calculated flow volume to indicate that slipping had occurred between sample and tube wall.

Occurrence of slippage is due to shear force acting between sample and pipe wall being greater than bond force. Therefore, if shear force at the pipe wall surface at a point (P or Q) where the measured flow volume curve deviates from the calculated flow volume curve in Fig. 3 is computed, the value will be equal to the bond force between sample and pipe wall surface. The shear force at the pipe wall surface is given by the following equation:

$$\tau_R = \frac{R}{2} \cdot \frac{\Delta P}{l} \quad \text{or} \quad = \frac{R}{2} \rho g I \qquad \cdots\cdots (14)$$

where, τ_R: shear force acting at interface of sample and pipe wall (gf/cm^2), $\Delta P/l$: pressure gradient (gf/cm^2/cm)

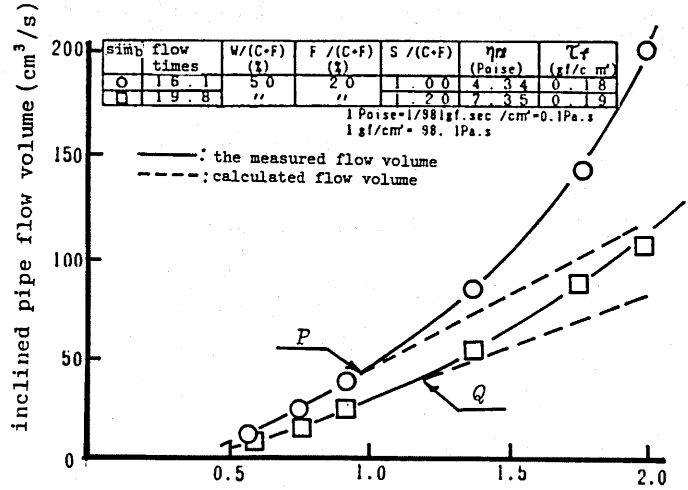

Fig. 3 relationship of hydraulic gradient and inclined pipe flow volume

Bond forces of grouts were calculated from a large number of test results[4],[5] varying pipe materials, pipe diameters, inclination angles, etc. for prepacked and prestressed concrete grouts, and these are shown in Fig. 4.

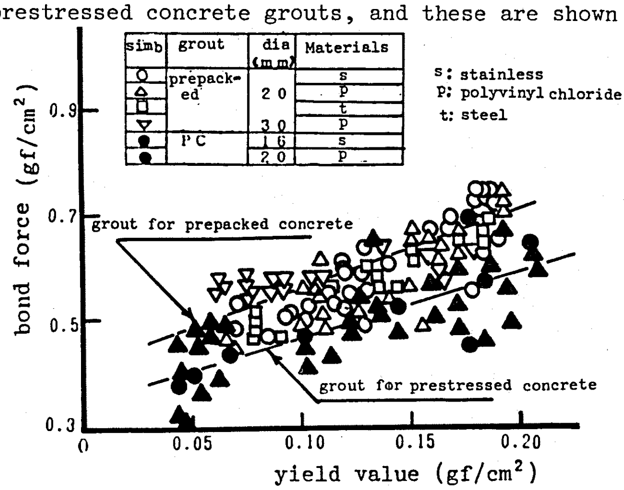

Fig. 4 relationship of bond force and yield value

Fig. 4 shows bond force in relation to yield value. The range of bond force is comparatively narrow and in case of prepacked concrete grout of flow time 16 to 20 s by P-type flow cone, the average is from 0.5 to 0.65 gf/cm^2 (49.1 to 63.8 Pa), while in case of prestressed concrete grout of flow time 6 to 12 s by J-type flow cone, the average is from 0.4 to 0.55 gf/cm^2 (39.2 to 54.0 Pa), while differences could not be seen between the pipes of stainless steel, polyvinyl chloride, and steel that were used.

Table 1 shows the results of a survey on pumping of grout in prepacked concrete work, with shear force at the pipe wall calculated from the diameter of the pipe used and the pressure gradient smaller than bond force of grout in 14 out of 19 cases, and it can be considered that most were cases of no slippage between sample and pipe wall. Accordingly, the results of inclined pipe tests can be utilized for grout pumping work. Furthermore, the inclined pipe testing method can be applied to prestressed concrete grout also. It is advisable in such case to make the diameter of the discharge tube 16 mm, and tube length 50 cm[2],[4],[5].

Table 1 The Results of a Survey on Pumping of Grout

Work	Equivalent strength pipe length (m)	Diameter of pipe (mm)	Pressure gradient	Shear stress acting at interface of pipe wall (gf/cm)
A	39.3	38	0.38	0.36
B	48.3	38	0.56	0.53
	68.3		1.27	1.21
C	39.6	50	0.38	0.47
D	9.8		0.86	1.07
	18.8		2.63	3.28
E	38.3	38	0.18	0.17
			0.20	0.19
F	22.3	40	0.56	0.56
	42.3		0.89	0.89
G	75.6	42	0.11	0.12
			0.13	0.13
H	16.4	64	0.40	0.59
I	27.6	50	0.24	0.30
			0.60	0.75
J	22.1	35	0.34	0.30
			0.79	0.69
K	50.9	32	0.28	0.23
	80.9		0.67	0.54

*Pipe length measurements converted into straight lengths is 1 m.

3. GROUT PUMPING TESTS USING PIPELINE

(1) Materials Used and Mix Proportions of Grout

The cements used for the experiments were ordinary portland cement manufactured by N Co. and fly ash manufactured by D Co., the physical test results and chemical components of these being as shown in Tables 2 and 3. The water-reducing admixture and grouting admixture were No. 8 and GF-800 manufactured by Co. N.

