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Division I

Pumping Performance of Ultra-high-performance Concrete with a Specified Compressive Strength of 150 MPa

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INTRODUCTION

In recent years, concrete with a compressive strength of more than 150MPa has been put to practical use in high-rise buildings. The authors have developed an ultra-high-performance concrete (UHPC) containing fibers with a strength of 150-200MPa and high fluidity, high fire resistance, and high toughness (Mitsui et al. 2010). By mixing polypropylene fibers and steel fibers with UHPC, it is possible to prevent the explosion of concrete in the case of fire and give high toughness.

It is known that high strength concrete generally has high viscosity and that the pumping load becomes larger than the ordinary concrete. In addition, there is a concern that a large amount of steel fibers may further reduce fluidity or form fiber balls in the piping.

Although the scale of the reactor facilities is large and concrete pumping is required to construct members, there are no pumping test data of 150 MPa UHPC containing more than 1 vol.% of steel fibers. Therefore, in this study, the pumping experiment was carried out in order to apply 150 MPa UHPC with fibers to the nuclear power plant. Pumping experiments of UHPC with and without steel fibers were carried out, and pressure loss and characteristic change after pumping and effect of steel fibers on it were examined. This study had been carried out in the project "Development of technical infrastructure for upgrading materials, structures and construction methods of nuclear power plant buildings"

EXPERIMENTAL PROGRAM

Concrete mixture composition

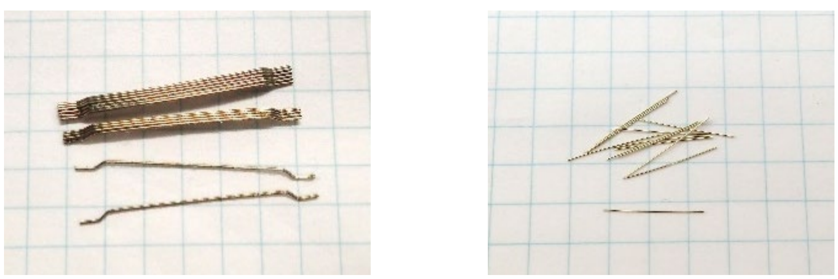
Table 1 shows the material properties of 150MPa UHPC. The cement was commercial silica fume cement produced by pre-mixing low heat Portland cement and ultra-fine silica fume in a mass fraction of 0.9 and 0.1. The spherical micro silica flour with an average diameter of 0.4 μm was added to enhance the flowability. Table 2 shows the mixture proportion of 150MPa UHPC. Two kinds of mixtures with and without steel fibers were prepared. In order to maintain the high toughness and the fluidity, two types of steel fiber (total 1.0 vol.%) was mixed in 150MPa UHPC as shown in Figure 1. This composition was determined in a preliminary study (Nishioka et al. 2018). Furthermore, the preliminary study showed that the reduction in flowability is suppressed by mixing the two types of steel fibers and that its mechanical performance was comparable to that reinforced with 1.0 vol.% long hooked end fibers.

Table 1: Material properties of 150MPa UHPC.

Materials	Notation	Properties / Specific gravity (g/cm^3)
Cement	SFC	Blaine fineness of 6160 cm^2/g / 3.08
Micro silica flour	MSF	A by-product of electro fused zirconia with 95.2% SiO_2 and BET surface area of 6.9 m^2/g / 2.20
Sand	S	Crushed sandstone / 2.63 (saturated-surface-dry)
Coarse aggregate	G	Sandstone <15mm / 2.65 (saturated-surface-dry)
High-range water-reducing agent	HRWRA	Polycarboxylate type / 1.05 ~ 1.13
Steel fiber	H	30 mm long with an aspect ratio of 80 / 7.85
	SS	13 mm long with an aspect ratio of 65 / 7.85
Polypropylene fiber	PP	2 mm long / 0.93

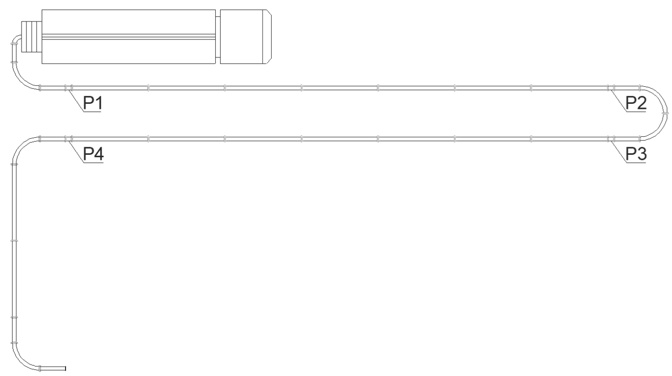
Table 2: Mixture proportions of 150MPa UHPC.

