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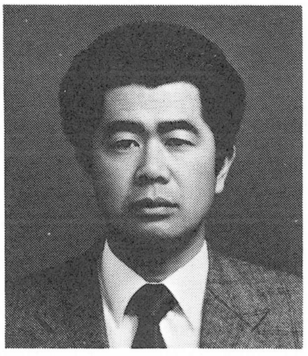
STUDIES ON CONCRETE FOR COLD WEATHER USE UTILIZING ULTRA-RAPID HARDENING CEMENT (JET CEMENT)

(Reprint from Transaction of JSCE, Vol. 348, V-1, 1984)



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SYNOPSIS

The contents of the study were first to clarify the strength characteristics of the ultra-rapid hadening cement at different temperature, secondly, to clarify what effect freezing exerts on the increase of strenght when the concrete is subjected to freezing at the initial period of hardening, and thirdly, to clarify the resistivity when the concrete at the initial period of hardening or after sufficiently hardened is subjected to the repeated rapid feezing and thawing. It was clarified by this study ① that the concrete using ultra-rapid hadening cement showed the very high manifestation of strenfh even at low temperature and short age, ② that when the concrete was subjected to freezing at the initial period of hardening, the lowest compressive strength just before freezing, with which the increase of strength was able to be expected by continuing freezing, was about 50 kg/cm^2 similarly to ordinary concrete.

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1. PREFACE

Ultra-rapid hardening cement is the cement developed by combining the independent research in two Japanese major cement manufacturers with the fundamental technique of "Regulated Set Cement"developed by the research institute of American cement association. Its marketing in Japan was begun in October, 1971.

The features of the concrete using this cement are ① that the practical strength arises in 2~3 hours, ② that the time of setting is short and freely adjustable, ③ that the stable increase of strength is shown over a long period, ④ that even at the time of low temperature, the manifestation of strength is remarkable, ⑤ that the drying shrinkage is small, and ⑥ that the water tightness is excellent.

As the fields of application, it has been used for various construction works, such as ① emergency construction works for roads, railways, runways and so on, ② construction works in cold weather, ③ secondary products of concrete, ④ binder materials for casting molds, grinding stones, ore granulation and so on, and ⑤ shotcrete.

Its properties are characterized by increasing the quantity of calcium alminate (which is $11CaO \cdot 7AL_2O_3 \cdot CaF_2$ instead of $3CaO \cdot Al_2O_3$), and corresponding to that, the quantity of calcium sulfate being much. It is considered that its superfast hardening property is due to the hydration of $C_{11}A_7CaF_2$, and the increase of strength for a long period thereafter is succeeded mainly by the hydration of calcium silicate.

When concrete is placed in cold season, the damage due to cold weather condition is frequently seen, such as the prescribed strength of concrete structures cannot be obtained, or the durability is remarkably poor.

When the freezing damage of concrete is considered, it is divided into the following two. The first is the initial freezing damage suffered at the initial phase of hardening, and the second is the case in which freezing and thawing are repeated after the strength of concrete has been fully arisen.

As the measures to execute the concrete construction works in cold weather, first, heat insulation and heating are considered, and the expense for this purpose occupies a large weight in construction cost. Therefore, as the countermeasures in the aspect of materials, the use of ultra-rapid hardening cement is recommended as it has the properties of superfast hardening and generating a large quantity of hydration heat at the initial phase.

Here, the research on the concrete for cold weather use utilizing superearly strengthening cement, carried out so far, is reviewed.

As the research related to alumina cement, are the research by Nagataki et al. reporting[1] that the setting of alumina cement and the manifestation of strength thereafter were remarkably affected by hydrating temperature and curing temperature, the research by Kuroi et al. reporting that when alumina cement was used for concrete in cold season, and the concrete suffered freezing damage at the initial phase of hardening, its strength remarkably lowered as compared with the concrete that did not suffer freezing damage, the research by Tsukayama, Hayashi et al. reporting that the resistance to freezing and thawing of alumina cement concrete was extremely durable in the case of without conversion, and the research by Maekawa et al. reporting that the resistance to freezing and thawing of alumina cement concrete after the conversion was different according to the kinds of cement, but as the water cement ratio was lager, its lowering rate was larger.

Besides, as the research related to ultra high early strength Portland cement, there is the reseach by Toki et al. reporting that ultra high early strength Portland cement is advantageous for the construction in cold weather because its hydration heat is higher, bleeding channel becomes little since the bleeding is smally, and the concrete is hard to suffer the deterioration due to hydrostatic pressure, and the adhesion of paste and aggregate is strong, as compared with ordinary cement. These results become very useful data when alumina cement and ultra high early strength Portrand cement are used for the concrete for cold weather use.

However, it is the present status that a series of the research on the concrete for cold weather use utilizing, ultra-rapid hardening cement has not yet been carried out.

Accordingly, for the purpose of using ultra-rapid hardening cement for the concrete for cold weather use, this research is to obtain the data required for it.

The contents are, that for clarifying the strength characteristics of ultra-rapid hardening concrete due to low temperature. Secondly, that for clarifying to what extent freezing affects the strength increase when the concrete suffers freezing at the initial phase of hardening. Thirdly, that for clarifying the resistance when the concrete at the initial phase of hardening or after fully solidified is subjected to the rapid repetition of freezing and thawing.

2. OUTLINE OF EXPERIMENT

2. 1 Materials used

a) Cement

The ulta-rapid hardening cement and ordinary Portland cement produced by S Co. were used. The chemical composition and the results of physical test are shown in Table 1~3.

