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STRENGTH AND INELASTIC PROPERTIES OF CONCRETE AT ELEVATED TEMPERATURE

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Experiments on strength, Young's modulus, Poisson's ratio and creep of concrete exposed to elevated temperatures were carried out. Based on the results of experiments, strengths of sealed specimens stored at elevated temperatures and the creep strains of prestressed specimens exposed to elevated temperatures or exposed to cycles of temperature changes are described, and some problems in application of concrete for nuclear reactor are discussed.

Keywords: age; compressive strength; concretes; creep properties; high temperature; modulus of elasticity; nuclear reactor containment; Poisson ratio; prestressed concrete; research; strains; thermal expansion.

In order to investigate fundamental properties of concrete in design of prestressed concrete for nuclear reactor, experiments at elevated temperature were carried out on strength, Young's modulus, Poisson's ratio and creep of concrete. This investigation is composed of Nishizawa's study(1) presented in section 1 and Okamura's presented in sections 2 and 3.

The authors would like to acknowledge the uninterrupted guidance and encouragement of Professor M. Kokubu. Mr. S. Kurasawa who was a graduate student at that time made a remarkable contribution(2) to the accomplishment of this investigation on creep and the authors take pleasure in acknowledging the important part played by him.

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1. STRENGTH, YOUNG'S MODULUS AND POISSON'S RATIO OF CONCRETE AT ELEVATED TEMPERATURE

Mix A and Mix B, as shown in Table 1, were used in the experiments of strength and elastic properties. Required compressive strengths of Mix A and Mix B were respectively 450 kg/cm^2 and 365 kg/cm^2 at age of 28 days.

Cylindrical specimens, 15ø x 30 cm, were cured in water of 20°c for 28 days or 300 days, and successively stored in sealed containers at 40°c, 70°c and 90°c for one week to 13 weeks. After the storing, compressive strength, Young's modulus and Poisson's ratio were measured at the same elevated temperature as in the storing. Specimens were covered with temperature control jacket during the strength test. At the same curing and storing condition were tested three or more specimens. Strain of concrete specimens in compression were measured axially and laterally by wire strain gages.

Figs. 1 and 2 show the relation between the compressive strength and the age of curing and storing. In the figures it is found that compressive strengths of specimens stored at elevated temperature after water curing at 20°c for 28 days or 300 days decreased in the early storing age, one week, and at the storing temperature of 90°c were about 12 percent lower than strength of specimens cured continuously in water. With increase in storing age, however, the strengths increased and recovered to the almost same strength of specimens cured continuously in water except at the storing temperature of 90°c. As shown in Fig. 2, the recovery of strength of specimens of w/c = 0.40 at 70°c was about 120 kg/cm^2 and the strength was about 10 percent higher than the required strength at age of 28 days.

From the above test results, it is considered to proper that the required compressive strength of concrete at elevated temperature up to 90°c are determined to be 15 percent higher than at ordinary temperature, considering decrease of strength at elevated temperature.

Fig. 3 shows the relation between the Young's modulus and the compressive strength of the sealed concrete at elevated temperature. Variations of test results are seen in the figure, but it seemed to consider practically that Young's moduli of concrete depend primarily on the compressive strengths regardless of the elevated temperature and the duration in storing.

Test results of Poisson's ratio were not influenced by the storing temperatures, and the values were within the range of 0.15 to 0.20.

From test results of Young's modulus and Poisson's ratio, it seems poper, in design of prestressed concrete for nuclear reactor, Young's moduli of concrete at elevated temperature are determined from the relationship between the Young's moduli and the compressive strengths at ordinary temperature, for example, the relationship recommended by Japan Society of Civil Engineers in Fig. 3, and that Poisson's ratio is the values of 0.15 to 0.20, for example 1/6.

2. CREEP OF CONCRETE EXPOSED TO ELEVATED TEMPERATURES

Strains of concrete specimens stressed at normal temperature of 20°c and exposed to elevated temperatures have been measured for the period of one year. Prism specimens of 15 x 15 x 55 cm as shown in Fig. 4 were used, and prestressed to compressive stress of 120 kg/cm^2 at age of 28 days. After seven days' loading at 20°c specimens were exposed to the elevated temperature of 70°c or 90°c. Strains and temperatures were measured with specially designed Carlson type strain gages. Before loading, the concrete specimens were sealed by thin copper plate. Weight loss measured of the specimens in the course of the creep tests were obserbed to be very small. Therefore, the role of the copper seal which was to keep the specimens in 100 percent relative humidity could be considered to have been played perfectly. The properties of concrete were shown in Table 2.

The results of measurements are shown in Fig. 5. From this figure following two main features on creep of concrete at elevated temperatures can be clearly understood.

