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A Long-term Exposure Test of Various Concretes concerned with the Difference of Frost Damage due to Weather Conditions

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Abstract

In a survey of concrete buildings in cold regions in Japan, regional differences of frost damage of concrete were observed. Different weather conditions of the regions seem to cause these differences. We carried out a long-term outdoor exposure test at 11 selected places, under different weather conditions. To find out the difference of frost damage, 25 kinds of concrete mix were selected in this test. Large differences in the compressive strength, the static modulus of elasticity, and the carbonation depth were observed depending on the weather conditions of exposure sites. The collapse by frost damage of some concrete mixes occurred at Kitami, where the highest degree for the risk of frost damage is expected in Japan, after more than 4 years outdoor exposure. Concrete mix with high water-cement ratio quickly decreases its compressive strength, and carbonation of the mix becomes greater. Frost damage of non-AE concrete was recognized at some exposure sites with severe weather conditions after ten years exposure.

1. Introduction

Regional differences in frost damage of concrete was observed by surveying reinforced concrete buildings in Hokkaido, Tohoku, and Chubu regions in Japan. It is considered that the differences may have occurred by the different weather conditions of the regions.

The external factors have a great influence on the frost damage among 3 factors concerned with the frost damage of concrete, (i.e. internal, external,and structural factors). Major external factors are the outdoor temperature, cooling speed, and water content of concrete during freezing and thawing. The seasonal repetition of wetting and drying, large temperature changes, which may cause cracks, and self-recovery effects or self-adhesion of cracks, are also considered as factors of frost damage. They are closely related to the regional weather conditions.

The authors made calculations of the risk of the occurrence of frost damage as numerical value (V_F) based on the weather data in winter, and on the results of freezing and

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thawing tests in the laboratory as well as outdoor exposure tests in Hokkaido. Five grades of the risk for frost damage (D_F) was proposed by authors, considering the relationship between the grade of damage and the calculated values (V_F)[1)2)]. (See Fig. 1)

2. Test specimens of concrete for long-term outdoor exposure

Concrete test specimens were made at 5 places located in 4 areas, as shown in Table 1. With regard to concrete materials, ordinary portland cement, high-early-strength and ultra high-early-strength portland cements were used as shown in Table 2. The physical properties of cement are shown in Table 2.

As shown in Table 3, the sand, gravel and crushed stone available at each place to make specimens and three types of artificial lightweight coarse aggregate in prewetting conditions were used for concrete mixes, 15 kinds of aggregate in total. Those physical properties are shown in Table 3. Expanding agents such as CSA (C), Expan (E), Gypcal (G) in powder shape and an air-entraining agent (Vinsol) were added.

Fig. 1 Places for exposure and the degree of risk of frost damage in case of concrete (D_F)

Concrete mixes and properties of the concrete are shown in Table 4. Five different water-cement ratios, such as 0.40, 0.50, 0.55, 0.60 and 0.70 were selected, and 25 kinds of concrete test specimens in accordance with the combinations shown in Table 4 were made in July and August of 1975.

The test specimens, $10\phi \times 20$cm in size, were cured in water for four weeks. The properties of fresh concrete and the compressive strength of concrete and the dynamic and static modulus of elasticity after 4 weeks curing are also shown in Table 4.

3. Procedure of exposure test

After 4 weeks curing in water, the test specimens were transported to the exposure places shown in Table 1, and outdoor exposure was started at each place simultaneously. The test specimens were placed with the upper face of specimens down on a roof slab.

The compressive strength, the dynamic and the static modulus of elasticity (Young' s modulus) were tested and the carbonation depth of the test specimens were measured, after 1 week storage in water before the tests in August after 1, 2, 4 and 10 years of exposure.

