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PROPERTIES OF CONCRETE MIXED WITH SAND FROZEN BY LIQUID NITROGEN

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SYNOPSIS

This paper presents a new precooling method which reduces the temperature of mixed concrete by mixing with sand frozen by liquid nitrogen.
The authors clarify the properties of both the frozen sand and the concrete mixed with the frozen sand. The results of a series of experimental studies indicate that the temperature of mixed concrete could be reduced by about 25°C, which is a reduction quantity larger than that achieved by conventional precooling methods. As a result, this method contribute to the improvement of the consistency and the compressive strength of the concrete. Furthermore, the advantageous effect of this precooling method is confirmed from the results of laboratory tests using massive concrete members.

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1. INTRODUCTION

In recent years large-sized concrete structures have remarkably increased in number as seen in the substructure of a huge bridge typified by Honshu-Shikoku connecting bridge, the bottom slab and side wall of an underground LNG tank and the base mat of a nuclear power plant. Controlling the thermal cracking caused by the heat of hydration of cement in such mass concrete structures has been an important subject from the viewpoint of safety and durability of the structure. From such a background, an overall examination on the control method of the thermal cracking in mass concrete was made and a guideline including the design and control was proposed[1]. Further, it was pointed out that the state of the strength revealment in mass concrete structures shows a different tendency from that in general concrete structures.

Various methods have been proposed in each stage from the design to execution as a method of controlling the thermal cracking caused by the heat of hydration in mass concrete. One of the methods is a precooling which could cool a part or all of concrete components beforehand to reduce the mixed up temperature of concrete. General precooling methods are the chilled water, ice as part of mixing water, utilize cold wind or chilled water to cool coarse aggregates or their combination. In many countries a method using liquid nitrogen at -196°C to make precooling has been in practice more than 10 years[2][3] and recently this kind of research for the precooling has been actively carried forward in Japan.

The conventional precooling method using liquid nitrogen could be divided into three categories, namely, a method of precooling concrete components, a method of injecting liquid nitrogen into concrete during mixing[4] and a method of injecting liquid nitrogen into concrete after mixing[5]. Most of the methods which have been in practice are second and third methods.

Direct cooling methods of concrete components by liquid nitrogen are mainly used to product the chilled water or ice, but not to product cooled aggregates.

These studies are performed on the various characteristics of materials and concrete based upon the results of laboratory-scale basic tests and full-scale actual plant tests in which precooling is made by reducing the mixed up temperature of concrete with fine aggregates directly cooled by liquid nitrogen.

2. OUTLINE OF PRECOOLING METHOD EXAMINED IN THESE STUDIES

The concrete mixed up temperature is affected by the temperature of a component with a higher unit quantity rather than that of other components. Therefore, it is considered that cooled coarse aggregates could have a larger cooling capacity compared with other cooled materials. Further, liquid nitrogen whose temperature is -196°C, has a larger cold heat capacity. Consequently, it may be possible that precooling with a comparatively large cooling capacity is obtained by combining both of them. Concrete enabling the reduction of the mixed up temperature may be produced by the following procedure. (1) First, freeze the surface water of the fine aggregate particles. (2) Next, cool the aggregate by mixing with the liquid nitrogen. (3) Mix the frozen aggregate with other concrete components using a mixer.

The basic concept of the precooling method discussed here is shown in Fig. 1.

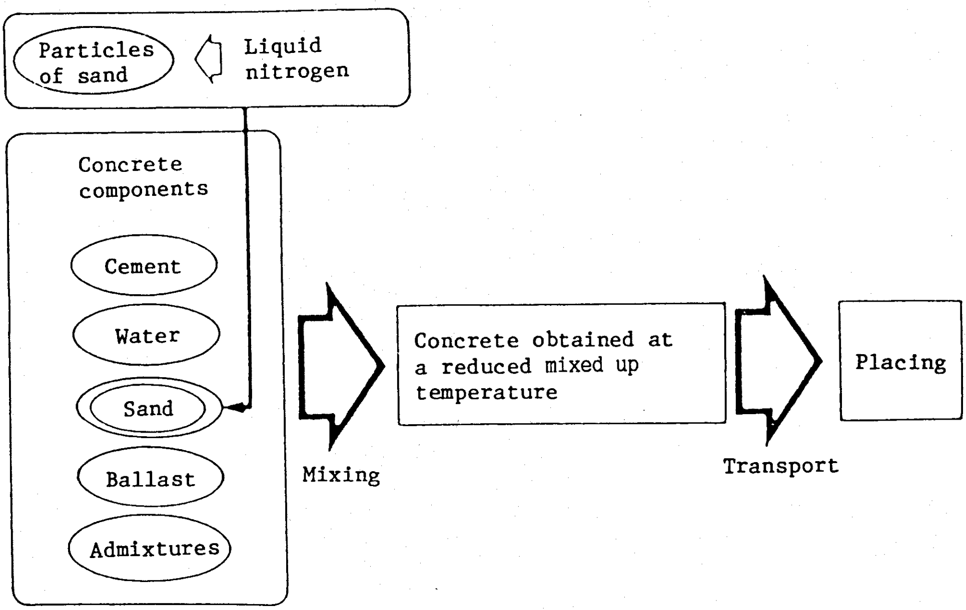

Fig. 1 Basic concept of precooling method examined in these studies

3. EXPERIMENTAL METHODS[6][7]

(1) Experiments program

Examination was made based on the combinations of items and experiments shown in Table 1 in developing the precooling method using frozen sand.

Table 1 Combination of examination items with experiments

Items \ Kinds of experiments	Basic experiments	Actual plant scale experiments	Laboratory-scale simulative experiments
① Effects of cooling by liquid nitrogen on fine aggregates	○	○	—
② Properties of concrete produced with frozen sand	○	○	—
③ Properties of concrete produced with frozen sand as mass concrete	—	—	○

The experiments could be roughly divided into two groups in their design. The former is the examination on item (1) and (2) and the latter on item (3). The experiments for the examination on item (1) and (2) are laboratory-scale basic experiments using trial prototype of frozen sand production equipment and actual plant-scale experiments using practical frozen sand production equipment installed in a concrete plant. In the actual plant-scale experiments, experiments using two different kinds of concrete plants with the different material and mix proportion conditions are designed to confirm the repeatability in the actual plant scale as well as results of the basic experiments. For item (3) laboratory-scale equipment is used to simulate behavior of actual mass concrete structural members.

(2) Production method for fine aggregates (frozen sand) cooled by liquid nitrogen

The frozen sand is produced by putting fine aggregates whose surface moisture content was measured beforehand into the frozen sand production equipment and injecting liquid nitrogen into it while the aggregates are being stirred. The frozen sand production equipment is basically a vortex type mixer with a universal rotating vane on a turbine type forced mixer. The whole equipment is insulated by heat insulators to reduce a heat loss. As the equipment is closed up tightly, vaporized liquid nitrogen is vented to the outside through an exhaust duct. As a result, dry frozen sand at minus scores degree C without lumps (a state in which frozen sand becomes a dumpling) may be obtained.