Table 1 Chemical composition of cement

Kind	ig.loss	insol.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	total (%)
Jet cement	0.5	0.4	14.5	11.7	1.9	57.3	0.7	11.6	98.6
Ordinary cement	0.5	0.1	21.9	5.4	3.0	64.9	1.4	1.8	99.0

Table 2 Results of physical test of cement (1)

Kind	Specific gravity	Powder size		Setting				
		Specific surface area (cm^2/g)	88μ left over (%)	Water content (%)	Initial setting (h−m)	Final setting (h−m)	Room temperature (℃)	Humidity (%)
Jet cement	3.04	5630	1.8	30.0	0−12	0−15	20.0	89
Ordinary cement	3.16	3050	2.5	26.3	2−24	3−37	20.0	89

Table 3 Results of physical test of cement (2)

Kind	Flow value	Bending strength (kg/cm^2)						Compressive strength (kg/cm^2)					
		3h	6h	1D	3D	7D	28D	3h	6h	1D	3D	7D	28D
Jet cement	218	26.7	29.3	33.0	36.1	56.0	72.5	110	154	210	251	334	415
Ordinary cement	245	—	—	—	32.4	48.8	69.6	—	—	—	131	228	402

b) Aggregate

As for the coarse aggregate, the river gravel produced in Tenryu River, Shizuoka Prefecture, was used after adjusting the grain size to maximum dimension of 25mm.

The fine aggregate was used by mixing the river sand produced in Ibi River, Gifu Prefecture and that produced in Kiso River, Aichi Prefecture, in the weight ratio of 7 : 3. The results of testing the aggregates are shown in Table 4.

Table 4 Results of test of aggregate used

Kind	Weight % passing through sieves											Finess modulus	Specific gravity	Unit weight (kg/m^3)	Absorption (%)	Solid volume percentage (%)
	30	25	20	15	10	5	2.5	1.2	0.6	0.3	0.15					
River gravel	100	90	64	51	27	0	0	0	0	0	0	7.10	2.66	1664	0.7	64
River sand						100	87	69	45	20	6	2.73	2.59	1785	2.4	67

c) Admixtures

At the time of using the ultra-rapid hardening cement, in order to obtain the handling time of about 30 min (the time enabling working), the reterder for special use was added by 0.3% in relation to the unit weight of cement. The retarder was used as the aqueous solution of 50%.

Besides, in the case of AE concrete, the air entraining agent made by T Co. was used by making the aqueous solution of 1% so that the air quantity became 4.5 ± 1%.

d) Mix proportion of concrete

The mix proportion of ultra-rapid hardening concrete and ordinary concrete were determined by trial mixing. The required slump was set at 7.5 ± 1.5 cm, and the air quantity was taken as 1.5 ± 1.0% for plain concrete and 4.5 ± 1.0% for AE concrete. At the unit weight of cement of 300, 350 and 400 kg/m^3, the slump test and air content test were carried out, thus the unit water quantity and the optimum sand percentage for obtaining the same workability were determined. The results obtained by the trial mixing are shown in Table 5. The symbols used for the kinds of concrete in the table are as follows.

Table 5 Mix proportion of concrete

Kind of concrete	Air (%)	w/c (%)	s/a (%)	Slump (cm)	Unit weight (kg/m^3)				Retar-der (g/m^3)	Air-ent. agent (g/m^3)
					Water	Cement	Sand	Gravel		
JC 300	1.5	50	41	7.5±1.5	150	300	773	1150	900	—
JC 350	1.5	45	39	7.5±1.5	157	350	712	1152	1050	—
JC 400	1.5	41	37	7.5±1.5	162	400	655	1154	1200	—
JAC 300	4.5±1.0	47	39	7.5±1.5	140	300	715	1158	900	25.0
JAC 350	4.5±1.0	41	37	7.5±1.5	145	350	658	1160	1050	29.0
JAC 400	4.5±1.0	38	35	7.5±1.5	150	400	603	1162	1200	33.0
OC 300	1.5	54	45	7.5±1.5	161	300	839	1062	—	—
OC 350	1.5	47	42	7.5±1.5	164	350	763	1091	—	—
OC 400	1.5	42	39	7.5±1.5	168	400	690	1116	—	—
OAC 300	4.5±1.0	50	42	7.5±1.5	150	300	763	1090	—	22.5
OAC 350	4.5±1.0	44	39	7.5±1.5	153	350	690	1117	—	26.2
OAC 400	4.5±1.0	39	36	7.5±1.5	157	400	618	1137	—	30.0

JC : plain concrete using ultra-rapid hardening cement,
OC : plain concrete using ordinary cement,
JAC : AE cpmcrete using ultra-rapid hardening cement,
OAC : AE concrete using ordinary cement.

Beseides, the numerals 300, 350 and 400 show the unit weight of cement (kg/m^3).

The mixing of concrete was made with a 100ℓ pan type forced mixing mixer, and the mixing time of 2 min was adopted.

2. 2 Experimental method

a) Experiment on strength characterisics of concrete using ultra-rapid hardening cement due to temperature change

The strength of the concrete using ultra-rapid hardening cement is remarkably affected by the temperature after mixing was finished and the temperature during curing period, therefore, it is very important to clarify the strength characterristics ultra-rapid hardening concrete due to low temperature. For this objective, the following experiment was carried out.

1) Making of test pieces, method of curing, compressive strength test

As for the test pieces, the cylindrical test pieces of 10cm diameter and 20cm height were adopted so that external temperature conducts in a short time to inside. Four test pieces were made for one series, and the internal temperature of the test pieces was measured by using one of them. The measurement was carried out with a self-registering thermometer from the time of making the test pieces.

The curing temperature was 0, 10, 20 and 30°C for ulta-rapid hardening concrete, and 10, 20, and 30°C for ordinary concrete.

The age of ultra-rapid hardening concrete was 2, 4 and 8 hours, 1, 3, 7 and 28 days, and that of ordinary concrete was 3, 7, 14 and 28 days.

Moreover, the test pieces were placed in a low temperature thermostatic apparatus (made by Tabai Co., internal volume 408 ℓ, mechnical single-stage refrigerating system, the accuracy of temperature adjustment ±0.3°C, temperature range −40°C∼85°C) 15 min after the start of mixing as they were in the forms, and left to carry out the moist air curing up to the prescribed age. At this time, in order to prevent the evaporation of water, the test pieces were sealed in vinyl bags.

The compressive strength test was carried out in accordance with JIS A 1108 on three test pieces having reached the prescribed age by applying sulfur capping to them.