	W/B (%)	s/a (%)	Unit (kg/m^3)					HRWRA (%. b)	Fiber (vol. %)		
			Water	Binder		Aggregate			H	SS	PP
				SFC	MSF	S	G				
A	16.0	64.0	155	947	22	855	485	2.4	0	0	0.11
B	16.0	64.0	155	947	22	855	485	2.8	0.5	0.5	0.11

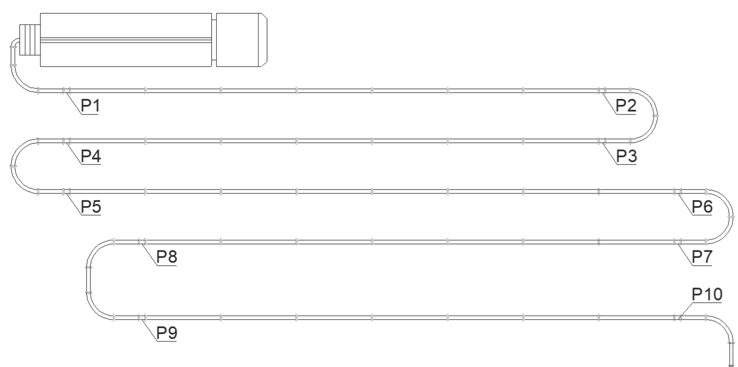

(a) Hook type (b) Straight type
Figure 1. Shape of steel fibers.

Pumping plan

As shown in Fig. 2, two patterns of piping lengths of 64 m and 140 m were carried out. Details of the piping used are shown in Table 3, and Table 4 shows the performance of the pumps used. The experiment was carried out in the standard pressure mode of the pump truck, and the maximum output of the pump truck in this mode is shown in Fig. 3. Pipe length and flow rate conditions of experiments are shown in Table 5. The discharge quantity was made to be 3 patterns of 20, 40, 60 m^3/h.



(a) Pipeline length 64m.



(b) Pipeline length 140m.

Figure 2. Piping layout.

Table 3: Specification of concrete pump pipe.

Type of pipe	Specification
Straight	Length:3m, 1m, 0.25m Inner diameter: φ130.8mm Thin: 4.5mm
Bend	Bending radius: 1.0m Inner diameter: φ130.8mm Thin: 4.5mm
Taper	Inner diameter: φ156.2→130.8mm Thin: 5.2mm
Joint	Pressure capacity: 7.0MPa

Table 4: Performance of the concrete pump truck.

Max. output: Standard pressure mode (Output × Pressure)	$106m^3/h$ × 15.0MPa
Cylinder diameter × Stroke	φ200mm × 2100mm (Capacity of cylinder: $0.066m^3$)
Capacity of hopper	$0.9m^3$

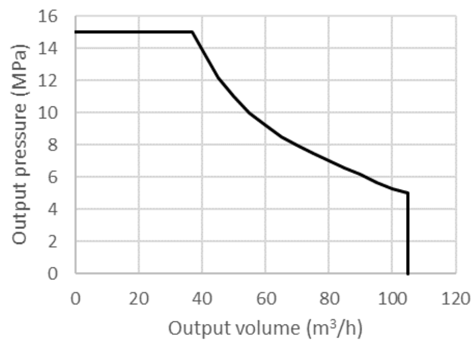


Figure 3. Relationship diagram between maximum output volume and pressure of concrete pump truck.

Table 5: Pipe length and flow rate conditions.

Notation	Type of concrete	Length of pipe(m)	Flow rate (m^3/h)
A64-20	A	64	20
A64-40			40
A64-60			60
A140-20		140	20
B64-20	B	64	20
B64-40			40
B64-60			60
B140-20		140	20

Pressure measurement

Diaphragm type pressure gauges were used for pressure measurement. The pressure gauges were set at P1 to P10 near the vent pipe. The pressure sensors were set in the horizontal direction as a gravitational middle part as shown in Fig. 4.

Figure 4. The pressure sensor.