4. BASIC EXPERIMENTS

These experiments are conducted with a trial prototypic frozen sand production equipment to grasp the effects of cooling with liquid nitrogen on the physical properties of fine aggregates and to grasp the properties of concrete produced with frozen sand. The frozen sand production equipment used in these experiments is a mixer with a 0.1 m^3 mixing capacity as shown in Photo 1.

(1) Outline of experiments

a) Factors and levels

Factors and levels in the tests to grasp the effects of cooling with liquid nitrogen on the physical properties of fine aggregates are shown in Table 2. As fine aggregates are generally used in a state with some surface moisture, the level of the surface moisture content of fine aggregates varies from saturated-surface-dry condition (0%) to about 10%. The cooling temperature of fine aggregates may be changed adjusting the injection quantity of liquid nitrogen. Factors and levels in the tests to grasp the properties of concrete (frozen sand concrete) produced with frozen sand are shown in Table 3. The frozen sand is used for the production of concrete after its surface moisture contents are checked.

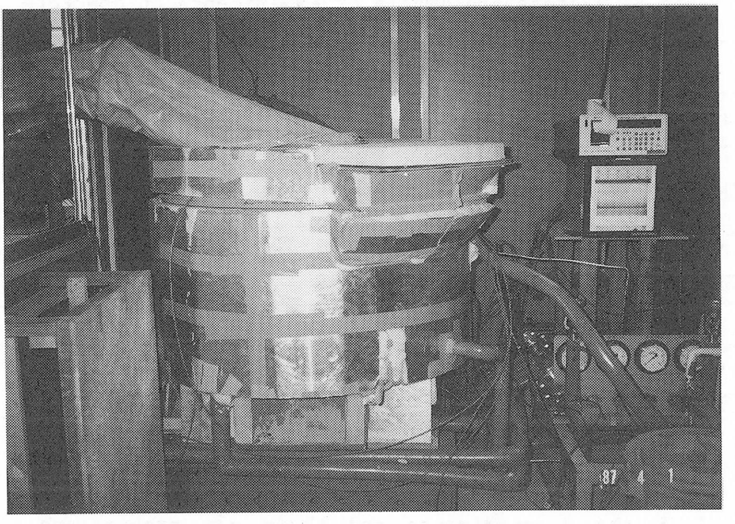

Photo 1 Frozen sand production equipment (Basic experiments)

Table 2 Factors and levels of experiments on fine aggregates

Factor	Level	
Kinds of fine aggregates	1	River sand
State of fine aggregates *	2	Ordinary temperature sand and frozen sand
Surface moisture of fine aggregates (%) **	4	0 (surface dried), 4, 7, 10

*: Ordinary temperature sand: fine aggregates not cooled, frozen sand: cooled fine aggregates
**: Values as a target

Table 3 Factors and levels of experiments on concrete

Factor	Level	
Water-cement ratio (%)	1	W/C=50
State of fine aggregates *	2	Ordinary temperature sand and frozen sand
Surface moisture of fine aggregates (%) **	4	0 (surface dried), 4, 7, 10

*: Ordinary temperature sand: fine aggregates not cooled, frozen sand: cooled fine aggregates
**: Values as a target

b) Materials used and mix proportions

Materials used in these experiments and their mix proportions are shown in Table 4 and 5, respectively. The mixing quantity of concrete is 0.1 m^3.

Table 4 Materials used

Material	Kind	Quality
Cement	Ordinary portland cement	Sp.Gr. : 3.16
Fine aggregate	Kinugawa river sand	Sp.Gr. : 2.59 absorption : 2.27% Fineness modulus : 2.90
Coarse aggregate	Kinugawa river coarse aggregare	Sp.Gr. : 2.61 absorption : 6.89%
Chemical admixture	AE agent	Anion type surfactant

Table 5 Mix proportions of concrete

Maximum size of coarse aggregate	Slump	Air content	W/C	s/a	Unit weight (kg/m³)				
(mm)	(cm)	(%)	(%)	(%)	W	C	S	G	Ad.
25	12± 2.5	4± 1	50	40	150	300	738	1119	0.045

c) Test items and test methods

i) Tests on fine aggregates: Tests on sieving, specific gravity, absorption and surface moisture are conducted in accordance with JIS.

ii) Fresh concrete tests: Tests on slump, air content, concrete temperature, weight per unit volume, breathing and setting hardening rate are conducted in accordance with JIS.

iii) Hardened concrete test: Test pieces (ϕ10 x h20 cm) prepared by a standard water-curing for the specified age (3, 7 and 28 days) were tested for compressive strength and tensile strength in accordance with JIS and for Young's modulus in accordance with ASTM.

(2) Results of basic experiments and consideration

a) Effects of cooling with liquid nitrogen on physical properties of fine aggregates

Various test results for properties of the same fine aggregates cooled and not cooled with liquid nitrogen are shown in Table 6. The temperature of fine aggregates not cooled are 17.0 through 23.9°C. For the purpose of testing frozen sand with a temperature range as wide as possible, frozen sand with temperatures roughly ranging from 0 to -140°C is produced.

Table 6 shows that specific gravity, absorption and fineness modulus of fine aggregates not cooled are 2.59, 2.27% and 2.90, respectively while those cooled are 2.59, 2.26% and 2.90, respectively. These data show no difference of values due to cooling or noncooling with liquid nitrogen. On the other hand, it shows the surface moisture of fine aggregates with a surface moisture content of 0 through 10% could decrease by about 0.4% on an average, if cooled, in spite of the large dispersion.

Table 6 Test results for fine aggregate

Items	Temperature (℃)		Sp.Gr.		absorption (%)		Fineness modulus		Difference of surface moisture *
	Non-cooling	Cooling	Non-cooling	Cooling	Non-cooling	Cooling	Non-cooling	Cooling	Δp (%)
Number of samples	17.0 to 23.9	0 to -136	1	6	1	6	1	6	42
Mean value			2.59	2.59	2.27	2.26	2.90	2.90	0.35
Standard deviation			——	0.01	——	0.02	——	0.05	0.85

*: ΔP = (Surface moisture at noncooling) - (Surface moisture at cooling)

b) Properties of concrete produced with frozen sand

Test results for fresh concrete produced with frozen sand and for that after hardening are shown in Table 7.