2) Method of summarizing results

At the time of summarizing the data, it was assumed that the compressive strength and cumulative temperature are in the relation of a function, and the following equation shown by Japan Society of Civil Engineers was adopted.

$$M=\sum_{\theta}^{t}(\theta+10)\Delta t$$

Here, M : maturity (°C·h), θ: concrete temperature during time Δt(°C), Δt : time (h).

b) Experiment on manifestation of strength of ultra-rapid hardening concrete suffering freezing at initial phase of hardening

Generally, it has been said that when concrete suffers freezing at the initial phase of hardening, it is necessary that a certain extent of the strength arises before the freezing.

This experiment is that for clarifying to what extent freezing affects the increase of strength when ultra-rapid hardening concrete suffers freezing in the period it does not sufficiently harden.

Therefore, this time, two kinds of experiment were carried out. In the first experiment, at the time when the compressive strength just before freezing of about 20, 30, 50 and 80 kg/cm² was obtained, the test pieces were freezed at −20°C, thawed after the lapse of the prescribed age, and immediately the compressive strength test was carried out to know the relation between the strength just before freezing and the manifestation of strength. In the second experiment, at the time when the compressive strength just before freezing of about 30 and 50 kg/cm² was obtained, the test pieces were freezed at −20°C for 24 hours, thereafter, the curing in water was carried out at 4°C up to the age of 14 days, and the compressive strength test was performed to know the relation betweeen the strength just before freezing and the recovery of strength. Moreover, the lowest atmospheric temperature in various places in Japan was referred to, and the freezing temperature was set at −20°C.

1) Making of test pieces, method of curing and compressive strength test

In both ultra-rapid hardening concrete and ordinary concrete, the unit weight of cement used was 350 kg/m³. As for the dimensions of test pieces, the cylindrical test pieces of ϕ10×20 cm were used, and for the curing, the same low temperature thermostatic apparatus as mentioned before was employed.

First, in order to freeze the test pieces at the initial phase of hardening, the time of leaving from placing concrete to putting in the low temperature thermostatic apparatus was changed variously. During the time of leaving, the test pieces were kept in a thermostatic curing room at 20°C, and after a proper time of leaving has elapsed, they were sealed in vinyl bags, and placed in the low temperature thermostatic apparatus at −20°C as they were in the forms. Besides, using the test pieces for temperature measurement, the internal temperature of the test pieces changing from time to time was recorded with a self-registering thermometer. Here, using a record sheet in Figure 1, the procedure of the second experimental method is explained. The symbols in the figure show the time as follows: ⓐ Placing of concrete. ⓑ Leaving the test pieces as they are in forms in a low temperature thermostatic apparatus at −20°C. ⓒ The internal temperature of the test pieces reached 1°C. Immediately, the strength test just before freezing is carried out. ⓓ Other test pieces are taken out of the forms. The test pieces are put in the water pillows for medical use together with water of about 1°C, and cured again at −20°C. ⓔ The internal temperature of concrete reached −20°C. ⓕ The freezing at −20°C for 24 hours finished. The test pueces as they are in water pillows are put in water at 20°C to thaw. ⓖ The curing in water at 4°C begins.

As seen in Figure 1, when the test pieces at the temperature after mixing of about 20°C were left in a low temperature thermostatic apparatus as they were in the forms, the rate of their temperature drop was such that the internal temperature of the test pieces reached about 1°C within one hour. When the temperature of the test pieces has reached about 1°C, sulfur capping was applied in a short time to three test pieces, and the compression test was carried out, then the test values were taken as the strength just before freezing. As it was confirmed that concrete freezed around −1°C, at the temperature of 1°C, the test pieces do not yet freeze in view of the accuracy of the low temperature thermostatic apparatus therefore, the strength is that just before freezing.

The test pieces were taken out of the low temperature thermostatic apparatus at the age of 1, 3, 7 and 28 days, and immersed for about two hours in water at 20°C as they were in water pillows. After the ice outside and inside the test pieces thawed perfectly, the compressive strength test was carried out in accordance with JIS A 1108.

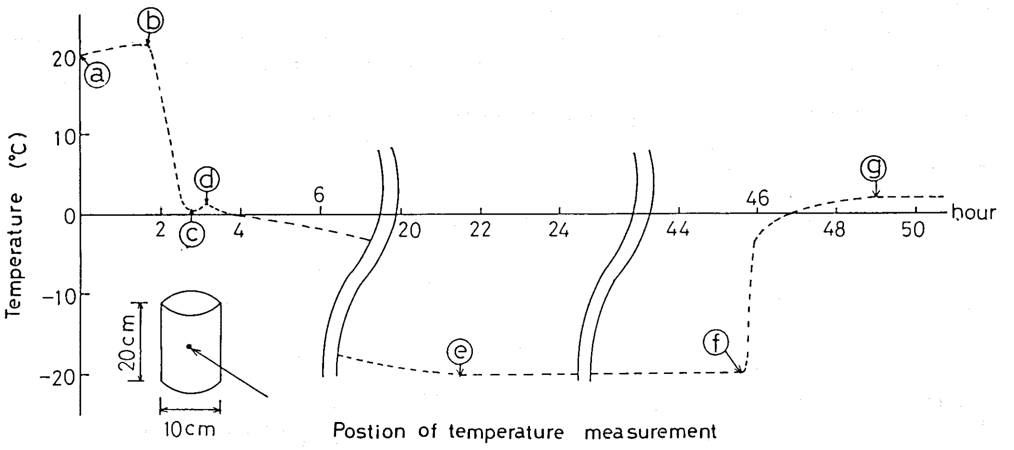

Fig. 1 Procefure of second experimental method and temperatur history

c) Experiment on resistance to rapid repetition of freezing and thawing of ultra-rapid hardening concrete at the initial phase of hardening or after sufficient hardening

In this test, supposing that the concrete after sufficient hardening is subjected to repeated freezing and thawing during long years, the rapid repetition of freezing and thawing was carried out in a laboratory, and by datermining the resistance of concrete to the repeated cycle, its durability was to be estimated. However, when the characteristics of ultra-rapid hardening concrete are considered, it is considered to demonstrate the merit in emergency construction works and the construction in cold weather. Accordingly, together with the test on the test pieces of 20°C standard curing and 14 days age, also the freezing and thawing test of the test pieces of short age and at the initial phase of hardening at low temperature was carried out.