Table 1 Places of making concrete specimens and for long-term exposure

Place of making specimens	Number of test specimens	Place for exposure (See Table 5)
Sapporo	7	All of places
Tokyo(N)	4	Main 5 places, Ofunato, Osaka
Tokyo(O)	4	Main 5 places, Ofunato, Niimi
Chichibu	6	Main 5 places
Oumi	4	Main 5 places, Shiojiri

Table 2 Physical properties of cement

Place of making specimens	Type of cement	Specific gravity	Blaine (Specific suface) (cm^2/g)	Setting time			Flow	Compressive strength (kgf/cm^2)			
				Amount of water (%)	Initial set (hr-min)	Final set (hr-min)		day			
								1	3	7	28
Sapporo	Ordinary port.	3.15	3,020	28.0	2-45	3-40	245		147	240	411
Tokyo(N)	Ordinary port.	3.16	3,260	27.5	2-40	3-45	256		158	224	405
	High E.S. port.	3.12	4,580	30.8	2-40	4-10	238	120	284	363	438
	Ultra H.E.S.port	3.11	5,920	33.5	2-20	3-30	245	206	361	433	472
Tokyo(O)	Ordinary port.	3.17	3,250	27.8	2-35	3-33	256		120	218	410
Chichibu	Ordinary port.	3.16	3,020	28.4	2-30	3-35	238		153	253	392
Oumi	Ordinary port.	3.16	3,210	27.4	2-42	3-40	246		138	244	403

Table 3 Physical properties of aggregates

Place of making specimens	Kind	F.M.	Spec. gravity		Water absorption (%)	Unit weight (kg/m³)	Absolute vol. of aggre. (%)
			Surface −dry	Oven −dry			
Sapporo	Hiroshima[1]	2.55	2.65	2.61	1.7	1,740	67
	Nishikioka[2]	2.57	2.84	2.82	0.6	1,960	70
	Tobetsu[4]	6.53	2.65	2.60	2.1	1,690	65
	Bilton[6]	6.39	1.53	1.24	23.5	804	65
Tokyo(N)	Fuji[3]	2.97	2.61	2.55	2.2	1,740	68
	Ooi[4]	6.88	2.64	2.61	1.0	1,670	64
Tokyo(O)	Kinu[3]	2.82	2.65	2.61	1.6	1,647	63
	Fuji[4]	6.89	2.66	2.63	1.0	1,671	64
	Mesalite[6]	6.40	1.54	1.27	21.5	744	59
Chichibu	Fuji[3]	2.73	2.63	2.59	1.6	1,789	69
	Sagami−5[5]	7.07	2.72	2.69	1.1	1,525	57
	Sagami−6[5]	6.27	2.71	2.67	1.6	1,500	56
	Sailite[6]	6.14	1.57	1.26	24.6	815	65
Oumi	Hime[3]	2.78	2.63	2.59	1.5	1,670	65
	Hime[4]	6.89	2.65	2.63	0.6	1,770	68

[1] Moutain sand, [2] Sea sand, [3] River sand, [4] River gravel, [5] Crushed stone,
[6] Artificial lightweight coarse aggregate (Prewetting)