Table 7 Test results for concrete

Items / Types	Concrete Temperature (℃)	Slump (cm)	Air content (%)	Weight per unit volume (kg/m^3)	Compressive strength (kgf/cm^2) *		
					Age at 3 days	Age at 7 days	Age at 28 days
Ordinary temperature sand concret	20.0 to 23.2	10.7 (0.91)	4.3 (0.51)	2262 (15.6)	145 (20.7)	231 (19.4)	332 (18.7)
Frozen sand concrete	1.1 to 13.4	10.2 (1.68)	4.2 (0.77)	2265 (22.1)	141 (12.8)	238 (7.9)	338 (15.0)

( ) indicates standard deviation
*: 1 kgf/cm^2 = 0.098 MPa

i) Properties of fresh concrete

The mixed up temperature of concrete without the frozen sand (ordinary temperature sand concrete) is 20 through 23°C while that with sand (frozen sand concrete) is 1 through 13°C. It is observed that temperature reduction is 22°C at maximum. It is found that this temperature reduction is relatively large compared with the practical temperature reduction range of 10 through 15°C[8] in the conventional concrete precooling technique using ice and like.

The mean values of slump and air content for the ordinary temperature sand concrete are 10.7 cm and 4.3%, respectively and satisfy the target values. The mean values of slump and air content for the frozen sand concrete in which frozen sand was used in stead of ordinary temperature sand are 10.2 cm and 4.2%, respectively and no difference by using frozen sand was found. Further, the weight per unit volume is not also affected by cooling.

ii) Properties of hardened concrete

The test results for the compressive strength of the frozen sand and ordinary temperature sand concrete are shown in Fig. 2.

The state of the compressive strength revealment of the frozen sand concrete shows a tendency for the strength to become somewhat lower than that of the ordinary temperature sand concrete at the age of three days. This is considered to be due to a lower concrete temperature at the time when the specimen is made. At the age of seven days and after, however, the frozen sand concrete shows the strength equal to or higher than that of the ordinary temperature sand concrete. It has been observed that the effect of the concrete temperature at the time, when the specimen is made, could be very small.

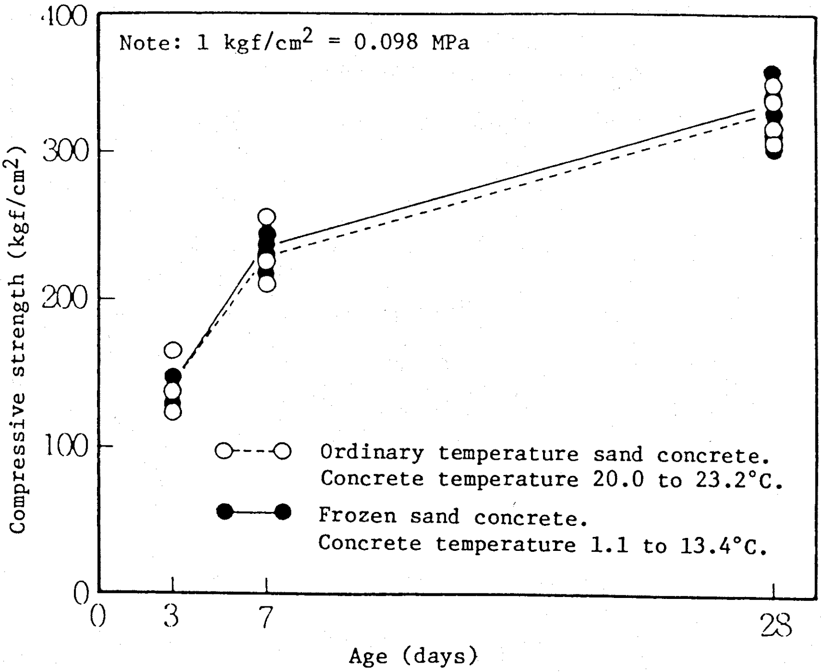

Fig. 2 Compressive strength revelation state

The relationships between compressive strength and tensile strength and between compressive strength and Young's modulus in the ordinary temperature sand concrete and frozen sand concrete are shown in Fig. 3 and Fig. 4, respectively.