Test of fresh concrete properties and compressive strength

Fresh test and compressive strength test were carried out before and after pumping concrete. Table.9 shows details and target range of fresh concrete test. Slump flow and air content were measured following JIS A 1150 (JSA 2020) and JIS A 1128 (JSA 2019). The test pieces for the compressive strength test were collected before and after pumping, and the compression test was performed following JIS A 1108 (JSA 2018). on the 28 and 91 days. Test specimens for strength tests were subjected to standard curing until the age of the test.

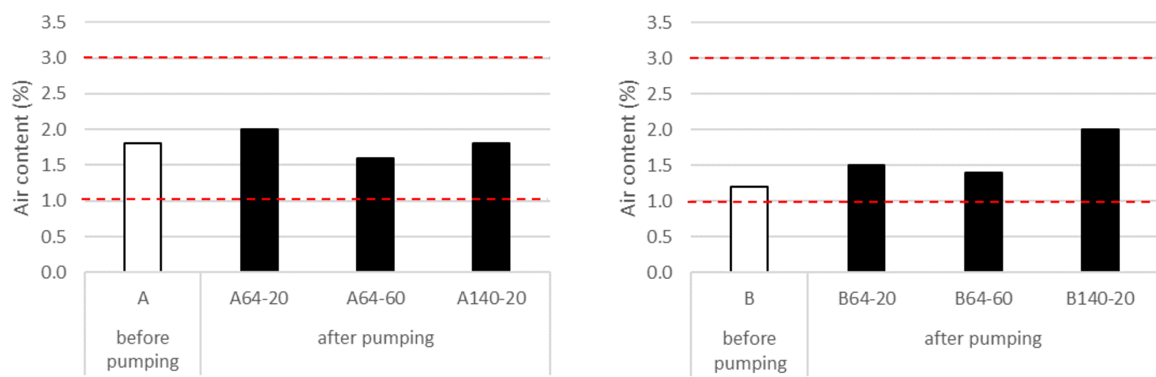
Table 6: Test of fresh concrete

	Measuring details and target range
Segregation	Visual inspection
Slump flow	60±10cm
Air volume	1.0-3.0%
Compressive strength	Standard curing (in water at 20degC) Age: 28d, 91d Cylindrical specimen (φ100×200mm)

EXPERIMENTAL RESULTS AND DISCUSSION

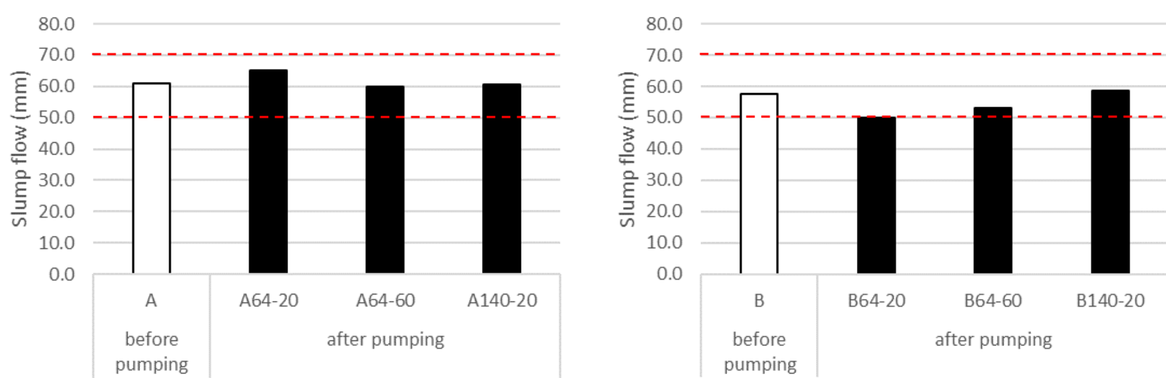
Differences in concrete properties due to pumping

Fig.5 compares the air content of concrete before and after pumping. The air content remained in the targeted range after pumping. The slump flow of concrete also remained around 60cm as shown in Fig.6. Material separation of fresh concrete was not in all batches.