The fine aggregate was sand from the Tone River, the physical properties of which are given in Table 4.

Table 2 The Physical Test Results and Chemical Componebts of Cement

Physical test results

Specific gravity	Fineness Blain method (cm^2/g)	Time of setting water (%)	Time of setting Initial (h-m)	Time of setting Final (h-m)	Soundness
3.16	3130	27.8	2-34	3-50	good

Flow	Strength (Kgf/cm) Bending strength 3 days	Bending strength 7days	Bending strength 28days	Compressive strength 3days	Compressive strength 7days	Compressive strength 28days
256	34	49	70	139	236	413

Chemical components

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	ig.loss	insol
22.3	5.4	3.0	63.4	1.4	0.5	0.8

Table 3 Physical Test Results and Chemicla Chemical Conponents of Fly Ash

specific gravity	Fineness Blain method (cm^2/g)	Chemical components (%) SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
2.19	3200	55.3	33.8	6.6	0.3	1.8	0.4

Table 4 Physical properties of fine aggregate

No.	production place	specific gravity	absorption rate (%)	unit volume (Kg/l)	actual results rate (%)	rate of coarse fineness (%)
1	Tonegawa River	2.52	4.26	1.49	60.1	2.17
2		2.56	4.02	1.44	58.8	2.05

*No.1 for case of straight pipeline, No.2 for case of bent pipeline

The prepacked concrete grout mix proportions were for water-binder ratio (W/(C+F)) of 0.50, and admixture ratio (F/(C+F)) of 20 percent, and these were for P-type flow cone flow times of about 16, 18, and 20 s, and for flow time of 30 s using GF-800, and the unit weights of the various materials are shown in Table 5.

Table 5 Mix Proportion of Prepacked Concrete Grout

object experiment	flow time of P-Type flow cone(sec) mixing time	pumping time	rate of proportion(%) W/C+F	F/C+F	S/C+F	A_d/C+F	unit weights (Kg/m^3) water W	cement	fly ash F	Fine aggregate S	admixture A_d (g)
experiments with straight pipelines	16.0	16.9			1.12		389	622	156	871	1945
	17.9	19.6	50.0		1.20	0.25	380	607	152	911	1898
	22.2	22.6			1.28		371	593	148	949	1855
	36.7	44.4	36.9	20.0	1.20	1.00	326	660	165	990	*8250
experiment with bent pipelines	15.7	15.7			1.10		391	626	157	861	1958
	18.6	18.6	50.0		1.17	0.25	383	613	153	897	1915
	19.7	19.7			1,25		374	598	150	935	1800

Furthermore, since a part of the experiments was performed at a different time, there were slight differences in the gradation of fine aggregate and other factors, and mix proportions were adjusted accordingly.

(2) Method of Testing

a) Case of Straight Pipeline

Using a grout mixer of 80 ℓ and with volume of one batch as 50 ℓ, mixing was done for 4 minutes at 650 rpm after which consistencies were measured by P-type flow cone, rotation viscometer, and inclined pipe testing apparatus, and grout was immediately pumped.

The pump was an atmospheric injection type with a capacity of 40 ℓ, and maximum pressure of 10 kgf/cm^2 (0.98 MPa).

The pipelines were horizontal, straight lines of lengths 40, 60, and 80 m coupling steel pipes 20 mm in diameter and 4 m in length. A view of the piping is shown in Photo. 2.

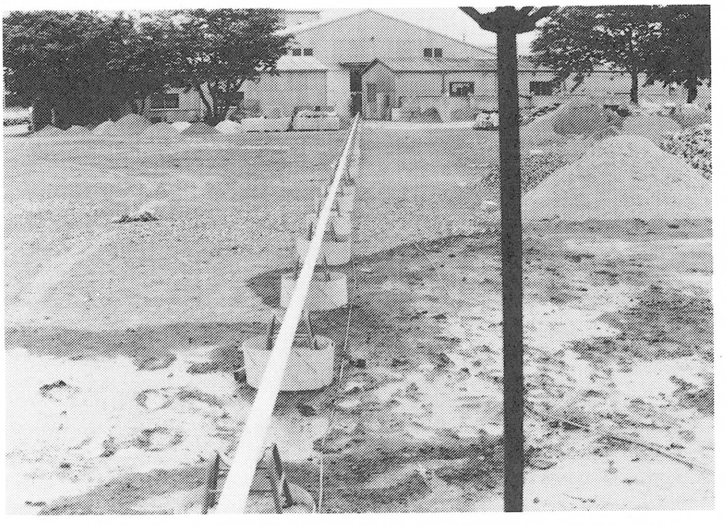

Photo. 2. view of the piping for grout

Volumes and pressures inside pipes were measured with pressure gradients at 0.625 and 0.9 gf/cm^2/cm (61.3 and 88.3 Pa/cm). The locations of pressure measurements were 0.1, 19.9, 39.9, 59.9, and 79.0 m from the pipeline inlet, and diaphragm-type pressure gauges of capacities 2, 5, and 10 kgf/cm^2 (0.20, 0.49, and 0.98 MPa) were used.

b) Case of Bent Pipeline

The pump used in a) above had agitating propellers, and with the volume of one batch as 40 ℓ, mixing was done for 4 minutes at a speed of 650 rpm. After completion of mixing, consistencies were measured using P-type flow cone, rotation viscometer, and inclined pipe testing apparatus, and pumping was immediately done at 250 to 470 gf/cm^2 (0.02 to 0.04 MPa) in case of horizontal bent pipe and 400 to 850 gf/cm^2 (0.04 to 0.08 MPa) in case of vertical bent pipe.