Table 4 Concrete mixes and properties of concrete

Place of making specimens	Sign of specimens	Mix proportion						Admixture (kg/m³) or (C×%)	Fresh concrete			Properties at 4 weeks		
		W/C	S/A (%)	Water (kg/m³)	Absolute vol. (ℓ/m³) Cement	Sand	Gravel		Slump (cm)	Air (%)	weight (kg/ℓ)	E_D (10^5kgf/cm²)	E_S (10^5kgf/cm²)	F (kgf/cm²)
Sapporo	H-55N	0.55	47.6	184	106	333	367		18.0	1.8	2.41	3.68	3.18	318
	H-70N	0.70	49.7	189	86	355	360		18.0	1.7	2.38	3.28	2.93	211
	H-70G	0.70	49.7	189	86	355	360	Gypcal(30)	18.0	1.8	2.36	3.29	2.65	194
	H-70C	0.70	49.7	189	86	355	360	CSA(30)	18.0	2.0	2.37	3.28	2.62	191
	H-70E	0.70	49.7	189	86	355	360	Expan(28)	18.5	2.1	2.37	3.22	2.83	186
	H-70A	0.70	48.6	175	79	343	363	Vinsol(0.02)	17.5	3.9	2.32	3.06	2.81	178
	H-70A-B	0.70	49.3	172	78	350	360	Vinsol(0.02)	17.0	5.8	1.92	2.14	1.99	172
Tokyo(N)	N-70G	0.70	47.0	188	85	337	380	Gypcal(30)	18.2	0.9	2.32	3.48	2.47	203
	N-V70N	0.70	46.0	204	93	319	374		18.4	1.0	2.32	3.39	2.60	270
	N-S70N	0.70	44.0	207	95	303	385		18.1	0.3	2.34	3.53	2.76	302
	N-S70N	0.70	42.0	190	87	287	396	Vinsol(0.065)	18.2	3.8	2.26	3.11	2.38	254
Tokyo(O)	O-55E	0.55	43.0	189	100	298	394	Expan(28)	18.0	1.0	2.39	3.85	2.89	284
	O-70E	0.70	45.0	194	87	319	390	Expan(28)	18.8	1.0	2.39	3.40	2.64	194
	O-70N	0.70	45.0	194	87	319	390		18.1	1.1	2.39	3.37	2.70	226
	O-70N-M	0.70	49.1	209	94	336	349		18.8	2..0	1.94	1.96	1.59	212
Chichibu	M-40N	0.40	42.0	222	175	249	344		17.4		2.38	4.23	3.29	544
	M-50N	0.50	43.8	210	132	284	364		18.6		2.38	4.12	3.18	436
	M-60N	0.60	46.0	204	107	311	368		18.6		2.38	3.92	2.90	355
	M-70N	0.70	47.9	193	87	340	370		18.1		2.38	3.76	2.86	290
	M-70A	0.70	46.6	190	85	319	366	Vinsol(0.05)	17.7	3.8	2.33	3.00	2.67	274
	M-70A-S	0.70	46.6	155	70	338	387	Vinsol(0.06)	17.0	4.8	1.83	1.89	1.57	165
Oumi	D-55C	0.55	43.6	193	101	299	387	OSA(30)	18.1	0.9	2.42	3.30	3.41	407
	D-70C	0.69	48.4	186	76	347	371	CSA(30)	17.2	1.3	2.38	3.57	2.68	261
	D-70N	0.69	48.4	186	85	348	371		17.6	1.3	2.39	2.98	2.83	266
	D-70A	0.64	47.3	173	85	332	370	Vinsol(0.03)	17.2	4.6	2.23	2.89	2.51	255

[Sign of specimens]
V(High−early−strength portland cement), S(Ultra high−early−strength portland cement),
N(Non−AE concrete), A(AE concrete),
C・E・G(Expanding agent), B・M・S(Artificial lightweight Coarse aggregate)

The weather conditions and the degree of risk of frost damage, including estimated value, at each place are shown in Fig. 1 and Table 5.

4. Properties of the concrete during ten years exposure

The compressive strength, the static modulus of elasticity (Youngs modulus), and the carbonation depth for 8 kinds of concrete during 10 years are shown in Fig. 2-9.

The results obtained from concrete test specimens made from the same batch differ considerably in the compressive strength, the static modulus of elasticity, and the carbonation depth, mainly by the difference in weather conditions. Although these differences vary depending on the kind of concrete, the range of diversion of the results in 10 years for the compressive strength was apporoximately 150kgf/cm^2, for the static modulus of elasticity was apporoximately 0.7×10^5kgf/cm^2, and for the carbonation depth was apporoximately 10 mm. It disperse over a very wide range. Differences in properties of the concretes can be observed from the first year after exposure.

These changes of properties shown by outdoor exposure are not caused only by frost damage but by various other factors as well. The carbonation depth is not considered to indicate deterioration by frost action, but is shown as a reference for understanding the change of air permeability on concrete.

Some test specimens collapsed after 4 years exposure in Kitami. Kitami has the most severe weather conditions in winter among all places (the degree of risk of frost damage : 5 in Table 5). It is possible to evaluate that Kitami area gives the highest value of the risk of frost damage.