(a) A mixture (no steel fibers) (b) B mixture (1.0 vol.% steel fibers)

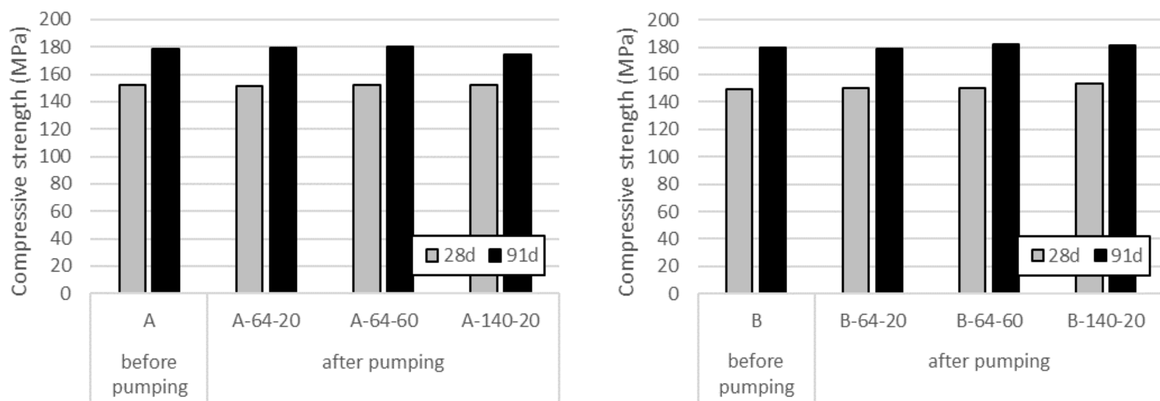
Figure 5. Air content



(a) A mixture (no steel fibers) (b) B mixture (1.0 vol.% steel fibers)

Figure 6. Slump flow

Fig.7 shows the compressive strength of concrete before and after pumping. There is no significant difference in the compressive strength before and after pumping in all cases. The strength reached about 180MPa at the age of 91days.



(a) A mixture (no steel fibers) (b) B mixture (1.0 vol.% steel fibers)

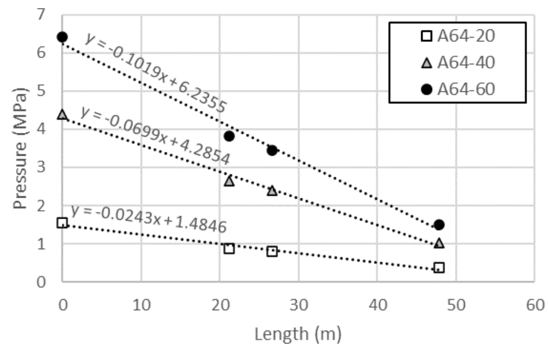
Figure 7. Compressive strength of concrete.

Calculation of pressure loss

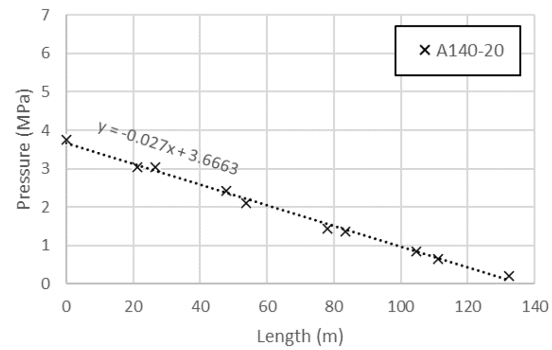
Fig. 8 shows the relationship between pipe length and pressure inside the pipe. The pressure inside the pipe was calculated by reading the pressure inside the pipe when the concrete was pumped stably in the pressure waveform for one stroke of the piston of the concrete pump truck, and averaging the four strokes. In this experiment, no change in pressure loss was observed in the bent pipe part compared to the straight pipe part.

The mechanical efficiency of pumping was estimated. The amount of concrete unloading from an agitator truck was calculated by subtracting the amount of concrete adhering to the drum from the amount of concrete loading, assuming that the amount of concrete adhering to the drum was 0.2 m^3 per truck. The theoretical discharge was calculated from the product of the cylinder volume of the pump truck (0.066 m^3) and the stroke number required for the pumping of concrete for 1 agitator truck, and the mechanical efficiency was calculated in comparison with the unloading quantity. The calculation results are shown in Table 7. The mechanical efficiency was 87% in the A mixture and 91% in the B mixture, and there was no effect of the steel fibers.