The pipelines consisted of polyvinyl chloride pipes of diameter 20 mm with bent pipes of the seven shapes shown in Table 6 coupled between two straight pipes of 2-m lengths laying the entire pipeline horizontally (called horizontally bent

Table 6 Shapes and Vessel Dimension of Bend Pipe

Angle of bend (°)	Length of bend pipe (cm) 2oR	3oR	4oR
3o	1o.5	25.7	34.6
6o	2o.9	—	—
9o	31.4	58.7	73.7

* R : radius of pipe

pipeline), and of horizontal straight pipes of 2-m pipe lengths to which bent pipes of curvature radii 20 cm and 40 cm and 90-deg bends were connected vertically upward (called vertically bent pipeline), and flow volumes and pressures inside the pipelines were measured. Measurements of pressure were at locations 15 cm on the outsides of the inlets and outlets of bent pipes, and were carried out with diaphragm type pressure gauges of capacity 2 kgf/cm^2 (0.02 MPa).

(3) Results of Pumping Experiments with Straight Pipelines

The results of rheological constant measurements of grouts of the various mix proportions by rotation viscometer and inclined pipe testing apparatus are given in Table 7, and the results of flow volume measurements at the pipelines in Table 8.

Table 7 Results of Rheological Constant

Flow time of P-type flow cone (sec)	rotaion viscometer plastic viscosity (poise)	yield value (gf/cm²)	inclined pipe test apparatus plastic viscosity (poise)	yield value (gf/cm²)	ration rotaion/inclined plastic viscosity	yield value
16.9	3.32	o.14	3.35	o.14	1.o1	o.99
19.6	3.87	o.14	3.89	o.14	1.o1	1.o1
22.6	6.o1	o.15	4.83	o.15	o.8o	o.81
44.4	8.54	o.oo1	3.33	o.114	o.39	114

*1 poise≒ 1/981gf·sec/cm²=o.1Pa s, 1gf/cm²=98.1Pa ● =GF-8oo is added.

Table 8 The Results of Flow Voulume Measurements at Straight Pipelines

flow time of P-type flow cone (sec)	l (m)	pressure gradient;o.625(gf/cm²/cm) Q_A (cm³/sec)	Q_R	Q_A/Q_R	Q_K	Q_A/Q_K	pressure gradient;o.9oo(gf/cm²/cm) Q_A (cm³/sec)	Q_R	Q_A/Q_R	Q_K	Q_A/Q_K
	4o	3o.7		o.98		o.98	68.5		1.1o		1.11
16.9	6o	28.9	3o.7	o.94	3o.8	o.94	61.4	62.o	o.99	61.8	o.99
	8o	29.8		o.97		o.97	63.7		1.o3		1.o3
	4o	24.5		o.92		o.94	49.o		o.92		o.93
19.6	6o	24.1	26.4	o.91	26.o	o.93	53.o	53.2	1.oo	52.7	1.o1
	8o	3o.2		1.14		1.16	56.o		1.o6		1.o8
	4o	22.6		1.42		o.89	47.1		1.42		1.oo
22.6	6o	27.8	15.9	1.75	25.3	1.o9	46.9	33.1	1.42	46.1	1.oo
	8o	28.o		1.76		1.11	51.5		1.55		1.o9
44.4	4o	36.8	28.1	1.31	37.6	o.98	67.7	4o.5	1.67	69.1	o.98
	6o	34.9		1.24		o.92	65.2		1.66		o.94

*Q ;Flow volume calculated using rheological constants determined by rotaion viscometer.
Q ;Flow volume calculated using rheological constants determined by an inclined pipe testing apparatus. Q_A;measured flow volume l; pipe length

In Table 7, the measured values of rheological constants of grouts in cases of P-type flow cone flow times less than 20 s are roughly equal regardless of the method of measurement to substantiate 2.(3). Contrasted to this, in case of grouts having P-type flow cone flow times longer than approximately 20 s, because of slippage occurring at the interface with the container, there were differences between the rheological constants obtained by rotation viscometer measuring flow velocity distributions of samples inside the viscometer, and the apparent rheological constants by the inclined pipe tests using flow volumes including slippage.

In Table 8, it is shown that in the cases of P-type flow cone flow times of 16.9 s and 19.6 s, measured flow volumes coincide approximately with the calculated flow volumes based on Eq. (11) using the rheological constants in Table 7 regardless of the differences in pressure gauges, and the ratios between the two are from 0.91 to 1.16. In contrast, when flow time by P-type flow cone becomes more than 20 s, slippage occurs between the sample and pipe wall, and the measured flow volume is larger than the flow volume calculated using the physical property values determined by rotation viscometer, and the ratios between the two are 1.42 to 1.76.

A separate study is being made regarding analysis of flow inside the pipe accompanied by slippage[6], but meanwhile the flow volume of grout with flow time by P-type flow cone exceeding 20 s coincides well with the calculated flow volume using the apparent rheological constants obtained from the inclined pipe tests shown in Table 7 and the flow volume in the pipe accompanied by slippage. This is because slippage occurs in the inclined pipe tests similarly to the pipeline, and if the apparent rheological constants were to be obtained before execution using an inclined pipe of the same diameter as the pipeline, it will be possible to predict the flow volume in the pipeline or the pumping pressure using that value.

Examples of the results of measurements on pressures inside pipelines are shown in Fig. 5.