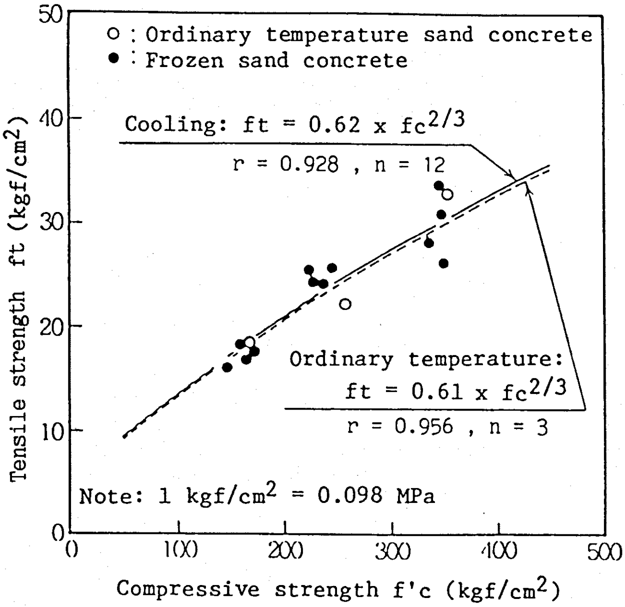

Fig. 3 Relationships between compressive strength and tensile strength

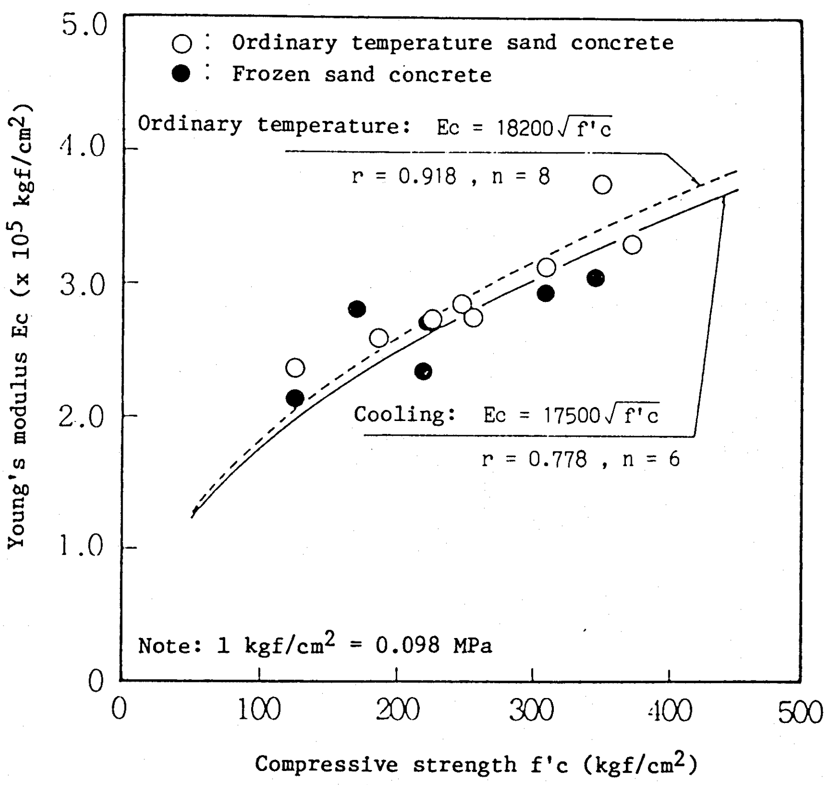

Fig. 4 Relationships between compressive strength and Young's modulus

These experimental results show that the relationship between compressive strength and tensile strength and relationship between compressive strength and Young's modulus in the frozen sand concrete are almost same as those in the noncooled concrete. These experimental results are discussed about the state of the strength revealment of the specimens prepared and cured according to JIS and the state of the strength revealment as the structural concrete is separately discussed in 6. of this paper.

5. ACTUAL PLANT-SCALE EXPERIMENTS

Actual plant-scale experiments using a practical unit of the frozen sand production equipment are conducted assuming the production of concrete in an actual plant. The experiments are conducted at two kinds of concrete plants in an ordinary concrete production process in corporating the frozen sand production process in accordance with an actual concrete production process. One is the experiment conducted at an experimental concrete plant owned by K-Iron Works (actual plant experiment No. 1) and the other is the experiment conducted at a concrete plant ship owned by Y-Construction Co., Ltd. (actual plant experiment No. 2). Principle of the practical unit of the frozen sand production equipment is basically the same as that of the basic experiments except for its mixing capacity was expanded to 0.5 m^3 under the assumption of an actual plant scale. The frozen sand production equipment used in these experiments is shown in Picture 2.

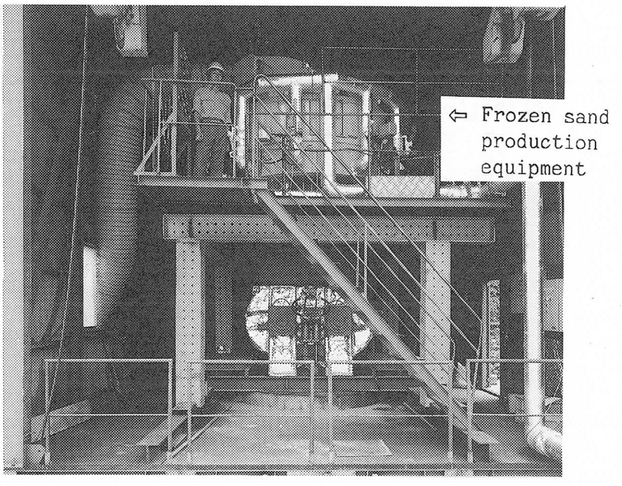

Photo 2 Frozen sand production equipment
(Actual plant-scale experiments)

(1) Outline of experiments

a) Factors and levels

Factors and levels of the experiments to grasp the effect of cooling by liquid nitrogen on the physical properties of fine aggregates are shown in Table 8. Factors and levels of the experiments to grasp the properties of the frozen sand are shown in Table 9. Reduction amount of concrete temperature was set to be at three levels in the actual plant experiment (No. 1) and constant in the actual plant experiment (No. 2). The frozen sand was checked for its surface moisture before it was used for concrete.

Table 8 Factors and levels of experiments on fine aggregates

Factor	Level	
Kind of fine aggregates	1	sea sand
State of fine aggregates	2	Ordinary temperature sand,frozen sand **
Surface moisture (%)	1	Sureface moisture in natural state
Initial temperature of fine aggregates	1	Temperature in natural state

*: Common to actual plant experiment (No. 1) and (No. 2)
**: Temperature of frozen sand was varied by changing the injection quantity of liquid nitrogen.

Table 9 Factors and levels of experiments on concrete

Kinds of experiments	Factor	Level	
Actual plant experiment (No.1)	Water cement ratio (%)	1	W/C = 58
	State of fine aggregates	2	Ordinary temperature sand, frozen sand
	Surface moisture of fine aggregates (%)	1	Surface moisture in natural state
	Temperature of fine aggregates (℃) *	4	Ordinary temperature,-10, -20,-50
Actual plant experiment (No.2)	Water cement ratio (%)	1	W/C = 50
	State of fine aggregates	2	Ordinary temperature sand, frozen sand
	Surface moisture of fine aggregates (%)	1	Surface moisture in natural state
	Temperature of fine aggregates (℃) *	2	Ordinary temperature, -80

*: Temperature as a target

b) Materials used and their mix proportions

Materials used in these experiments and their mix proportions are shown in Table 10 and 11, respectively. The capacity of a concrete mixer in the actual plant experiment (No. 1) and (No. 2) is 1 m^3 and 3 m^3, respectively.

Table 10 Materials Used

Kinds of experiments	Material	Kind	Quality
Actual plant experiments (No.1)	Cement	Ordinary portland cement	Sp.Gr. : 3.16
	Fine aggregates	Takaneshima sea sand	Sp.Gr. : 2.49 absorption : 3.07% Fineness modulus : 2.56 to 2.85
	Coarse aggregates	Arayamachi broken stone (2010) Arayamachi broken stone (1005)	Sp.Gr. : 2.72 Fineness modulus : 6.90 Sp.Gr. : 2.71 Fineness modulus : 6.73
	Chemical admixture	AE agent	Anion type surfactant
Actual plant experiments (No.2)	Cement	Portland blast-furnace slag cement B-type	Sp.Gr. : 3.05
	Fine aggregates	Sea sand	Sp.Gr. : 2.55 absorption : 1.58% Fineness modulus : 2.85
	Coarse aggregates	Broken stone	Sp.Gr. : 2.64 Fineness modulus : 6.73
	Chemical admixture	Standard AE water reducing admixture	Lignin sulfonic acid compound polyole complex

*** Coarse aggregates used is a mixture of broken stone 2010 and broken stone 1005 in a ratio of 7 to 3.**

Table 11 Mix proportions of concrete

Kinds of experiments	Max. size of coarse aggregates (mm)	Slump (cm)	Air content (%)	W/C (%)	s/a (%)	Unit weight (kg/m³)				
						W	C	S	G	Ad.
Actual plant experiments (No.1)	20	8± 2.5	4± 1	58	47.3	198	340	700	934	0.020
Actual plant experiments (No.2)	20	12± 2.5	5± 1	50	43	169	338	732	1008	0.845

c) Test items and test methods

i) Tests on fine aggregates: Tests on sieving, specific gravity, water absorption ratio and surface moisture are conducted in accordance with JIS.

ii) Fresh concrete tests: Tests on slump, air content, concrete temperature and weight per unit volume were conducted in accordance with JIS.

iii) Hardened concrete test: Test pieces (ø10 x h20 cm) prepared by the standard water-curing for the specified age (7, 28, 91 days) were tested for compressive strength in accordance with JIS.