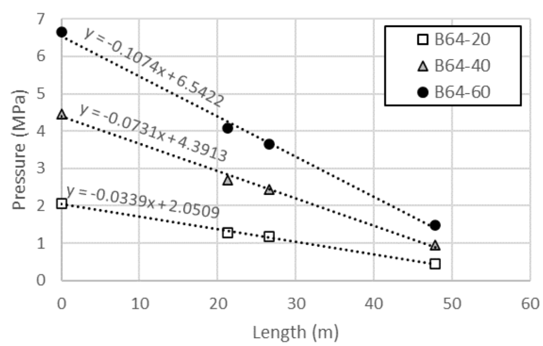
The mean pressure loss is shown by a slope which is a linear approximation of measured results of pipe pressure and pipe length. Fig. 9 shows the relationship between the pressure loss and the actual flow rate. The actual flow rate was calculated by multiplying the theoretical discharge calculated from the time per stroke read from the pipe pressure waveform and the cylinder volume by the mechanical efficiency shown in Table 7. When the flow rate is small (about 20 m^3/h), the pressure loss of B mixture is about 1.3 times that of A mixture, but when the flow rate was increased, the pressure loss was almost the same or smaller.



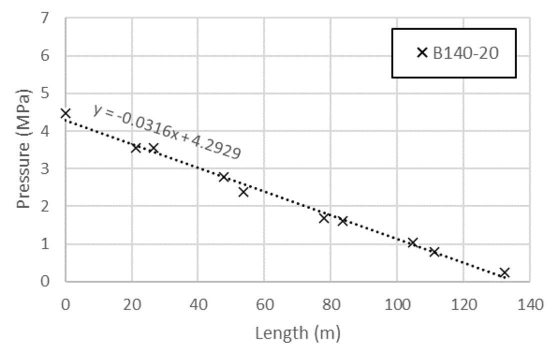
(a) A64m



(b) A140m



(c) B64m



(d) B140m

Figure 8. Pipe length and pumping pressure.

Table 7: Mechanical efficiency of the concrete pump truck

Concrete type	Amount of unloading concrete (m^3)	Number of strokes (-)	Theoretical discharge (Capacity of cylinder × Number of strokes) (m^3)	Mechanical efficiency (%)
A	8.0	139	9.17	87
B	6.6	110	7.25	91

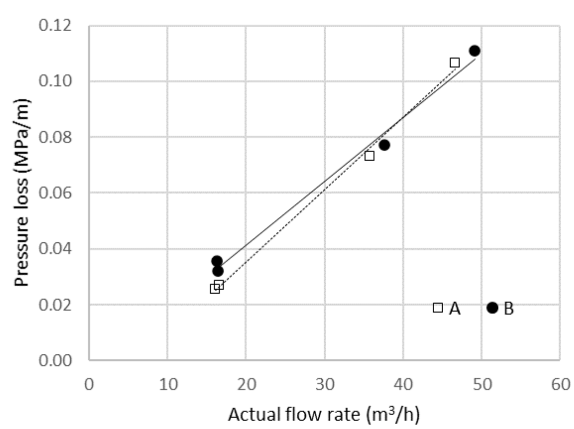


Figure 9. The pressure loss and actual flow rate considering the working efficiency.

Trial calculation of pumping load assuming actual construction

Assuming an actual construction to a nuclear power building, the pumping load at the base of a concrete pump truck was calculated by Equation 1 under the following conditions: piping length 125 m (vertical height 50 m), vent pipe (1 m) × 3 places, flexible hose (10 m) × 1 place, and discharge quantity 30 m^3/h. From Fig. 9, the pipe pressure loss of horizontal piping of B mixture was 0.0605 MPa/m at a discharge rate of 30 m^3/h, and the unit volume weight of fresh concrete was 25 kN/m^3. The safety factor was set to 1.25.

$$P = K (L + 3B + 2T + 2F) + WH\times10^{-3} \times S = 13.2 \text{ (MPa)} \quad (1)$$

Where, P is the load on pumping (MPa), K is pressure loss (MPa/h), L is length of straight pipe (m), B is length of bend pipe (m), T is length of taper pipe (m), F is length of flexible hose (m), W is weight of fresh concrete (kN/m^3) and H is height to pump (m), S is safety factor.

Equation 1 is based on the concrete pumping guidelines of the Architectural Institute of Japan (AIJ 2009). This result was within the range of the capability diagram of Fig. 3, and it was shown that the pumping of UHPC to the nuclear power building was possible.

CONCLUSION

In this study, the pumping experiment of 150MPa UHPC was carried out. This paper shows that there is no difference in basic physical properties of concrete before and after pumping, and that there is no large effect on pumping performance by the existence of steel fibers. Experimental study confirmed that UHPC pumping can be applied to nuclear buildings as well as ordinary concrete.

ACKNOWLEDGEMENT

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