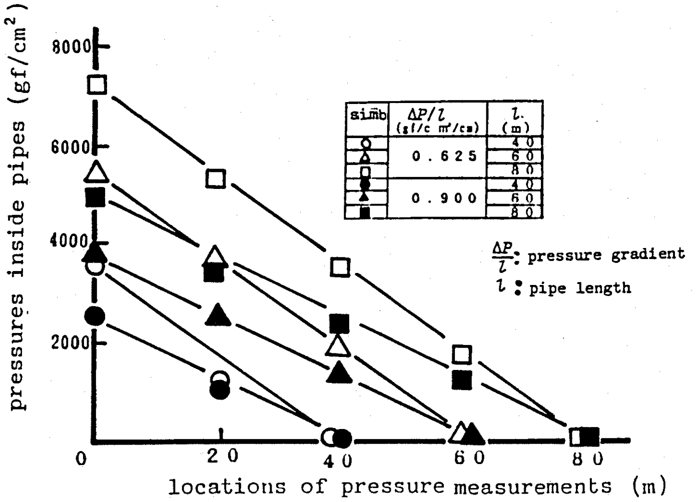

Fig. 5. the results of measurements on pressures in straight pipelines

In Fig. 5, the measured values of pressure decrease more or less linearly from the inlet of the pipe toward the outlet, with pressure at the inlet of the pipe the pumping pressure and that at the outlet zero, a distribution the same as for pressure of a fluid[7].

(4) Results of Pumping Experiments with Bent Pipelines

Table 9 gives the results of flow volume and pipe length measurements converted into straight lengths, and Table 10 the results of pressure measurements and pressure losses in bent pipes, and these are for cases of P-type flow cone flow time of 18 s. The apparent pressure gradients (pumping pressure divided by actual length of piping) are taken to be approximately 0.6, 0.8, and 1.0 gf/cm^2/cm (58.9, 78.5, and 98.1 Pa/cm). In Table9 the measured flow volume is smaller than the calculated flow volume obtained with the entire pipeline assumed to be a straight horizontal line. This is because of the pressure loss due to bending.

Table 9 The Results of Flow Volume and Pipe Length Measurements converted

curvature radius (cm)	plastic viscosity (poise)	yield value (gf/cm^2)	bend angle θ	P_o (gf/cm)	Q_A (cm^3/sec)	Q (cm^3/sec)	P_o/l'	l" (m)	L (m)	L_b(m)	ratio = L_b/L
20	2.98	0.17	30	260	13.4	24.6	0.53	4.94	0.84		1.06
				320	29.1	41.6	0.66	4.83	0.73	0.89	1.22
				420	47.1	71.2	0.81	5.19	1.09		0.82
			60	260	12.3	21.6	0.52	5.04	0.94		1.15
				320	26.4	38.5	0.64	4.99	0.89	1.08	1.21
				420	44.2	38.7	0.89	5.34	1.24		0.87
			90	260	10.5	20.5	0.50	5.21	1.11		1.14
				320	21.2	37.2	0.60	5.37	1.27	1.26	0.99
				420	42.1	64.9	0.77	5.46	1.36		0.93
30	2.26	0.19	30	255	11.7	21.4	0.53	4.83	0.73		1.11
				340	37.9	52.3	0.71	4.79	0.69	0.81	1.17
				472	66.7	86.9	0.89	5.32	1.22		0.66
			90	275	11.4	21.4	0.53	5.23	1.13		1.03
				376	28.0	55.6	0.65	5.83	1.73	1.17	0.68
				430	60.1	90.3	0.85	5.07	0.97		1.21
40	2.36	0.19	30	296	16.0	23.3	0.57	4.74	0.64		1.20
				362	42.7	54.8	0.75	4.81	0.71	0.77	1.08
				455	69.3	89.7	0.92	4.93	0.83		0.93
			90	283	17.1	20.5	0.58	4.92	0.72		1.57
				376	32.8	48.6	0.69	5.48	1.38	1.13	0.82
				432	54.7	67.3	0.83	5.20	1.10		1.03

* l" is shown as a unit 'm' of ezuivalent straight pipe distance l'.
P_o: pumping pressure Q_A: mesured flow volume Q calculated flow volume
P_o/l': effective pressure gradient . l": equivalent straight pipe distance
L: equivalent straight pipe length of bent pipe L_b: calculated values of equivalent straight pipe length of bent pipe byeq.(21)

Applying the energy equation to the inlet and outlet of the bent pipe,

$$\frac{V_1^2}{2g} + Z_1 + \frac{P_1}{\rho g} = \frac{V_2^2}{2g} + Z_2 + \frac{P_2}{\rho g} + f\,\frac{V_2^2}{2g} \quad \cdots\cdots (15)$$

where, V_1, V_2: average flow velocities at inlet and outlet of bent pipe, respectively (cm/s), Z_1, Z_2: location energies at inlet and outlet of bent pipe, respectively (cm), $f\,\frac{V_2^2}{2g}$: energy loss at bent pipe (cm)

Since $V_1 = V_2$,

$$P_1 - P_2 = \rho g \left(f\,\frac{V_2^2}{2g} + Z_2 - Z_1\right) \quad \cdots\cdots (16)$$