(2) Results of actual plant-scale experiments and consideration

a) Effects of cooling with liquid nitrogen on physical properties of fine aggregates

Various test results for properties of the same fine aggregates cooled and not cooled with liquid nitrogen are shown in Table 12. The temperature of the fine aggregates not cooled were 22.4 through 30.8°C and 23.5 through 24.5°C, respectively. For the purpose of testing frozen sand with a temperature range as wide as possible, frozen sand with a temperature of -1 through -130°C and -20 through -140°C, respectively was produced.

Table 12 Test results for fine aggregates

Items / Kinds of experiments		Temperature (°C)		Specific gravity		absorption (%)		Fineness modulus		Differenace of surface moisture
		Non-cool-ing	cool-ing	Non-cool-ing	cool-ing	Non-cool-ing	cool-ing	Non-cool-ing	cool-ing	Δp (%)
Actual plant experiments (No.1)	n	22.4 to 30.8	-1 to -133	3	3	3	3	6	6	184
	$\overline{X}$			2.49	2.50	3.07	2.90	2.69	2.77	0.63
	$\sqrt{V}$			0.01	0.01	0.06	0.11	0.10	0.09	0.40
Actual plant experiments (No.2)	n	23.5 to 24.5	-18 to -142	15	15	15	15	15	15	30
	$\overline{X}$			2.55	2.55	1.58	1.60	2.85	2.89	0.42
	$\sqrt{V}$			0.00	0.01	0.09	0.09	0.04	0.04	0.27

When n: Number of samples
$\overline{x}$: Mean value
$\sqrt{v}$: Standard deviation
*: ΔP = (Surface moisture at noncooling) - (Surface moisture at cooling)

In both experiments, it has been observed that cooling could not remarkably affect specific gravity, absorption and fineness modulus of fine aggregates while cooling could reduce surface moisture of fine aggregates by about 0.4% and 0.6% on an average, respectively. These results indicate the tendencies similar to those of the basic experiments. Fig. 5 shows the test results for surface moisture in the case of cooling and noncooling. It also shows that reduction of surface moisture tends to become larger with the surface moisture of fine aggregates. For example, the surface moisture of fine aggregates with about 5% surface moisture is considered to reduce by 0.5%. This could be due to a little vaporization of the surface at the instant of the freezing with liquid nitrogen.

In conclusion, it is found that cooling and freezing of fine aggregates with liquid nitrogen to about 0 through -140°C may not change their specific gravity, absorption and fineness modulus but slightly reduce their surface moisture.

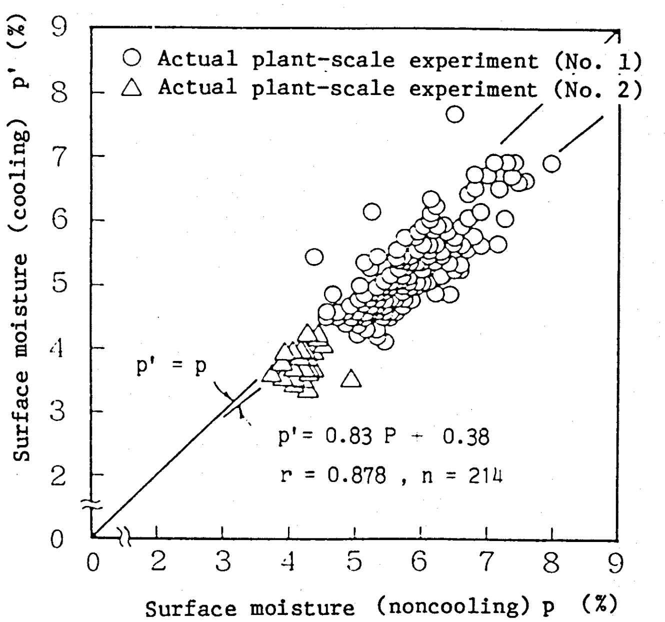

Fig. 5 Comparison of surface moisture

b) Properties of concrete produced with frozen sand

Test results for the concrete produced with frozen sand are shown in Table 13.

i) Properties of fresh concrete

The mixed up temperature of the concrete without the frozen sand (ordinary temperature sand concrete) were 22 through 27°C and 23.5°C, respectively while that with the frozen sand was 0 through 14°C and about 11°C, respectively. It is observed that a temperature reduction is about 25°C at maximum. These results demonstrate that temperature reduction could be also obtained in the actual plant-scale experiments to the same degree as that in the basic experiments.

The mean values of slump for the ordinary temperature sand concrete were 8.2 cm and 12.2 cm, respectively and satisfied the target values. On the other hand, the mean values of slump for the frozen sand concrete in the same mix proportion were 13.2 cm and 14.9 cm, respectively. It is found that the frozen sand concrete tends to give higher slump values in both experiments. Fig. 6 shows the relationships between the mixed up temperature of concrete and its slump values.

Table 13 Test results for concrete

Kinds of experiments \ Items		Concrete temperature (℃)	Slump (cm)	Air content (%)	Weight per unit volume (kg/cm³)	compressive strength * (kgf/cm²)		
						Age at 7 days	Age at 28 days	Age at 91 days
Actual plant experiments (No.1)	Ordinary temp. sand concrete	21.6 to 27.4	8.2 (2.47)	4.6 (0.39)	2244 (15.6)	185 (11.8)	247 (14.5)	292 (14.1)
	Frozen sand concrete	-0.1 to 14.0	13.2 (1.89)	4.8 (0.39)	2247 (13.0)	199 (4.9)	272 (7.8)	315 (9.5)
Actual plant experiments (No.2)	Ordinary temp. sand concrete	23.5	12.2 (1.91)	4.8 (0.35)	2202 (9.19)	187 (16.3)	336 (36.8)	415 (21.9)
	Frozen sand concrete	11.0 to 11.7	14.9 (1.03)	5.3 (0.50)	2217 (7.78)	197 (9.5)	358 (15.0)	445 (20.1)

( ) indicates standard deviation.
*: 1 kgf/cm^2 = 0.098 MPa

It is found that change of the mixed up temperature of concrete by 10°C may cause the change of the slump value by about 2 cm in the actual plant-scale experiments though materials, mix proportions and slump were different each other. In the basic experiments, however, the tendency for slump values to increase due to reduction of concrete mixed up temperatures was not found. Though one of the causes is considered a difference of mixing capacity, it could not be clarified in the scope of these studies.