1) Making of test pieces, testing method and measurement of bubble structure

The making of test pieces and the test were carrried out on the basis of "The chemical admixtures for concrete, Attached document 2, The method of freezing and thawing test for concrete" (JIS A 6204). The dimensions of test pieces were $7.5\times10\times40$ cm. The freezing and thawing cycle for these dimensions was the lowering of the temperature of test pieces from 5°C to -18°C and the subsequent raising from -18°C to 5°C, and this alternating mechanism was carried out at 8 cycles per day and 3 hours per cycle (freezing time 2hr 20 min, thawing time 40 min).

The curing method and the age of test pieces were

A. curing in a constant temperature curing pool at 20°C for 14 days,
B. moist air curing for one day in a thermostaic curing room at 20°C,
C. moist air curing for one day in a low temperature thermostatic apparatus at 10°C,
D. moist air curing for four days in a low temperature thermostatic apparatus at 4°C,
E. moist air curing for two days in a low temperature thermostatic apparatus at 4°C, and
F. moist air curing for one day in a low temperature thermostatic apparatus at 4°C.

Moreover, at the time of beginning freezing and thawing, the compressive strength test on the test pieces of the same age was carried out, and the relation between the compressive strength and the resistance to the repetition of freezing and thawing was examined.

Next, in order to know the effect that the structure of the air bubbles brought along into concrete exerted on the durability, the bubble structure of hardend concrete was measured. The measurement of the bubble structure of hardend concrete was carried out by the corrected point count method of ASTM-C45-71.

3. RESULTS AND EXAMINATION

3. 1 Experimental results on strength characteristics of ultra-rapid hardening concrete due to low temperature and examination

In order to show the relation among varrious curing temperature, age and compressive strength, the equation for cumulative temperature was applied, and the results shown are Figure 2. Figure 2 is the case of plain concrete.

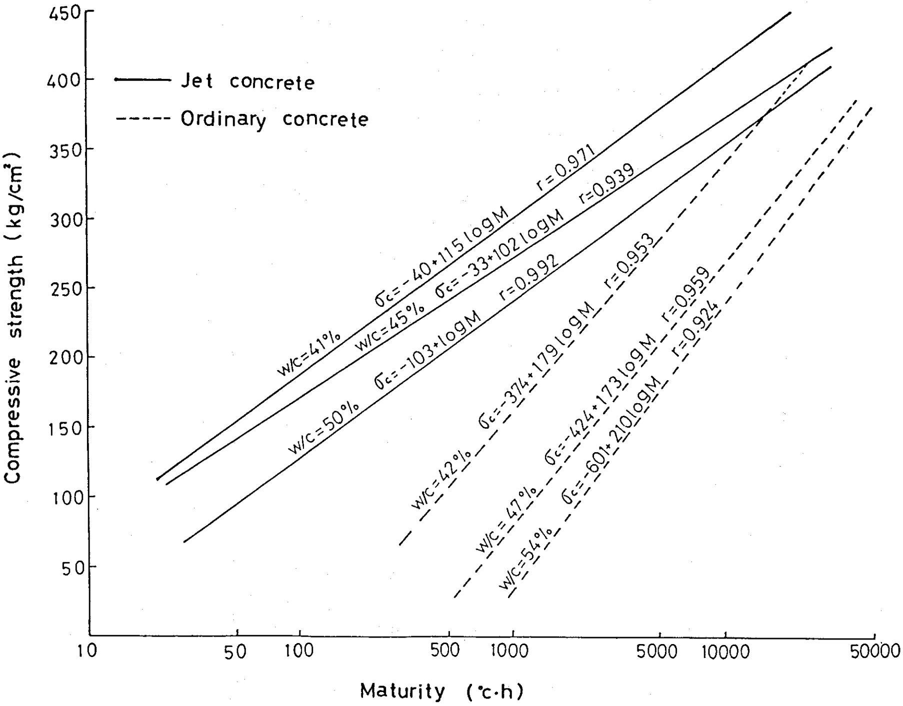

Fig. 2 Relation between maturity and compressive strength of plain concrete

Plowman reported that if cumulative temperature is shown by logarithmic scale, the relation between strength and the cumulative temperature can be represented with straight lines, and it can be said also from the results of the authors.

From Figure 2, the compressive strength at an arbitrary cumulative temperature in respective water to cement ratio can be estimated. The contimuous lines (ultra-rapid hardening) and the broken lines (ordinary concrete) in the figure were determined by least squares method, and the approximate equations and the correlation coefficient r are shown.

As seen in Figure 2, the compressive strength of ultra-rapid hardening concrete for each cumulative temperature was higher than that of ordinary concrete, and even if cumulative temperature was lowered, the decrease of strength as ordinary concrete was not shown. In other words, in ultra-rapid hardening concrete, even at low temperature and in short age, the manifestation of strength was very high.

Here, the strength of ultra-rapid hardening concrete and ordinary concrete having the same unit weight of cement were compared. For example, when the unit weight of cement of 350 kg/m^3 (ultra-rapid hardening concrete : W/C=45%, ordinary concrete : W/C=47%) was taken, at 720°C·h (corresponding to the age of one day by 20°C curring) and 2160°C·h (the age of three days by 20°C curring), the strength of ultra-rapid hardening concrete was 260 kg/cm^2 and 310 kg/cm^2,whereas that of ordinary concrete was about 50 kg/cm^2 and 150 kg/cm^2. From this fact, it is known that in ultra-rapid hardening concrete, high strength can be expected at early age.

3. 2 Experimental results on strength manifestation of ultra-rapid hardening concrete suffering freezing at initial phase of hardening and examination

a) Strength manifestation of concrete suffering freezing at initial phase of hardening

The relation between the strength and age of the AE concrete with the unit weight of cement of 350 kg/m^3 suffering freezing at the initial phase of hardening is shown in Figure 3. The continuous line shows the case of ultra-rapid hardening concrete, and the broken line shows the case of ordinary concrete.

In Figure 3, the strength of ultra-rapid hardening concrete just before freezing was 21, 28, 46 and 80 kg/cm². The time of leaving for obtaining this strength was 1 hr 34 min, 1 hr 39 min, 2 hr 15 min and 3 hr 20 min, respectively.