Table 10 The Results of Pressure Measurements and Pressure Losses in Bent pipe

curvature radius R_b (cm)	η_{pl} (poise)	τ_f (gf/cm)	bending angle θ (°)	puming pressure P_0 (gf/cm²)	P_0/l'	V	R_{eb}	pressure (gf/cm²) 1) P	2) P	P_1' (gf/cm²)	P_2' (gf/cm²)	Loss factor f	ΔP (gf/cm²)	ΔP_b (gf/cm)	ratio = $\Delta P_b/\Delta P$
	260			260	0.53	4.3	0.39	160	75	160	109	2379	44	37.9	0.90
			30	320	0.66	9.3	2.15	198	85	184	136	548	48	57.0	1.18
				420	0.81	15.0	5.66	263	108	254	166	384	88	75.8	0.86
				260	0.52	3.9	0.32	163	73	154	106	3085	48	47.1	0.97
20	2.98	0.17	60	320	0.64	8.4	1.76	202	81	109	131	791	57	66.4	1.16
				420	0.79	14.1	5.01	269	98	259	161	482	98	89.5	0.92
				260	0.50	3.3	0.23	106	66	157	102	4842	55	49.8	0.90
			90	320	0.60	6.8	1.09	205	78	198	122	1621	76	67.7	0.90
				420	0.77	13.4	4.55	272	89	262	158	569	104	98.1	0.94
				255	0.53	3.7	0.27	155	82	147	108	2752	39	32.3	0.84
			30	340	0.71	12.1	3.18	208	101	194	146	333	49	60.6	1.24
30	2.26	0.19		470	0.89	21.2	10.0	267	123	290	182	237	108	83.9	0.78
				275	0.53	3.6	0.21	172	87	167	108	4466	59	60.4	1.02
			60	376	0.65	8.9	1.65	239	112	244	132	1392	112	72.8	0.65
				430	0.85	19.1	8.19	305	120	256	174	223	82	109	1.33
				269	0.57	5.1	0.48	161	94	153	116	1396	37	36.0	0.98
			30	362	0.75	13.6	4,10	220	117	218	154	288	54	56.0	1.05
				455	0.92	22.1	10.8	282	141	226	189	157	77	75.8	0.98
40	2.36	0.19		283	0.58	5.4	0.55	175	100	185	118	1580	47	51.5	1.09
			90	355	0.69	10.4	2.34	236	128	235	141	861	95	68.9	0.73
				432	0.83	17.4	6.80	274	125	262	170	300	92	90.8	0.99

1)Pressure measurements at locations 15 cm on the outsides of inlets of bent pipes. 2)Pressure measurements at locations 15 cm on the outsides on outlets of bent pipes. 3)Estimated pressure at the inlets of bent pipe using measured flow volume and effective pressure gradient. 4)Estimated pressure at the outlets of bent pipe using effective pressure gradient. 5)Pressure loss of bent pipe calculated by eqs. (16),(17). P_0/l': effective pressure gradient (gf/cm²/cm)
V : average flow velocity Δp : estimated values of pressure loss of bent pipe
P -P = P ΔP_b: calculated values of pressure loss of bent pipe

where, f: loss factor of bent pipe

The loss factor of the bent pipe can be computed from the pressure differential between the inlet and outlet of the pipeline. The pressures and flow volumes at locations 15 cm on the outsides of the inlets and outlets of bent pipes were measured in these experiments so that the pressures at the inlets and outlets of bent pipes could be estimated either from the pressure measurements or from measured flow volumes, but it was decided to estimate by the latter in consideration of stability of measured values. The estimated pressures are given in Table 10.

Calculation of the loss factor of a bent pipe can be performed by Richter's equation, Weisbach's equation, or Creager's equation, and as a result of study it was decided to use Richter's equation changing the Reynolds number in it to the Reynolds number of a Bingham body.

$$f = \beta \left(\frac{R_b}{D}\right)^i \theta^j R_{eb}{}^k \quad \cdots\cdots (17)$$

where, D: diameter of pipe (cm), R_b: curvature radius of bent pipe (cm), θ: bending angle (deg), β, i, j, k: experiment constants, R_{eb}: Reynolds number of Bingham body.

It was decided to use Tomita's equation below for the Reynolds number of a Bingham body. It is said this coincides well with the test results of suspensions of clay, sludge, etc.[8].

$$R_{eb} = \frac{\rho v D(4\alpha a)}{\eta_{pl}} F(a) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (18)$$

where, ρ: density of grout (g/cm^3), v: average flow velocity (cm/s), a: specific plug diameter (r_f/R), α: $(a^4 - 4a + 3)/12a$, $F(a) = 9/5\{(5 + 6a - 11a^2)/(3 + 2a + a^2)^2\} \doteqdot 1 - a$

Using values of R_b, θ, R_{eb} and D given in Table 10 and determining the experiment constants of Eq. (17) by the method of least squares, $\beta = 1100$, $i = -0.44$, $j = 0.30$, and $k = -0.70$ were obtained. The calculated values of loss factor and pressure loss obtained from Eq. (17) using the above values are shown in Table 10. In Table 10, the ratios of the calculated and estimated values of pressure losses in bent pipes are mostly in a range of 0.84 to 1.18, and the average is 1.01. Similar relationships were found for cases of P-type flow cone flow times 16 s and 20 s.

It is possible to calculate pressure loss in a bent pipe using Eq. (17) as indicated above, but this method is generally troublesome and as a practical matter the equivalent straight-pipe length (L) of the bent pipe is used. The equivalent straight-pipe length was calculated by the following equation as the value determined by deducting the actual length of the straight pipe portions from the equivalent straight pipe distance (l') of the entire length of the pipe obtained by dividing the pumping pressure by the measured flow volume and the effective pressure gradient calculated by Eq. (11).

$$L = 0.01 \left(\frac{P_o}{q} - S\right) = 0.01 \,(l' - S) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (19)$$

where, L: equivalent straight-pipe length of bent pipe (m), P_o: pumping pressure (gf/cm^2), q: effective pressure gradient ($gf/cm^2/cm$), l': equivalent straight-pipe distance of entire pipeline (cm), S: actual length of straight-pipe portion (cm)

The results of calculations of equivalent straight-pipe length by Eq. (19) are given in Table 9.