As for the air content and weight per unit volume, differences due to the use of the frozen sand were not found similarly to the case of the basic experiments.

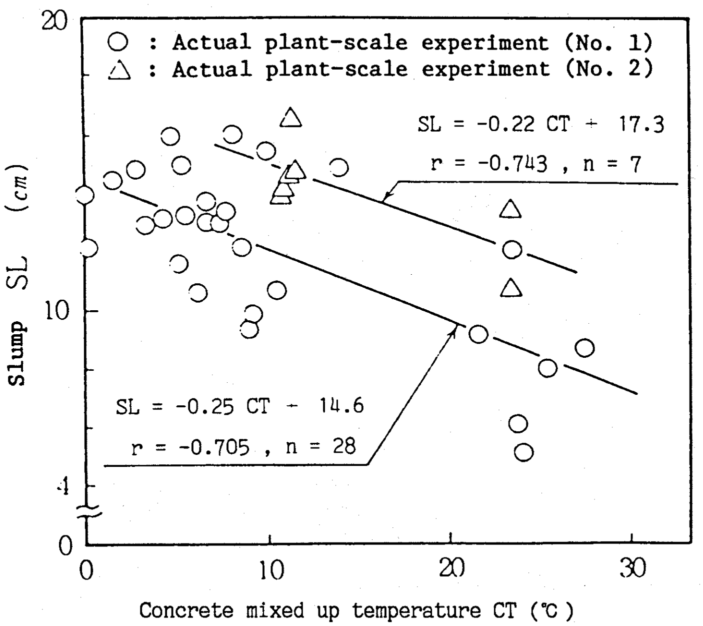

Fig. 6 Relationships between slump and concrete mixed up temperature

ii) Properties of hardened concrete

The test results for compressive strength of the frozen sand and ordinary temperature sand concrete are shown in Fig. 7 and Fig. 8. The compressive strength of the frozen sand concrete at the age of seven days and after is found to be equal to or higher than that of the ordinary temperature sand in both experiments. These results show a tendency similar to those in the basic experiments. In the basic experiments, which show the results for the period until the age of 28 days, this tendency could be more remarkable at the higher age as in these experiments. The compressive strength of the frozen sand concrete at the age of 91 days is larger by about 8% than that of the ordinary temperature sand concrete in these experiments. The relationships between the concrete mixed up temperature and the compressive strength at the age of 91 days are shown in Fig. 9. This figure shows that the strength becomes larger as the mixed up temperature of concrete becomes lower. It is also found that the decrease of the concrete mixed up temperature by 10°C increases the strength by about 10 through 25 kgf/cm^2 (0.98 to 2.45 MPa).

It is reported that when concrete with a different mixed up temperature is given a standard curing afterward, concrete with a lower mixed up temperature will show larger compressive strength than that with a higher mixed up temperature as the age of concrete becomes higher. Such tendency has been found in the results of these experiments.

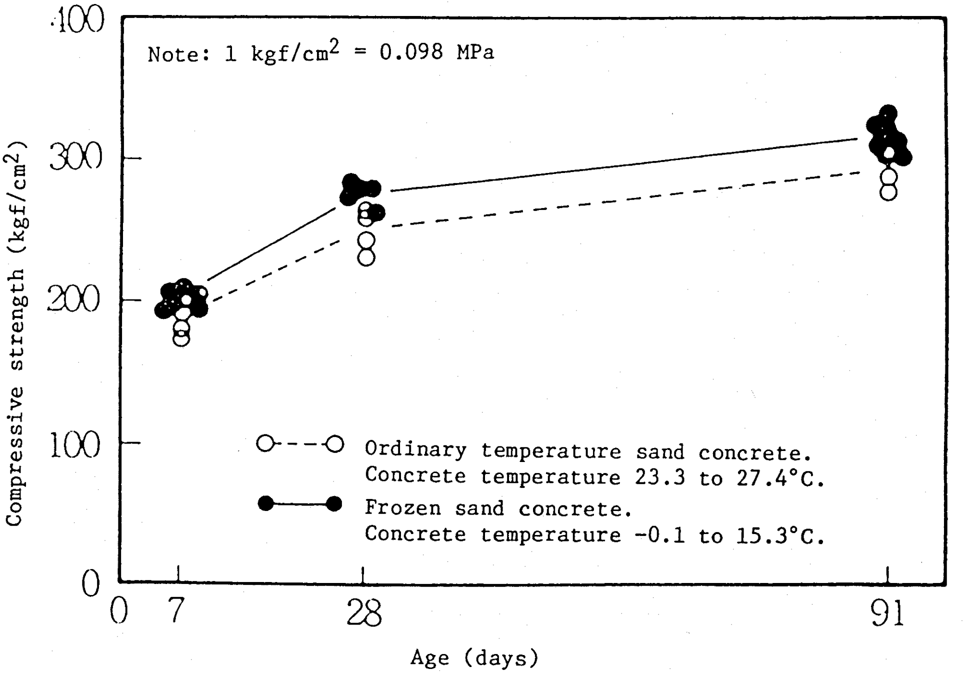

Fig. 7 Compressive strength revelation state
(Actual plant-scale experiment (No. 1))

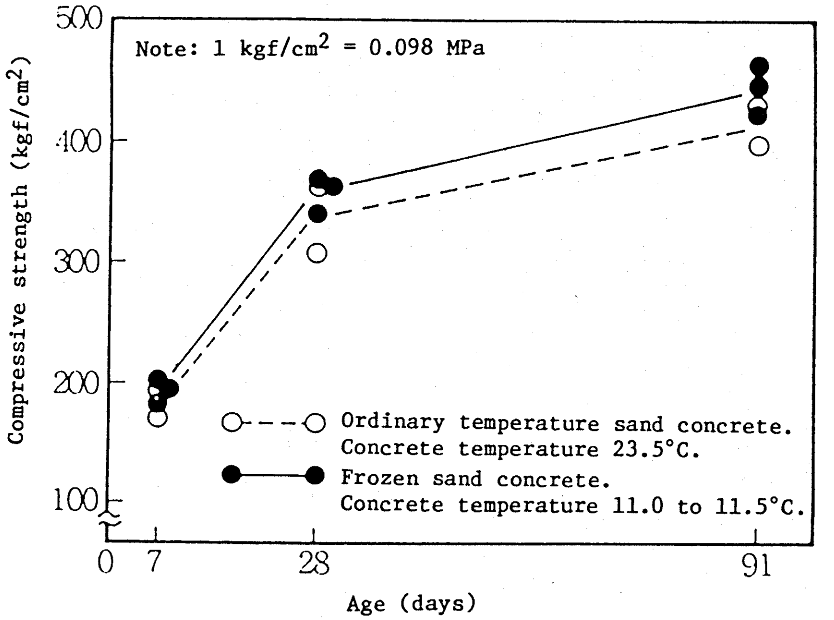

Fig. 8 Compressive strength revelation state
(Actual plant-scale experiment (No. 2))