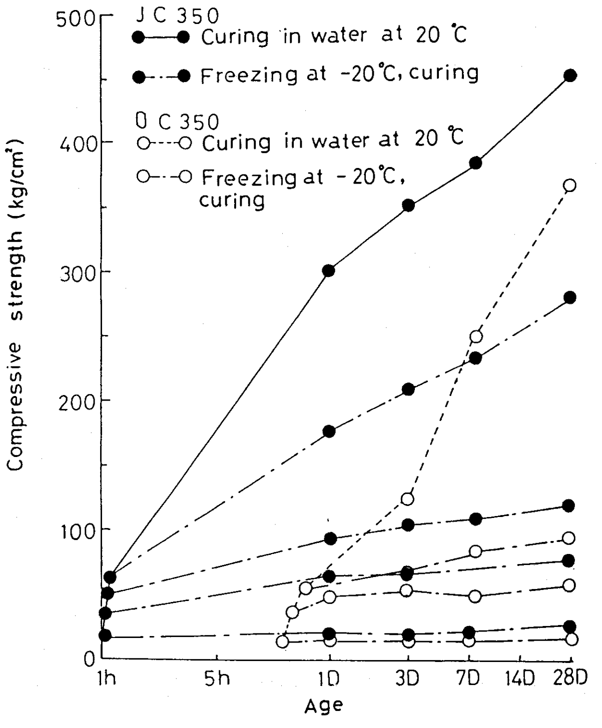

Fig. 3 Property of strength manifestation of AE concrete suffering freezing at initial phase of hardening

The strength of ordinary concrete just before freezing was 19, 40 and 74 kg/cm², and the time of leaving for obtaining this strength was 13 hr, 26hr 8 min and 32 hr 15 min, respectively.

In this way, it is known that the time of leaving for ultra-rapid hardening concrete is remarkably short as compared with that for ordinary concrete.

Besides, the temperature just after the finish of mixing in this experiment was 15～18.5°C in ultra-rapid hardening concrete, and 15～16°C in ordinary concrete.

As shown in Figure 3, demarcating at the strength just before freezing about 50 kg/cm², conspicuous difference was observed in the increase of strength thereafter. In the test pieces of ultra-rapid hardening concrete having the strength just before freezing of 21, 28 and 46 kg/cm², the increase of strength thereafter was hardly observed. However, in the case of the strength just before freezing of 80 kg/cm², the increase of strength was able to be clearly observed. In this case, the compressive strength at the age of 28 days has reached 180 kg/cm², and it was about 50% of the strength of the test piece with standard curing.

Also as to ordinary AE concrete, the almost similar tendency to that of ultra-rapid hardening concrete was shown. In two test pieces having the strength jsut before freezing below 50 kg/cm² (19 and 40 kg/cm²), the increase of compressive strength at the age thereafter was hardly observed. However, in the case of the test piece having the strength just before freezing of 74 kg/cm², though the increase of strength as the case of ultra-rapid hardening concrete having the strength just before freezing of 80 kg/cm² was not observed, the strength tended to increase. In this case, the compressive strength at the age of 28 days was 101 kg/cm² and about 30% of the strength of the test piece with standard curing.

Subsequently, the relation between the strength and age of the plain concrete of the unit weight of cement of 350 kg/cm², suffering freezing at the initial phase of hardening is shown in Figure 4. It is seen in Figure 4 that its time of manifesting the strength just before freezing was shorter than the case of AE concrete in Figure 3. As the reason of this, it is considered that the temperature just after the finish of mixing was 20.5～26.0°C in ultra-rapid hardening concrete and 16～25°C in ordinary concrete, and these were higher than that of AE concrete. Besides, it is considered also that because air entraining agent was not used, hydration occurred somewhat early.

It is seen in Figure 4 that similarly to AE concrete, also in plain concrete, both ultra-rapid hardening concrete and ordinary concrete changed remarkably the state of increasing their strength demarcating at the strength just before freezing of 50 kg/cm².

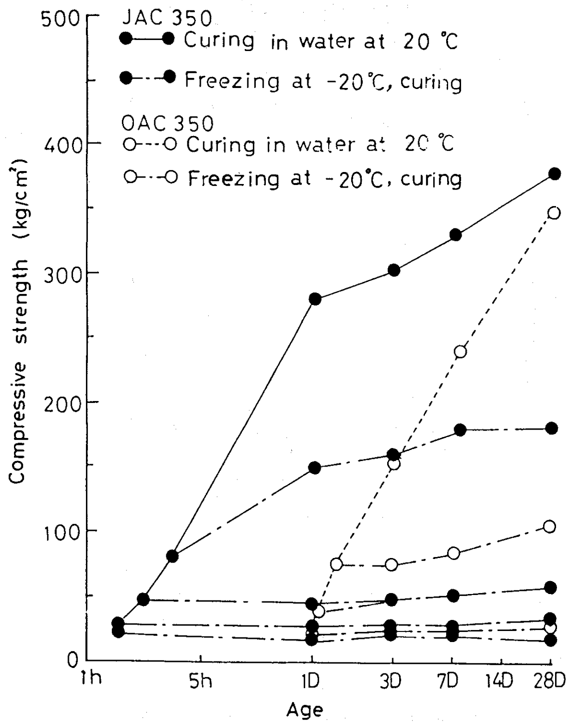

Fig. 4 Property of strength manifestation of plain concrete suffering freezing at initial phase of hardening

By these experiments, it is considered that similarly to ordinary concrete, if the ultra-rapid hardening concrete in the case of continuing freezing at −20°C has manifested the strength just before freezing exceeding 50 kg/cm², the increase of strength thereafter can be expected even though it is subjected to freezing.

b) Recovered strength of concrete freezed for 24 hours at initial phase of hardening and thereafter cured in water at 4°C

This experiment was to clarify the relation between the strength just before freezing and recovered strength by freezing test pieces at −20°C for 24 hours at the time point of having obtained the compressive strength just before freezing of about 30 and 50 kg/cm², thereafter curing in water at 4°C up to the age of 14 days, and carring out the compressive strength test.