The equivalent straight-pipe length differs depending on the ratio between pipe radius and curvature radius and the angle of bend, while within the range of grouts used in these experiments the influences of consistency and pumping pressure were comparatively small. Consequently, the following equation with constants determined by the method of least squares based on experimental values can be proposed as a practical equation for equivalent straight pipe length of a horizontally bent pipe:

$$L_{90} = 5.1 \left(\frac{R}{R_b}\right) + 1.0 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (20)$$

$$L_b = L_{90} - 0.006\,(90 - \theta) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (21)$$

where, L_{90}: equivalent straight-pipe length in case of bending angle 90 deg (m), R_b: curvature radius (cm), L_b: equivalent straight-pipe length at bending angle θ (m)

The ratios of calculated values and equivalent straight-pipe lengths from these Eqs. (20) and (21) were mostly in a range of 0.80 to 1.24, and the average was 0.9.

Table 11 gives examples of flow volume measurement results and equivalent straight-pipe lengths and Table 12 pressure measurement results and pressure losses, both of vertically bent pipe, and cases of P-type flow cone flow time of 18 s. The apparent pressure gradients were approximately 1.4, 1.6, and 1.8 $gf/cm^2/cm$ (137, 157, and 177 Pa/cm).

Table 11 The Flow Volume Measurements Results and Equivalent Straight Pipe Length on Bent Pipe

curvature radius R_b (cm)	flow time of P-tpye flow cone (sec)	rheological constants		vertical pipeline length (m) {height differential} (m)	pumping pressure P_o (gf/cm^2)	measured flow volume Q_A (cm^3/sec)	calculated flow volume Q (cm^3/sec)	effective pressure gradient P_o/l' ($gf/cm^2/cm$)	equivalent straight pipe length L (m)	* L_b (m)	ratio = L_b/L
		plastic viscosity (poise)	yield value (gf/cm^2)								
20	18.6	3.67	0.19	0.50 {0.75}	408	20.6	94	0.68	1.17	1.25	0.94
					466	34.3	115	0.82	1.23		0.98
					525	47.7	136	0.95	1.32		1.06
				1.00 {1.25}	478	8.3	94	0.54	1.06		0.85
					546	23.4	115	0.71	1.03		0.82
					615	42.1	136	0.90	0.94		0.75
				1.50 {1.75}	540	0.4	92	0.41	0.97		0.78
					630	12.5	116	0.59	1.07		0.89
					750	41.4	148	0.89	0.85		0.68
40	18.2	3.56	0.19	0.50 {0.95}	516	44.7	121	0.91	0.96	1.13	0.85
					581	53.8	142	1.00	1.30		1.15
					545	72.7	164	1.17	1.26		1.12
				1.00 {1.45}	596	26.0	121	0.73	1.06		0.93
					671	43.8	142	0.90	1.09		0.96
					746	57.3	164	1.03	1.29		1.14
				1.50 {1.95}	676	13.3	120	0.60	1.13		1.00
					761	30.3	142	0.77	1.15		1.02
					846	46.7	164	0.97	1.26		1.12

* ; Equivalent straight pipe length of bent pipe by eq.(20) or (21).

In Table 12 the ratios between estimated and calculated values of pressure losses deducting head due to dead weight of sample in the vertical pipe from the pressure loss obtained by the same method as for horizontally bent pipe, were, with partial exceptions, 0.80 to 1.17.

The equivalent straight-pipe length of the vertically bent pipe in Table 11 was determined by the following equation upon obtaining the effective pressure gradient from measured flow volume similarly to horizontally bent pipe, and expressing the pressure loss due to dead weight of sample in the bent pipe and the vertical straight pipe by the head differential in the bent pipe:

$$L = 0.01\left(\frac{P_o - \rho g h}{q} - S\right) \qquad \text{.............................} \quad (22)$$

where, L: equivalent straight-pipe length of bent pipe (m), h: height differential in piping (cm)

The equivalent straight-pipe lengths of vertically bent pipes are as shown in Table 11. The ratios between the estimated values of equivalent straight-pipe lengths and the calculated values from Eqs. (20) and (21) are mostly in the range of 0.75 to 1.15, and the equivalent straight-pipe lengths of vertically bent pipes can be handled in the same manner as with horizontally bent pipe by giving consideration to height differentials in the piping.

Consequently, if the mix proportions of the grout and piping conditions are given, the flow volume in relation to pumping pressure, or the pumping pressure of the pump in relation to flow volume can be estimated by the following procedure;