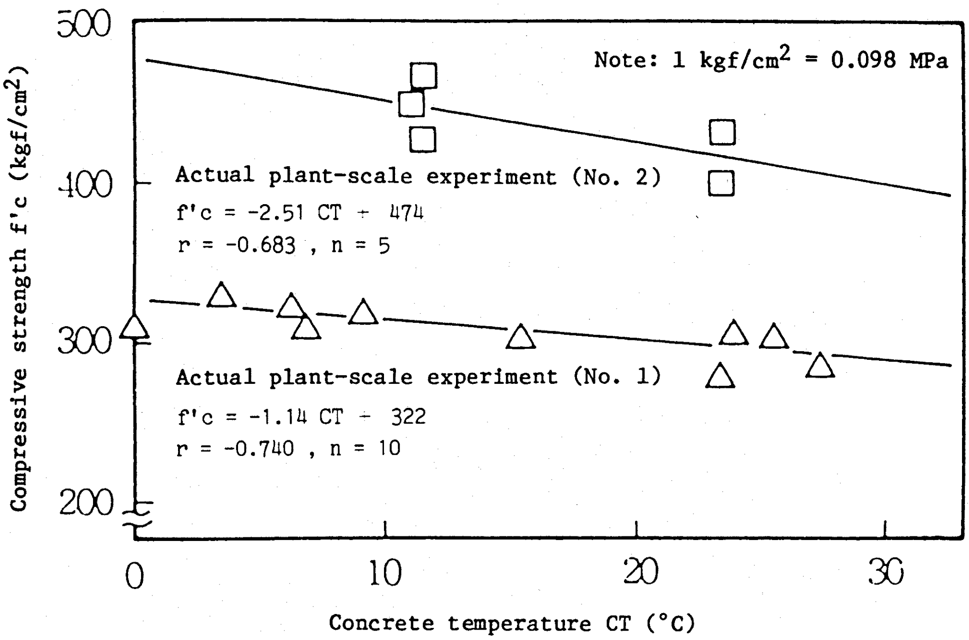

Fig. 9 Relationships between compressive strength and concrete temperature

6. EXPERIMENTS ON MASS CONCRETE

Simulative experiments using a laboratory scale testing unit were conducted to grasp the properties of mass structures consisting of the concrete with frozen sand.

(1) Outline of experiments

Experiments were conducted by using a mass concrete thermal simulation system and a strength control system[9] as shown in Fig. 10. The thermal simulation system could simulate the heat evolution of mass concrete members due to hydration and thermal conduction and heat transferring behavior in the dimensional direction of the smallest members to forecast temperature changes with time and temperature distribution state in such direction.
The strength control system could give a temperature hysteresis identical to member temperatures obtained at the thermal simulation system to a water tank in which concrete specimens are placed at real time to forecast the strength revealment state of mass concrete members.

Mass concrete with a smallest member dimension of 1,600 mm was assumed and the experiments were designed for two cases consisting of the concrete placed at an ordinary temperature (about 20°C) and the concrete placed at a temperature lowered by about 10°C by using frozen sand.

The materials, mix proportions and concrete production conditions were the same as chapter 4 in the basic experiments.

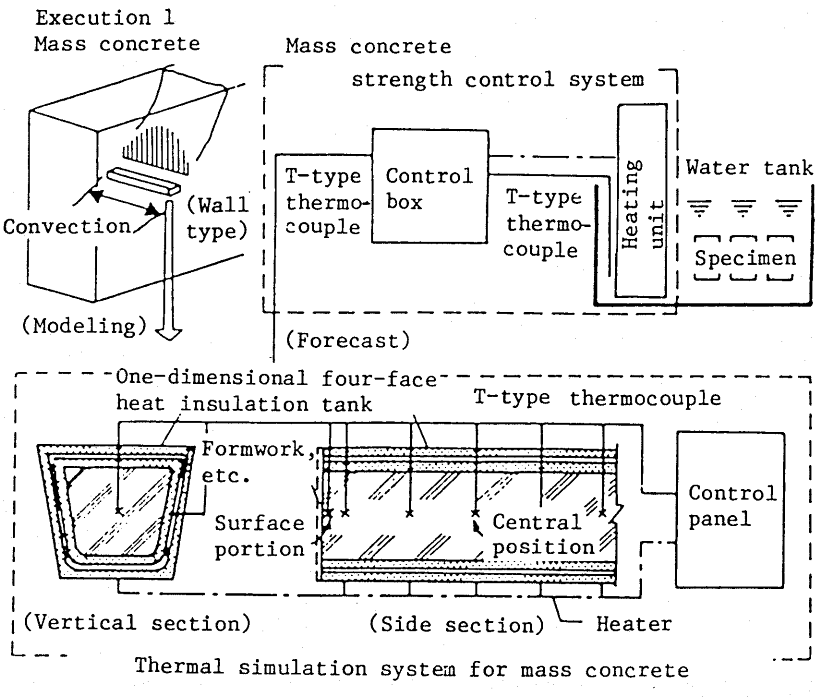

Fig. 10 Thermal simulation and strength control system

(2) Testing methods

Concrete is placed into the equipment shown in Fig. 10 under each condition and the temperature hysteresis of the central and surface sections of specimens was measured for a period from the time just after the placement to the age of 12 days. Surrounding temperature was kept at 20°C during the test period and plywood formworks on the side were removed at the age of three days. The temperature hysteresis obtained was also put into the strength control system to give the temperature condition identical to the detected temperatures to the specimens in the water tank and tests on the compressive strength were conducted at the age of 1, 3, 7 14, 28, 56 and 91 days. Specimens by the standard water-curing were also tested for compressive strength at the same age.

(3) Experiment results and consideration

Concrete produced with ordinary temperature sand and concrete precooled with frozen sand were tested for their temperature characteristics and compressive strength characteristics as mass concrete.

The placement temperature of concrete was 22.8°C for the ordinary temperature sand concrete and 11.0°C for the frozen sand concrete. This shows the placement temperature of concrete could be reduced by 11.8°C by precooling.

a) Temperature characteristics

Comparison of the temperature hysteresis of the ordinary temperature sand concrete and frozen sand concrete as mass concrete is shown in Fig. 11 and Table 14.