A large pattern crack was observed at the bottom of the collapsed concrete (the upper

Table 5 Weather data and degree of frost damage at 11 places for exposure

Place for exposure	Degree of frost damage	Daily min. temp. Jan. mean(℃)	Water vapor pres. annual (mb)
Kitami (Hokkaido)	5	−16.2	(8.6)
Sapporo (Hokkaido)	3	−8.9	9.4
Kamiiso (Hokkaido)	(2)	(−7.6)	10.3
Morioka (Iwate)	2	−6.5	10.9
Ofunato (Iwate)	0	(−3.0)	11.4
Tokyo (Tokyo)	0	+0.5	13.4
Chichibu (Saitama)	1	−5.5	12.8
Shiojiri (Nagoya)	(2)	(−6.1)	10.9
Oumi (Niigata)	(0)	(−0.5)	13.0
Osaka (Osaka)	0	+2.2	14.0
Niimi (Okayama)	(1)	(−1.3)	(14.4)

( ) : the estimated values

face when placing). In case of non-AE concrete with a water-cement ratio of 0.60 and 0.70, cracks occured and caused discrete and collapsed.

Seven kinds of concrete made at Hokkaido University, Sapporo, were exposed at all 11 places, and the test results after 10 years for the compressive strength and the carbonation depth are summarized in Table 6.

The compressive strength of the concrete was greatest among all concrete specimens, and almost equal values are shown at Kamiiso and Niimi. Assuming that the strength measured at Kamiiso as 1.00, the ratio of compressive strength at other places are given in Table 6. The lowest value,approximately 2/3 of Kamiiso and Niimi, was observed at Morioka, and low values,are observed at Kitami, Osaka, and Sapporo. In spite of its mild climate, the relatively large decrease of strength was observed at Osaka. There would be other decreasing factors in Osaka, however, and it may be impossible to clarify the main reason.

The lowest value of the carbonation depth was observed at Shiojiri. Low values were found at Oumi, Sapporo, and Morioka. The highest value was observed at Osaka, 3.4 times

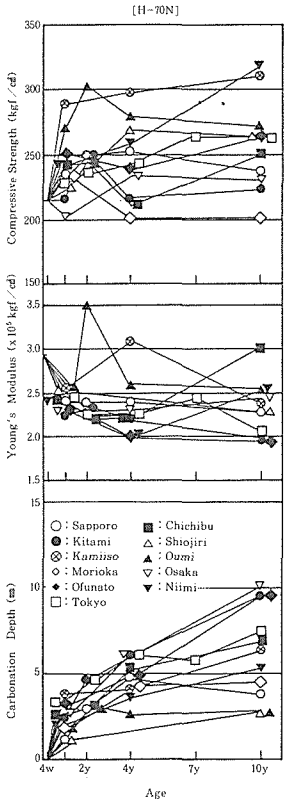

Fig. 2 Properties of concrete during ten years exposure——(1).

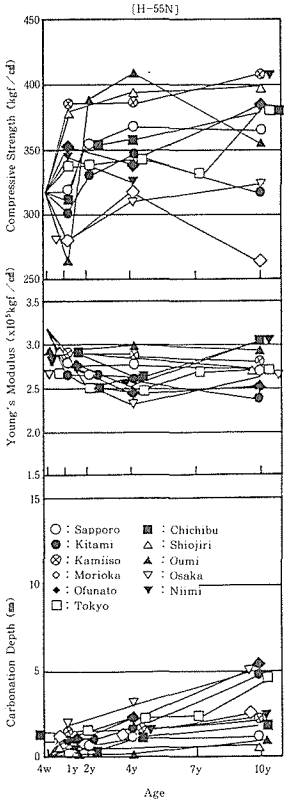

Fig. 3 Properties of concrete during ten years exposure——(2).

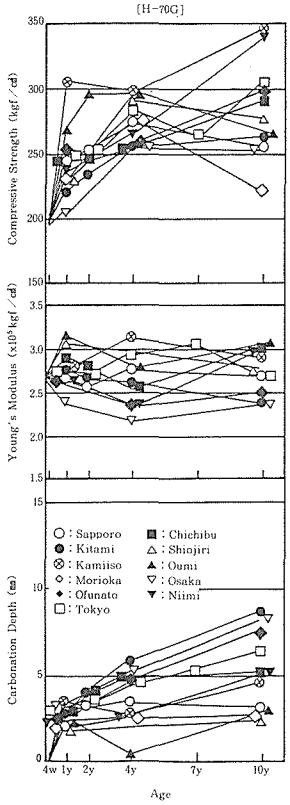

Fig. 4 Properties of concrete during ten years exposure——(3).

of the data at Shiojiri. These results show that greater dry weather, such as hot, less humid, and less snow which has an influence on the carbonation of concrete.