So far, it has been clarified that the amout of strength increase after freezing was largely affected by the strength just before freezing. In the case of freezing at −20°C, if the strength just before freezing is higher than 30 kg/cm² in moist air freezing and higher than 50 kg/cm² in the freezing in water, the increase of strength thereafter can be expected even if concrete is subjected to freezing. Accordingly, the target strength just before freezing for this experiment was set at 30 kg/cm² and 50 kg/cm², and the recovered strength was determined. The results are Figures 5 and 6. Figure 5 shows the case of the AE concrete having the unit weight of cement of 350 kg/cm², and Figure 6 shows the case of the plain concrete having the unit weight of cement of 350 kg/cm². In Figure 5, the recovery of strength when freezing thawed was larger as the strength just before freezing was higher. This fact is known by observing the strength later than one day in ultra-rapid hardening concrete and later than three days in ordinary concrete. By the way, the strength of the test pieces of ultra-rapid hardening concrete having the strength just before freezing of 29 and 45 kg/cm² at the age of 14 days was 17% and 50% of the strength in standard curing, respectively. Also the strength at the age of 14 days of the ordinary concrete having the strength just before freezing of 36 and 49 kg/cm² was 59% and 77% of the standard strength, respectively.

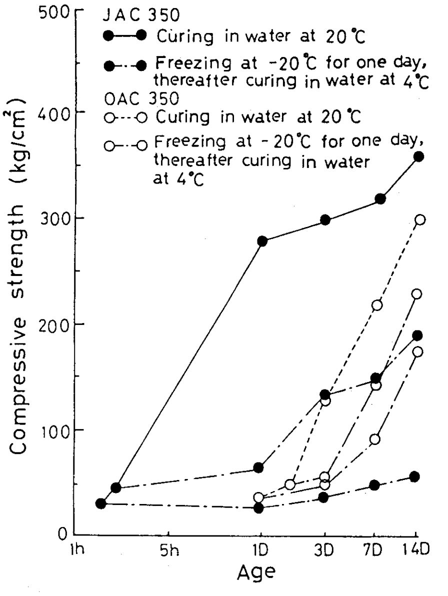

Fig. 5 Property of strength recovery of AE concrete freezed for one day at initial phase of hardening, thereafter cured in water at 4°C

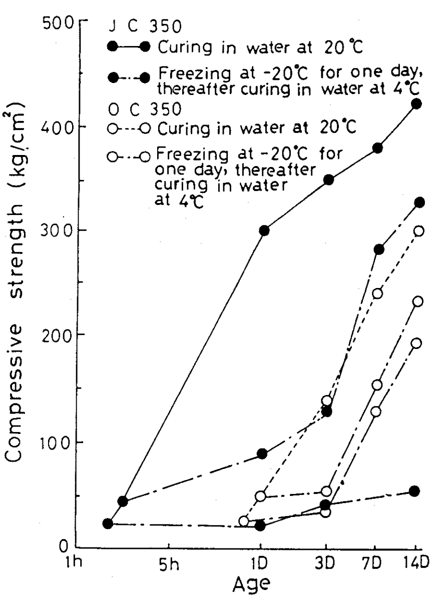

Fig. 6 Property of strength recovery of plain concrete freezed for one day at initial phase of hardening, thereafter cured in water at 4°C

Figure 6 shows the case of plain concrete. As a whole, the state of strength recovery similar to the case of AE concrete was shown. But it is noteworthy that the strength recovery of the test piece of ultra-rapid hardening concrete having the strength just before freezing of 44 kg/cm^2 was remarkably large. The recovered strength at the age of 14 days reached 77% of the strength in standard curing.

C) Strength just before freezing and increase of strength

Figure 7 shows the ratio of the strength after the freezing at -20°C up to the age of 28 days to the strength of the test piece in the standard curing at 20°C, in respective strength just before freezing. Both ultra-rapid hardening concrete and ordinary concrete showed the increase of strength of same degree below the strength just before freezing of 50 kg/cm^2. Besides, it is seen that as compared with ordinary concrete, if ultra-rapid hardening concrete manifested the strength just before freezing exceeding 50 kg/cm^2, the increase of strength thereafter became conspicuously high.

As seen in Figure 7, in order to obtain the strength 50% of that of the ultra-rapid hardening concrete cured by the standard process at the age of 28 days, the strength just before freezing of plain concrete and AE concrete becomes 60 kg/cm^2 and 80 kg/cm^2, respectively.

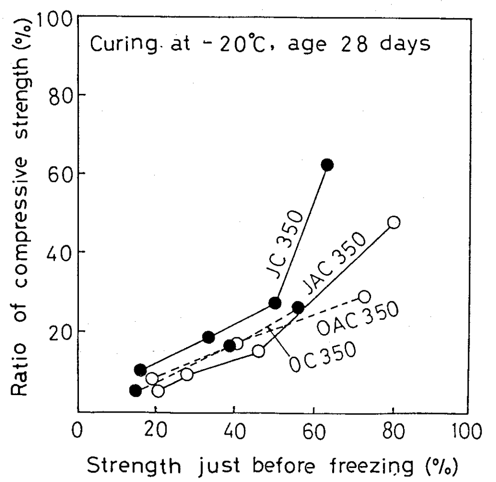

Fig. 7 Strength just before freezing and increase of strength

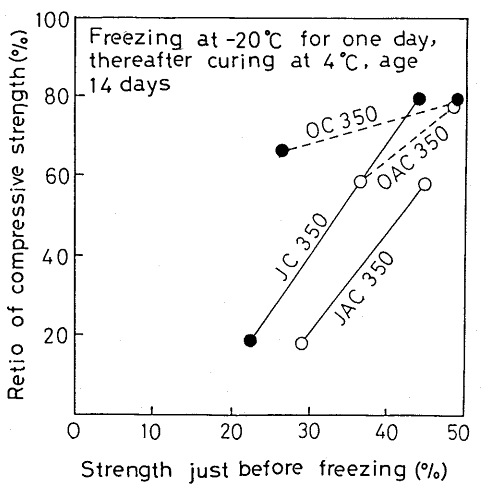

Fig. 8 Strength just before freezing and increase of strength

Figure 8 shows the ratio of the strength at the age of 14 days obtained by freezing at $-20^{\circ}C$ for 24 hours at the time point of having obtained the target strength just before freezing and thereafter curing at $4^{\circ}C$ to the strength of the test piece cured by the standard process. It is observed in Figure 8 that the strength ratio of the ultra-rapid hardening concrete having the strength just before freezing below 40 kg/cm^2 was low as compared with that of ordinary concrete. As the reason of this, it seems that in the case of ultra-rapid hardening concrete, when its freezing thawed and it came in contact with water at $4^{\circ}C$, the hydration rapidly advanced and much ettringite was formed accompanying it, but the test pieces did not manifest the strength sufficiently, therefore, cracks arose due to the expanding pressure of ettringite formation, and the strength was lowered.