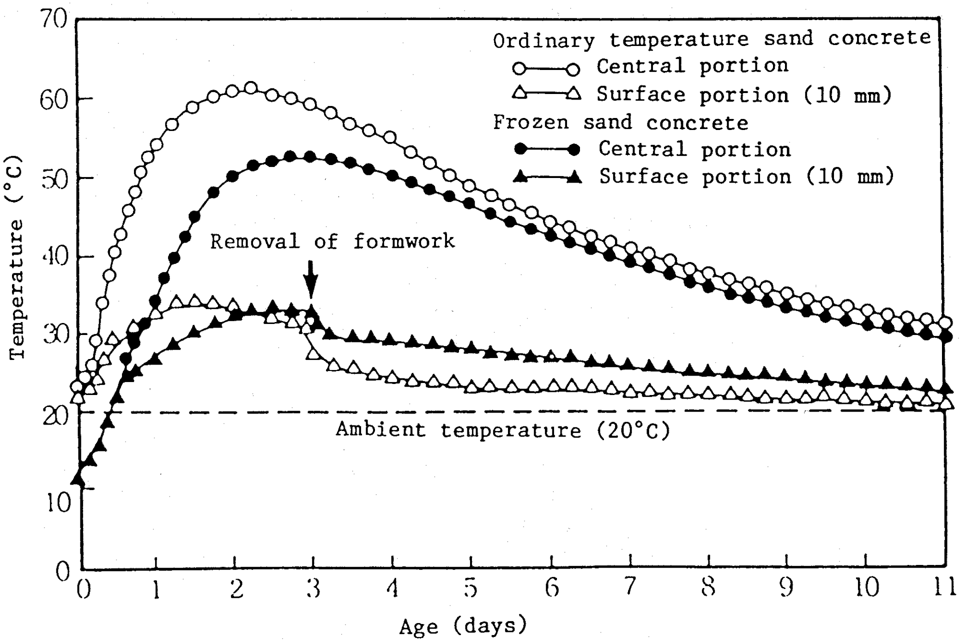

Fig. 11 Effects of precooling on temperature hysteresis

Table 14 Maximum temperature of central portion of each mass concrete

Kinds \ Items	Concrete placement temperature (℃)	Conditions at max. central portion temp.		
		Central portion temperature (℃)	Surface portion temperature (℃)	Age (days)
Ordinary temperature concrete	22.8	60.0	32.8	2.13
Frozen sand concrete	11.0	52.6	32.8	2.92

The maximum temperature of the mass concrete placed at an ordinary temperature is 60.0°C while that of the mass concrete using the frozen sand is 52.6°C. This shows the maximum temperature could be reduced by 7.4°C by precooling. Difference of the temperature between the member central portion and member surface portion at the highest temperature at the member central portion could be reduced from about 27°C to about 20°C. Further, it is found that the precooled mass concrete shows a gradual rate of the temperature change when temperature goes up or down. Thus, lowering the concrete placement temperature effectively reduce temperature stress[1] and therefore, precooling with frozen sand could effectively control temperature crack.

b) Strength characteristics

Comparison of the strength revealment of the ordinary temperature sand concrete and frozen sand concrete as mass concrete is shown in Fig. 12.

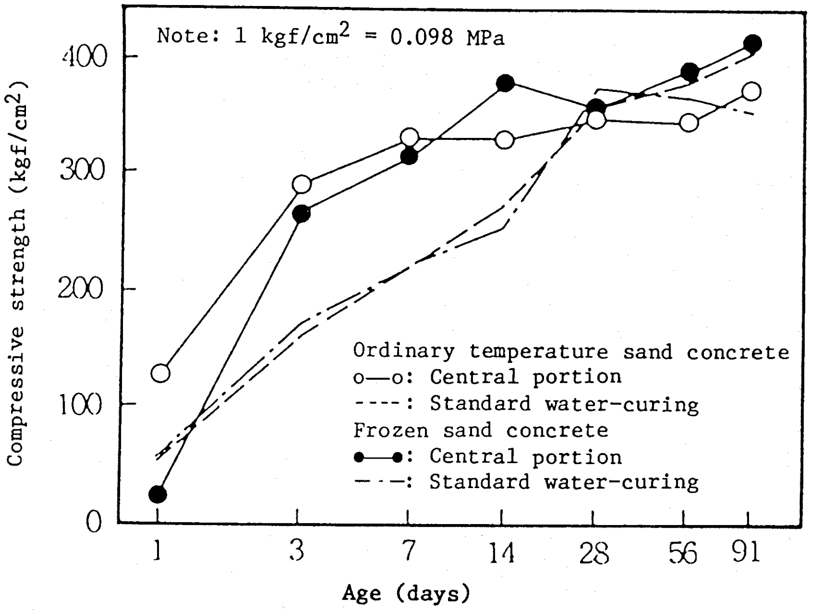

Fig. 12 Effects of precooling on strength revealment

Compressive strength of the central portion of the mass concrete using the ordinary temperature sand rapidly increases until the age of about 7 days but slowly increases after that age. On the other hand, compressive strength of that using the frozen sand shows smaller values than that using the ordinary temperature sand until the age of about 7 days but shows larger values after the age of 14 days. Thus, in an insulated state like mass concrete, the strength at the long-term age could be influenced by the concrete temperature at placement. Concrete with a lower placement temperature shows a bigger increase in strength as previously reported[9][10]. Therefore, it is considered that precooling with frozen sand is also effective in improving the strength of mass concrete at the long-term age.

7. CONCLUSIONS

These studies examine the various characteristics of the fine aggregates and concrete when concrete is precooled with fine aggregates directly cooled with liquid nitrogen (frozen sand) based on the results of basic experiments and actual plant-scale experiments using actual plants. Main conclusions obtained in the scope of these studies are as follows:

(1) Fine aggregates cooled to about -140°C with liquid nitrogen are not different from those not cooled in their specific gravity, absorption and fineness modulus. Surface moisture of the fine aggregates tends to be slightly decreased by cooling;

(2) Method of producing concrete with frozen sand has made it possible to get a higher temperature reduction than the conventional precooling technique using ice and the like. Its amount of temperature reduction is 25°C or more.

(3) The production with frozen sand does not affect the air content and weight per unit volume of concrete. Slump tends to become larger by cooling and its degree is about 2 cm for the mixed up temperature reduction of 10°C.

(4) Compressive strength under standard water-curing conditions of concrete produced at a mixed up temperature lowered by 10 to 25°C with frozen sand is equal to or higher than that of ordinary temperature sand concrete whose mixed up temperature is not lowered. It is observed that the lower the mixed up temperature is, the larger the strength at the long-term age becomes.

    Relationships between tensile strength and compressive strength and those between Young's modulus and compressive strength for concrete produced with frozen sand are not different from those for ordinary temperature sand concrete.

(5) It is considered that characteristics of the concrete precooled with frozen sand as mass concrete are effective in controlling temperature crack because they keep the maximum temperature lower and decrease the temperature difference between the member central portion and surface portion. Further, they may be also effective in improving the strength at the long-term age.

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