5. Influence of concrete mix on the properties of concrete

5-1. Influence of water-cement ratio (Fig. 10, 11)

The influence of the water-cement ratio was relatively clear-concrete mixes with low water-cement ratio gave high compressive strength and the static modulus of elasticity. Even after 10 years these values were higher than that of tested at the start of the exposure. In case of higher water-cement ratio, such as 0.60 and 0.70, the increase of these values becomes small. And some concrete mixes with 0.70 water-cement ratio showed a decrease of the values.

Some specimens made with non-AE concrete mixes collapsed by severe winter weather conditions. The carbonation depth also increased in case of higher water-cement ratio.

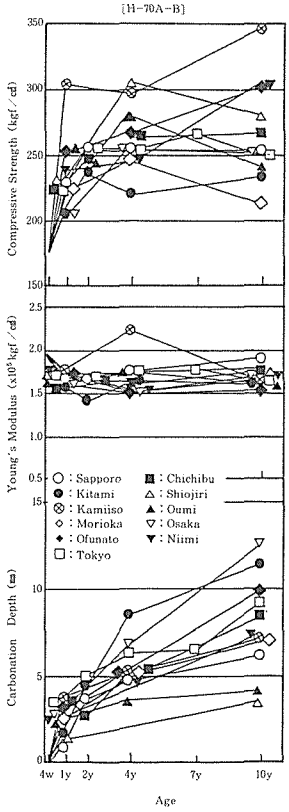

Fig. 5 Properties of concrete during ten years exposure—(4).

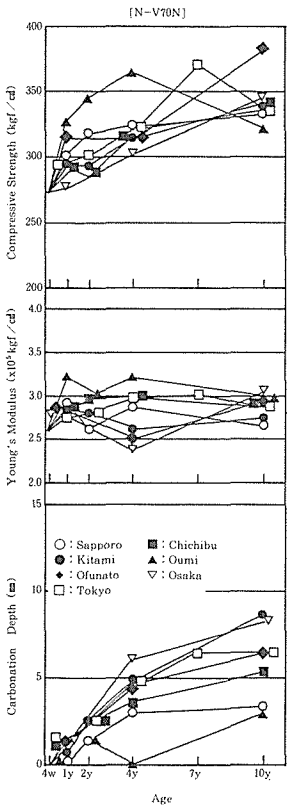

Fig. 6 Properties of concrete during ten years exposure—(5).

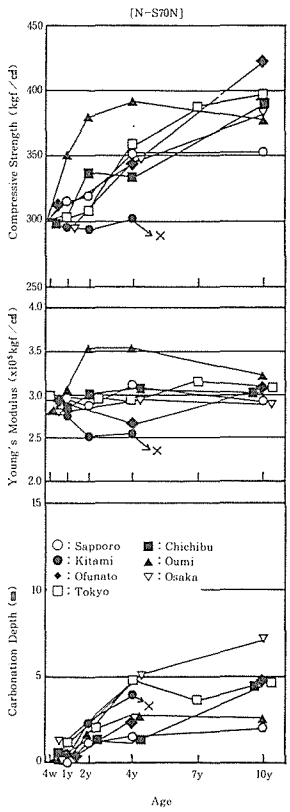

Fig. 7 Properties of concrete during ten years exposure—(6).

5-2. Influence of admixtures(Fig.12,13)

Although there is no significant difference in the compressive strength between non-AE concrete and AE concrete exposed at Kitami and Shiojiri, however, the static modulus of elasticity and the carbonation depth of concrete deteriorated considerably. A concrete mix with AEA, which gave 2.8×10^5kgf/cm^2 of the static modulus of elasticity at the start of exposure, decreases to 1.6×10^5kgf/cm^2 after ten years, and a rather larger carbonation was seen in this concrete. The reason for the larger decrease compared other concrete mixes would be difficult to explain.