Table 12 The Pressure Measurement Results and Pressure Loss of Bent Pipe

curvature radius R_b (cm)	rheological constants: plastic viscosity (poise)	rheological constants: yield value (gf/cm²)	vertical pipeline (m) {height differential} (m)	pumping pressure P_o (gf/cm²)	effective pressure gradient P_o/l (gf/cm²/cm)	average flow velocity V (cm/sec)	Reynolds number	measured pressure value (gf/cm²): P 1)	measured pressure value (gf/cm²): P 2)	P_1 3) (gf/cm²)	P_2 4) (gf/cm²)	loss factor f	estimated values of pressure loss $P_1-P_2=P$ (gf/cm²)	calculated values of pressure loss P_b (gf/cm²)	ratio $=P_b/P$
20	3.68	0.19	0.50	408	0.68	6.6	0.95	270	68	167	37	1601	128	123	0.86
				466	0.82	10.9	2.74	308	67	196	45	761	152	134	0.89
			{0.75}	525	0.95	15.2	5.20	347	63	228	52	485	176	156	0.89
			1.00	474	0.54	2.6	0.12	360	64	164	57	6718	107	89	0.83
				546	0.71	7.5	1.25	411	85	197	75	1318	122	116	0.95
			{1.25}	615	0.90	13.4	4.10	463	118	228	94	574	134	148	1.10
			1.50	540	0.47	0.1	0	445	74	152	63	—	98	—	—
				630	0.59	4.0	0.31	519	121	204	92	3481	112	98	0.89
			{1.75}	750	0.89	13.2	3.97	618	182	263	138	587	125	146	1.17
40	3.56	0.19	0.50	516	0.91	14.2	4.62	359	82	228	50	389	234	163	0.70
				581	1.00	17.1	6.54	406	104	274	55	305	219	174	0.79
			{0.95}	645	1.17	23.1	11.30	448	122	303	65	209	238	197	0.82
			1.00	596	0.73	8.3	1.55	467	83	243	77	836	167	141	0.84
				671	0.90	13.9	4.44	528	113	283	95	400	188	162	0.86
			{1.45}	746	1.03	18.2	7.34	586	138	332	108	281	224	179	0.80
			1.50	676	0.60	4.2	0.36	564	137	249	92	2335	157	124	0.79
				761	0.77	9.6	2.13	634	139	298	120	609	178	146	0.82
			{1.95}	846	0.93	14.9	5.02	705	163	350	144	367	206	165	0.80

Atten.1)Pressure measurements at locations 15cm on the outsides of the inlets of bent pipe. 2)Pressure measurements at locations 15cm on the outsides of the outlets of bent pipe. 3)Pressure at the inlets of bent pipe estimated using measured flow volume and effective pressure gradient. 4)Estimated pressure at the outlets of bent pipe just as 3).

i) The rheological constants of the grout are determined by the inclined pipe test.

ii) The approximate value of the equivalent straight-pipe length is calculated from Eqs. (20) and (21) using the curvature radius of the bent pipe, the diameter of the pipe, and bending angle.

iii) The flow volume correlative to pumping pressure is calculated from the Buckingham equation (Eq. (11)) using the equivalent straight-pipe distance adding the actual length of the straight pipe portion to the equivalent straight-pipe length of the bent pipe. However, in the case of a vertical pipeline calculations are performed with the value obtained by deducting the pressure loss due to height differential in the piping from the pumpi ing pressure as the pumping pressure.

iv) When determining the pressure load of the pump for the required flow volume, it is calculated by the following equation using the equivalent straight-pipe length of the bent pipe:

$$\Delta P = \frac{8l\eta pl}{\pi R^4} Q + \frac{8l\tau f}{3R} \quad \text{.............................} \quad (23)$$

Eq. (23) is a modification of the Buckingham equation omitting the term of $(r_f/R)^4$, and the error due to omission is less than 6 percent.

Pressure load (P_O) of pump
Case of horizontal pipeline $P_O = \Delta P$
Case of vertical pipeline $P_O = \Delta P + \rho gh$

v) When calculating the pressure load of the pump using the loss factor f of bent pipe given in Eq. (17), ΔP is obtained using the actual length of the straight pipe portion as l in Eq. (23), and $\rho g(f\frac{V^2}{2g})$ is added to obtain the the pressure load.

Further, this experiment was conducted with grout temperature of 20°C, and since the physical properties of grout differ according to temperature as shown in Table 13, rheological constants correlative to temperature variation may be obtained by the inclined pipe test in the above calculations.

Table 13 Influence of temperature variation on rheological constant

temperature of grout (°C)	ratation plastic viscosity (poise)	viscometer yield value (gf/cm)	inclined pipe plastic viscosity (poise)	testing appratus yield value (gf/cm)
1o.7	4.21	o.15	5.24	o.14
22.o	5.43	o.16	6.46	o.16
27.1	7.63	o.17	7.65	o.17

4. CONCLUSIONS

Studies were made of methods of predicting flow volumes and pumping pressures of grouts in pipelines including bends with the objective of rationalizing grouting work. However, the objects of study were limited to cases in which slippage at the interface of grout and pipe wall is not produced with the diameter and pressure gradient of pumping pipe of the degree normally used, such as grouts for prepacked concrete and prestressed concrete.

An inclined pipe testing method was proposed in the process of this study as a simple method of measuring rheological constants of grout. The results obtained within the scope of this study may be summarized as follows:

(1) The inclined pipe test method proposed as an improvement on the flow-cone method not only provides a good yardstick for consistency of grout, but the apparatus functions as a type of slender-tube viscometer and it is possible to measure rheological constants of grouts normally used for prepacked concrete and prestressed concrete with simplicity. Rheological constants obtained by the inclined pipe testing method roughly agree with values obtained by double cylinder rotating viscometer, the ratios between the two being 0.96 to 1.13 in case of plastic viscosity and 0.94 to 1.15 in case of yield value, the coefficients of variation of the measurements being 1.9 to 7.6 percent and 5.1 to 8.2 percent, respectively.

(2) The bond forces of grouts for prepacked concrete and prestressed concrete are respectively 0.5 to 0.65 gf/cm^2 (49.1 to 63.8 Pa) and 0.4 to 0.55 gf/cm^2 (39.2 to 54.0 Pa), and from the fact that diameters of pumping pipes used in grouting projects of general nature are 30 to 50 mm, with pressure gradients 0.1 to 0.8 gf/cm^2/cm (9.8 to 18.5 Pa/cm), it may be considered that slippage does not normally act at the pipe wall.