3. 3 Experimental results on resistance to rapid repetition of freezing and thawing of ultra-rapid hardening concrete at initial phase of hardening or after full hardening and exmination

a) Resistance of AE concrete to rapid repetition of freezing and thawing

The test results for ultra-rapid hardening AE concrete and ordinary AE concrete are shown in Figure 9. In Figure 9, it was observed that in the case of ultra-rapid hardening AE concrete, if the unit weight of cement was more than 350 kg/m^3 and W/C was below 41%, even the (B) test pieces cured in moist air at $20^{\circ}C$ for one day showed the high resistance almost same as that of the test pieces cured by the standard process for 14 days. However, even if ultra-rapid hardening concrete was AE concrete, in the test pieces (F), (E) and (D) cured at low temperature of $4^{\circ}C$ for one day, 2 days and 4 days, in which the manifestation of strength was insufficient, the high resistance to freezing and thawing was not observed in all cement quantity. By the way, in the test piece (D) of ultra-rapid hardening AE concrete having the unit weight of cement of 400 kg/m^3 and cured in moist air at $4^{\circ}C$ for 4 days (JAC 400-D), the relative dynamic modulus of elasticity of 21% resulted from 15 cycles of freezing and thawing cycle.

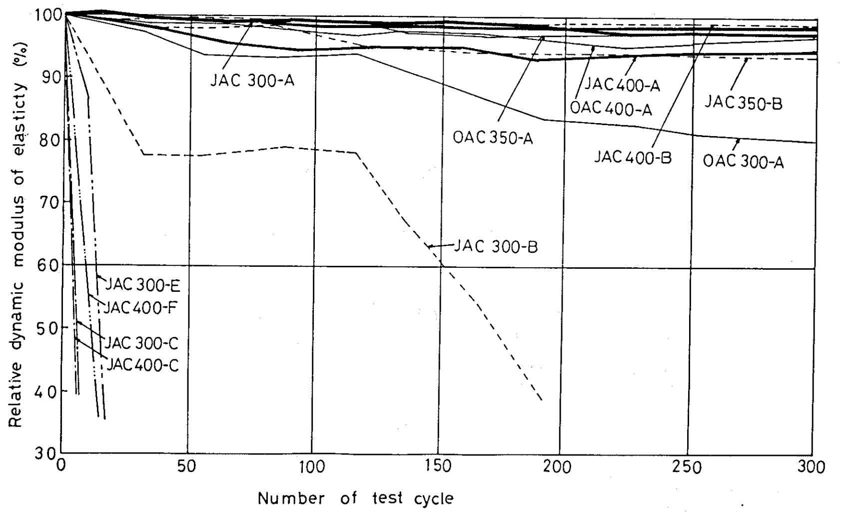

Fig. 9 Results of freezing and thawing test of AE concrete

Next, the results of measuring the coefficent of bubble intervals are shown in Table 6. In Table 6, when the concretes with same cement quantity were compared, the coefficient of bubble intervals tended to be smaller in ultra-rapid hardening concrete than in ordinary concrete.

Table 6 Results of freezing and thawing test and results of measuring bubble structure

Kind of concrete	Curing method	Test piece No.	Air quantity (%)	Compressive strength (kg/cm^2)	Freezing and thawing test: Final number of cycles	Freezing and thawing test: Relative dynamic modulus of el. (%)	Freezing and thawing test: Rate of weight change (%)	Freezing and thawing test: durability index (%)	Bubble structure: Air quantity (%)	Bubble structure: Specific surface area (cm^2/cm^3)	Bubble structure: Coeffcient of bubble intervals (μ)
JC 300	A	1	2.1	424	248	59	-2.35	48			
	B	2		287	63	44	-7.20	9	2.44	83	489
	F	3		48	—				2.08	88	516
JC 350	A	4	1.6	430	208	49	-7.24	34			
	B	5		366	141	36	-1.10	17	1.52	140	400
	F	6		40	—				1.60	115	596
	E	7		53	—						
JC 400	A	8	1.5	459	300	96	-7.60	96			
	B	9		415	132	46	-8.48	20	1.56	87	676
	C	10		371	132	37	-1.75	16	1.44	95	640
JAC 300	A	11	4.2	410	300	97	-1.59	97			
	B	12		331	191	40	-0.62	25	4.52	133	164
	F	13		60	7	39	-17.09	1	4.28	129	179
	E	14		73	17	24	-9.10	1			
JAC 350	A	15	5.0	419	300	99	-0.84	99			
	B	16		342	300	94	-0.13	94	4.72	161	151
	F	17		52	—				4.72	132	185
	E	18		80	—						
JAC 400	A	19	4.6	463	300	95	-0.69	95			
	B	20		435	300	99	-0.21	99	4.52	132	221
	F	21		59	7	21	-5.63	0	4.40	131	229
	D	22		91	15	28	-6.30	1			
O C 300	A	1	1.9	298	43	59	-0.04	8	1.68	81	607
O C 350	A	2	1.5	378	58	35	-12.80	7	1.56	82	665
O C 400	A	3	1.7	436	58	48	-1.24	9	1.44	78	763
OAC 300	A	4	4.4	266	300	81	-8.53	81	4.88	115	169
OAC 350	A	5	4.0	304	300	97	-5.22	97	4.68	138	172
OAC 400	A	6	3.6	334	300	97	-5.58	97	3.16	147	272

When consideration was given in connection with the test pieces of freezing and thawing, in the case of the test pieces cured by the standard process for 14 days, it can be said that if the coefficient of bubble intervals is less than about 250μ, both concretes show the high resistance even if they are subjected to 300 cycles of freezing and thawing action, similarly to the results of past research. However, even in the ultra-rapid hardening AE concrete with the coefficient of bubble intervals less than 250μ, in the case of the test pieces with insufficient manifestation of strength, the high resistance to freezing and thawing was not able to be expected.

b) Resistance of plain concrete to rapid repetition of freezing and thawing

The test results for ultra-rapid hardening concrete and ordinary concrete are shown in Figure 10.