On the other hand, non-AE concretes with a 0.70 water-cement ratio, mixed with three kinds of expansive agent (C, E, and G), show similar or somewhat improved properties, compared with non-AE concrete without the admixture.

5-3. Concrete made with artificial lightweight coarse aggregates (Fig.14,15)

Concrete made with artificial lightweight coarse aggregate deteriorated rapidly in the laboratory test of freezing and thawing in water, but the results of outdoor exposure showed no deterioration even in the case of concrete with water-cement ratio of 0.70, which generally

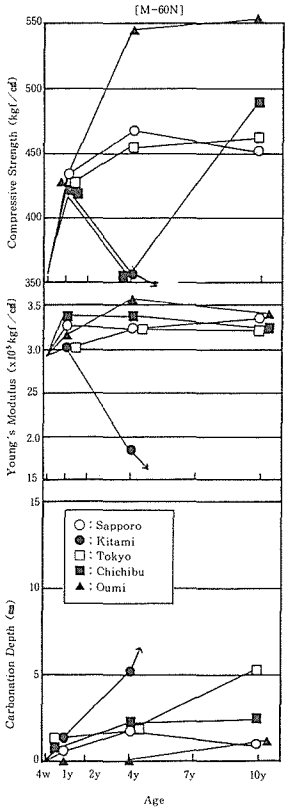

Fig. 8 Properties of concrete during ten years exposure——(7).

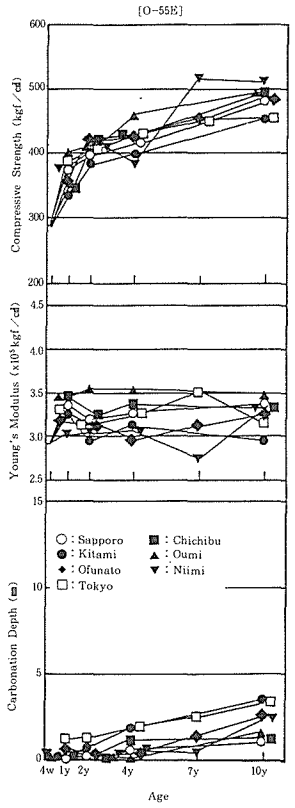

Fig. 9 Properties of concrete during ten years exposure——(8).

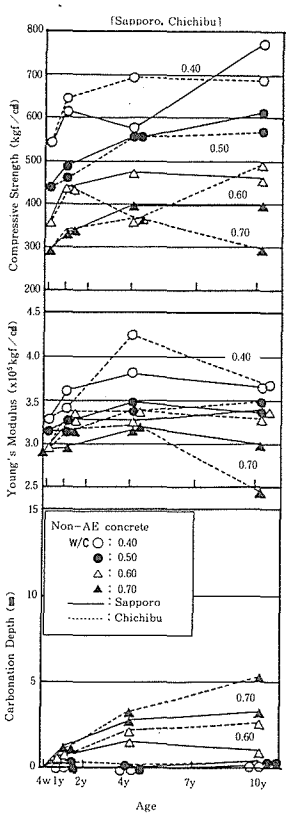

Fig. 10 Influence of water—cement ratio on the properties of concrete——(1).

had very good properties. This is mainly because that the concrete was dried to a certain extent before being exposed to freezing and thawing in winter. Once dried, it would not easily absorb water to the critical degree of water content which makes it vulnerable to frost damage.

The compressive strength after ten years increased approximately 100 kgf/cm^2 after the start of exposure. The carbonation depth varies depending on the place of exposure, and it was observed that one place with dry weather tends to have relatively high carbonation depth, such as 10 mm.

5-4. Influence of the type of cement (Fig. 16,17)

Non-AE concrete with a water-cement ratio of 0.70 made of ultra high-early-strength portland cement collapsed at Kitami after 4 years. But in case of AE concrete and high-early-strength portland cement, no frost damage can be seen even after ten years, and in fact the compressive strength actually increased.