(3) In case slippage does not occur between sample and pipe wall with pipe diameter and pressure gradient not more than 20 mm and 1.0 gf/cm^2/cm (98.1 Pa/cm), respectively, as a result of pumping experiments with prepacked concrete grout in straight pipelines of lengths from 40 to 80 m, the measured flow volumes and the calculated flow volumes according to Buckingham's plastic flow equation coincide approximately, and the ratios of the two are from 0.93 to 1.16.

(4) As a result of pumping experiments of prepacked concrete grout using horizontally bent pipes with curvature radii 20 to 40 times pipe radius and bending angles 30 to 90 deg, and using vertically bent pipes with curvature radii 20 to 40 times pipe radius and bending angle 90 deg, the loss factor (f) of bent pipe is given by the following equation:

$$f = 1100 \left(\frac{R_b}{D}\right)^{-0.44} \cdot \theta^{0.30} \cdot R_{eb}^{-0.70}$$

where, D: diameter of pipe (cm), R_b: curvature radius (cm), θ: bending angle (deg), R_{eb}: Reynolds number of Bingham body

The pressure losses of bent pipes calculated using the loss factor of bent pipes agreed roughly with the estimated value using the measured flow volume, and the ratios of the two were mostly in the range of 0.80 to 1.24, and the average was 0.94.

The following expressions were proposed as practical equations for equivalent straight-pipe lengths of horizontally bent pipes:

$$L_{90} = 5.1\,(R/R_b) + 1.0$$

$$L_b = L_{90} - 0.006\,(90 - \theta)$$

where, L_{90}: equivalent straight-pipe length in case of bending angle 90 deg (m), R: radius of pipe (cm), L_b: equivalent straight-pipe length in case of bending angle θ (m)

The pressure losses of vertically bent pipes coincided roughly with the values calculated using estimated values and loss factors obtained from measured flow volumes, further considering the dead weight of the sample in the vertical pipe, and the ratios of the two were from 0,80 to 1,17.

Regarding equivalent straight-pipe lengths of vertically bent pipes, consideration of the height differentials in the pipelines resulted in ratios of estimated and calculated values of equivalent straight-pipe lengths of 0.75 to 1.15, and vertically bent pipe can be handled as horizontally bent pipe by giving consideration to height differential in the pipeline.

(5) Calculation of the flow volume or pumping pressure when the piping conditions during grout pumping have become definite, in case of a horizontally bent pipeline, can be done by the Buckingham equation using the equivalent straight-pipe length converting the bent pipe to straight pipe based on the conditions of piping and adding the actual lengths of the straight-pipe portions. In case of a vertical pipeline, calculations are performed considering the value obtained by deducting the head differential of the vertical pipe portion of the pipeline from the pumping pressure as the pumping pressure.

In case of estimating the pumping pressure from the required flow volume, it can be done from the following equation using the equivalent straight-pipe distance:

$$\Delta P = \frac{8l\eta_{pl}}{\pi R^4} Q + \frac{8l\tau_f}{3R}$$

where, ΔP: pumping pressure (gf/cm^2), l: equivalent straight-pipe distance (cm), η_{pl}: plastic viscosity (gf·s/cm^2), Q: flow volume (cm^3/s), τ_f: yield value (gf/cm^2)

However, ΔP is to be taken as the pumping pressure in case of a horizontal pipeline, and a value adding the head differential to ΔP as the pumping pressure in case of a vertical pipeline.

When using the loss factor of a bent pipe in calculation of pumping pressure, ΔP is obtained using the actual length of the straight-pipe portion as l in the abovementioned pressure calculation equation, and by adding $\rho g(f \frac{V^2}{2g})$ to this. In case of vertical piping, the dead weight of the sample in the vertical piping added to the abovementioned calculated value is to be taken as the value.

Refenece

[1] J.Murata, H.Kikukawa, "A Proposal on Method of Measuring Rheological Constants of Fresh Concrete," Trans.of JSCE, No.284, P117～126, 1979 (in Japanese).

[2] J.Murata, K.Suzuki, "Measuring Rheologicai Constants of Grouts by Inclined Pipe Method," Proc.of Symosium on Measurement of Pysical Properties and Behavior of Fresh Concrete, P1～8, Japan Society of Civil Engineers, 1983 (in Japanese).

[3] J.Murata, Y.Ogiwara, K.Suzuki, "Placeability of Superplasticized Concrete," Reports of Institute of Industrial Technology, College of Industrial Technology, Nihon University, P23～24, 1983 (in Japanese).

[4] J.Murata,K.Suzuki,"Method of Measuring Consistency of Grouts by Inclined Pipe Testing Method," Review of the 36nd Genenal Meeting-Technical Session, The Cement Association of Japan, P175 ～178,1982,(in Japanese).
[5] J.Murata,K.Suzuki,"New Method of Testing Consistency of Injection Mortar," Cemente & Concrete, JCA, No.413,P23 ～29, 1981, (in Japanese)
[6] J.Murata,K.Suzuki,"Pipe Flow of Mortar with Slippage,"Review of the 38nd General Meeting, Japan Society of Civil Engineers, 1983 (in Japanese).
[7] Ede.A.N,"The Resistance of Concrete Pumped Through Pipelines," Magazine of Concrete Resesrch,Vol.9,No.27,PP125～140,1957.
[8] Y.Tomita,"Rheology," Korona Publishing Co.,P333 ～334,1980, (in Japanese).