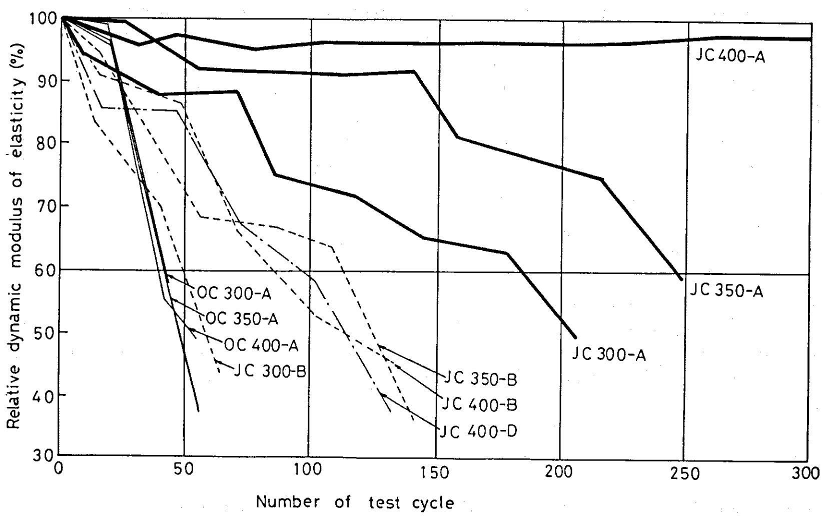

Fig. 10 Results of freezing and thawing test of plain concrete

It was observed in Figure 10 that the ultra-rapid hardening concrete cured by the standard process, even if it was plain concrete and in the case of every cement quantity, showed the conspicuously high resistance as compared with ordinary concrete. Especially in the case of the ultra-rapid hardening concrete having the unit weight of cement of 400 kg/m^3 and cured by the standerd process (JC 400-A), the high resistance was shown even though it was subjected to 300 cycles of the repetition of freezing and thawing. As the reason of this, it is considered that because the bleeding water of ultra-rapid hardening concrete was very little, the bleeding channel became few, therefore the concrete was hard to suffer the deterioration due to hydrostatic pressure, and the adhesion of paste and aggregate was strong.

According to the experiment on bleeding water carried out by the authors in the past, it was slightly observed at W/C=90%, but the result that it was less than the case of W/C=40% in ordinary concrete was obtained.

Besides, even in ultra-rapid hardening concrete, in the case of the test piece (B) cured in moist air at 20°C for one day and the test piece (C) cured in moist air at 10°C for one day, the relative dynamic modulus of elasticity reached 60% line around 80 cycles even if the unit weight of cement was 400 kg/m^3. From this fact, it is known that the resistance was low as compared with the test pieces cured by the standard process.

4. CONCLUSION

For the purpose of using ultra-rapid hardening concrete as the concrete for cold weather use, experimental examination was carried out, and the following facts were clarified.

(1) For showing the relation among curing temperature, age and compressive strength, the equation for cumulative temperature was applied, and when the cumulative temperature was indicated on logarithmic scale, the relation between compressive strength and the cumulative temperature maintained linear relation in both ultra-rapid hardening concrete and ordinary concrete.

Besides, ultra-rapid hardening concrete manifested conspicuously high strength even though the cumulative temperature was taken low as compared with ordinary concrete. Owing to this fact, the ultra-rapid hardening concrete is suitable to the concrete for cold weather use.

(2) In ultra-rapid hardening concrete, the time of leaving required for manifesting the target strength just before freezing can be made remarkable short. However, when it was freezed by making the strength just before freezing same as that of ordinary concrete, the property of manifesting strength thereafter became almost same as that of the ordinary concrete. at this time, the lowest strength just before freezing with which the increase of strength can be expected by continuing freezing at −20°C may be considered as about 50 kg/cm^2 similarly to ordinary concrete.

Besides, the recovered strength when freezing was thawed halfway and low temperature curing was carried out was higher as the strength just before freezing was higher in both ultra-rapid hardening concrete and ordinary concrete. However, the recovered strength of the test pieces of ultra-rapid hardening concrete having the strength just before freezing below 40 kg/cm^2 was low as compared with that of ordinary concrete.

(3) Concerning the resistance to the repetition of freezing and thawing, if ultra-rapid hardening concrete was made into the AE concrete of the unit weight of cement more than 350 kg/m^3 and W/C less than 41%, it showed almost same resistance as the test pieces cured by the standard process for 14 days, even though the test pieces were cured in moist air at 20°C for one day.

Since ultra-rapid hardening concrete becomes very compact concrete as compared with the ordinary concrete of same cement quantity, if it is the plain concrete of cement quantity=400 kg/m^3 and W/C=41% cured by the standard process, it can sufficiently withstand 300 cycles of the repetition of freezing and thawing.

Besides, in the case of the AE concrete cured by the standard process, it was confirmed that if the coefficient of bubble intervals was less than about 250μ, both concretes showed the high resistence even though they were subjected to 300 cycles of freezing and thawing action, similarly to the results of research in the past.

Moreover, this research has been continuously carried out so far since the Yoshida research promotion subsidy of Japan Society of Civil Engineers was awarded in 1978, and based on the experimental data, this paper was written.

Finally, deep gratitude of the authors is expressed to the graduates of Nagoya Institute of Technology and Toyota National Technical College concerned who tool the trouble to carry out this research.

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