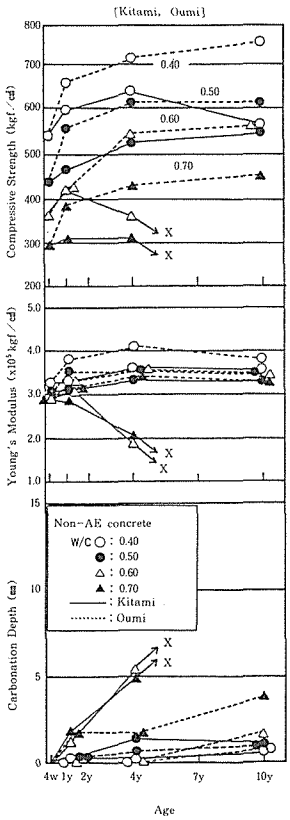

Fig. 11 Influence of water-cement ratio on the properties of concrete——(2).

6. Summary

(1) Relatively large deviation in the compressive strength, the static modulus of elasticity, and the carbonation depth was observed depending on the weather conditions at the exposure places. These deviations were clear after only one year exposure.

(2) The collapse of some concrete occurred at Kitami, which was expected to have the highest degree of risk of

Table 6 Ratio of the compressive strength and the carbonation depth

Place for exposure	Ratio of comp. strength	Ratio of carbonation depth
Kitami	0.77	3.1
Sapporo	0.81	1.4
Kamiiso	1.00	1.9
Morioka	0.68	1.7
Ofunato	0.94	2.9
Tokyo	0.86	2.1
Chichibu	0.86	2.1
Shiojiri	0.87	1.0
Oumi	0.83	1.3
Osaka	0.78	3.4
Niimi	1.00	2.1

frost damage among all exposure places, after more than 4 years exposure.

(3) Less deterioration of the compressive strength of concrete was observed at places, which have small yearly and daily changes of temperature and humidity. The places with relatively little snow and considerable changes of temperature caused the decrease of the compressive strength.

(4) High carbonation depth of concrete was observed at places with relatively dry conditions with high temperature, low humidity, and little snow. The same concrete differs in the carbonation depth depending on the location of exposure. As an example, the highest was three times of the lowest.

(5) Concrete with high water-cement ratio quickly loses its compressive strength and also becomes carbonated, and the frost damage were recognized at some location with severe weather conditions in winter.

(6) The deterioration of AE concrete with the same water-cement ratio as non-AE concrete is greater in both the static modulus of elasticity and the carbonation depth.

(7) No particular difference in deterioration can be seen between the concrete mixed with

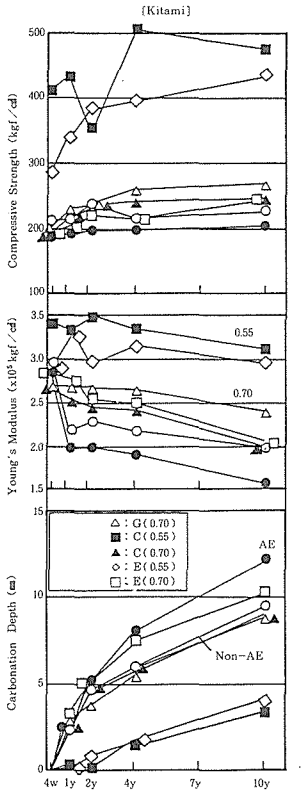

Fig. 12 Influence of admixtures on the properties of concrete——(1).

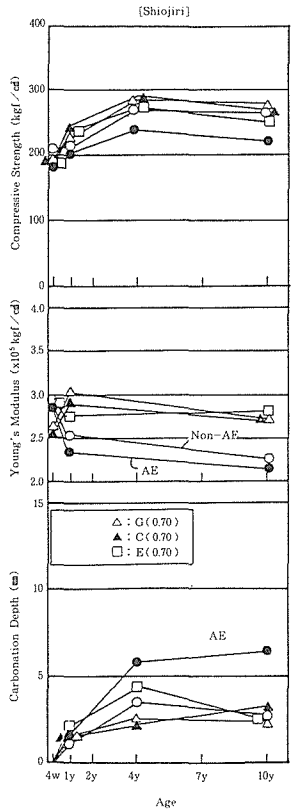

Fig. 13 Influence of admixtures on the properties of concrete——(2).

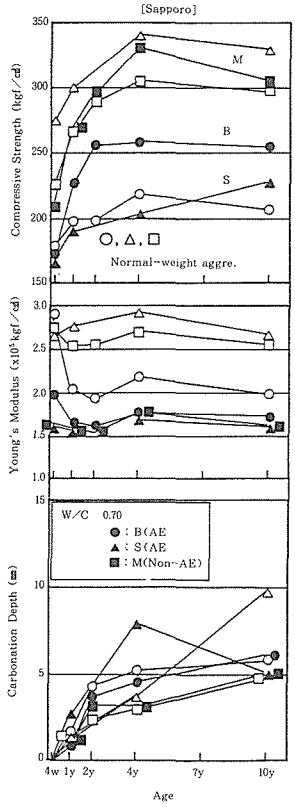

Fig. 14 Concrete made with artificial lightweight coarse aggregates——(1).

expansive agent and concrete mixed without expansive agent — the former shows very good properties when exposed outdoors.

(8) The properties of concrete made with prewetted artificial lightweight coarse aggregates did not deteriorate even in non-AE concrete with a water-cement ratio of 0.70 —— they remained fairly good after 10 years. This is probably because the concrete dried out before winter.

(9) Non-AE concrete with a water-cement ratio of 0.70, made from ultra high-early-strength portland cement, collapsed after 4 years exposure at Kitami by frost action occuring under severe weather conditions.

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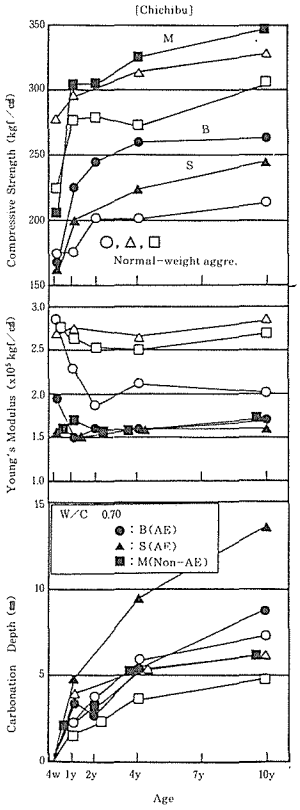

Fig. 15 Concrete made with artificial lightweight coarse aggregates——(2).

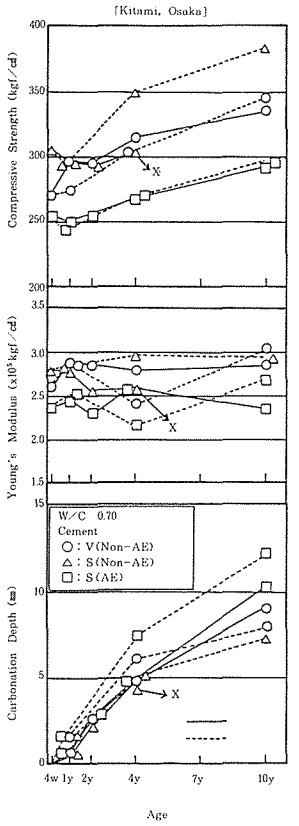

Fig. 16 Influence of the type of cement on the properties of concrete——(1).

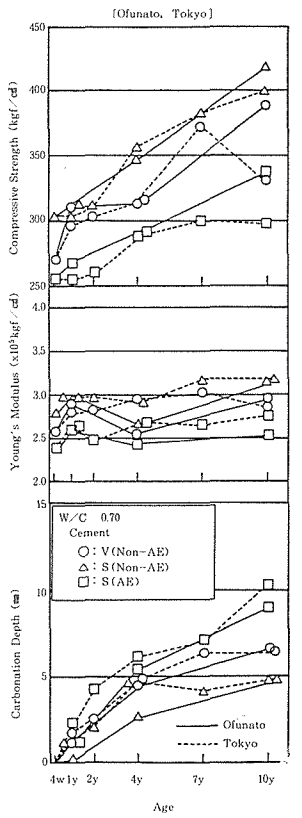

Fig. 17 Influence of the type of cement on the properties of concrete——(2).

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