(1) When the prestressed specimens were exposed to elevated temperatures the creep strains increased very rapidly. These rapid increases were found in very short period, say, within a week, immediately after the exposure to elevated temperatures. Creep strain occurred in the first one day after exposure to elevated temperature, for example to 90°c, was 1.5 times as much as the elastic strains at the normal temperature of 20°c.

(2) After the rapid increases, creep strains increased in proportion to the time in logarithmic scale, and the time-dependent increasing rate was larger when the temperature was higher. For example, the ratios of increasing creep for the period of one year counting from 7 days after the exposure to 20°c, 70°c and 90°c were about 1, 2 and 3.8 respectively.

As prestressing bars were not restressed, stress in concrete decreased due to both creep of concrete and relaxation of steel. The loss of prestress should be larger when the temperature is larger, however, the above mentioned ratios are to be little different, even if the loss of prestress is taken into account.

What is mentioned in paragraph (2) can be justified with the idea that the acceleration of creep is caused by the elevated temperatures. But, as to the paragraph (1), further investigations beeing necessary, the following experiments were carried out to clarify the problem.

Prism specimens of 10 x 10 x 42 cm stressed to 130 kg/cm^2 or 70 kg/cm^2 together with unstressed control specimens were put into hot water immediately after prestressing and strains were measured at various temperatures. Temperature of water was elevated gradually from 20°c to 70°c at 10°c intervals, keeping constant temperatures for 30 minutes at every ten degrees' elevation and then decreased reversely from 70°c to 20°c in the same procedure. Thirty minutes were selected to be the shortest time necessary for making temperature of specimens uniform. The results of measurements are shown in Fig. 6. As is obvious from the figure, strain in the unstressed specimens increased in proportion to the temperature, and the coefficient of linear expansión was 8.2×10^{-6}/°c. Smaller expansive strains were recognized in stressed specimens during elevating of temperature, and contractive strains were found in the lapse of 30 minutes at 70°c, whereas they did not appear in unstressed specimens. When the strains in unstressed specimens were subtracted from those in stressed specimens, there remained contractive strains formed during elevating of temperature and they did not change during the fall of temperature. The contractive strains in Fig. 7 were resulted from persistent stress; they were approximately proportional to the stress and increased with duration of stress. Since these features of the contractive strains are perfectly identical to those indicated by creep, the strains which increase very rapidly just after the exposure to elevated temperatures should be called as "creep".

3. CREEP OF CONCRETE EXPOSED TO CYCLES OF TEMPERATURES CHANGES

Fig. 8 indicates the measured creep strains obtained from the specimens exposed to repeated temperature changes. From this figure it will be concluded that when the prestressed specimens are exposed to cycles of temperature changes, very rapid increases of creep strain are found during elevation of temperature in the first cycle, while they are not found in the second.

Stressed specimens together with unstressed ones were exposed to cycles of temperature changes with the different maximum temperatures. The temperature was changed from 20°c to 40°c then from 40°c to 20°c in the first cycle, and from 20°c to 70°c then from 70°c to 20°c in the second cycle. The results of measurements shown in Fig. 9 indicate that if the specimens are exposed to new cycles of higher temperature range the rapid increases of creep can be found again as if exposed to the first cycle of elevated temperatures.

Lastly, stressed specimens together with unstressed ones were exposed to four cycles of temperature changes in air from 20°c to 90°c. The results of measurements were shown in Fig. 10 together with the results of the specimens kept at 20°c with 50 % RH. Remarkable creep strain of 600×10^{-6}, corresponding to 1.5 times of the elastic strain, was found at the first elevating of temperature, while rapid increase of creep strain was not found in the second cycle or thereafter. Once large creep was obtained due to elevating of temperature, creep strain showed very little increase at normal temperature. These results indicate that creep of concrete exposed to temperature change within the range of 20°c to 90°c is remarkably affected by the highest temperature rather than by the history of temperature change.

4. CONCLUSION

From the results of experiments at elevated temperatures, the following results were obtained.

(1) Compressive strengths of sealed specimens stored at elevated temperatures after water curing at 20°c decreased in early storing ages. The higher the storage temperatures were, the larger the decrease of strength were. For example, at storing temperature of 90°c, the strength were about 12 percent lower than strength of specimens cure in water of 20°c. After decrease of strength, however, with increase in storing ages, the strengths increased and were about 10 percent higher than the required strengths at age of 28 days.

(2) Young's moduli of sealed concrete at elevated temperature seemed to depend on the compressive strengths without regard to temperatures in storing. Poisson's ratios were not influenced by the storing temperatures, and the values were within the range of 0.15 to 0.20.

(3) When the prestressed specimens were exposed to elevated temperatures, the creep strains increased very rapidly. These rapid increases were found in very short period, say, within a week, immediately after the exposure to elevated temperatures. Creep strain occurred in the first one day after exposure to elevated temperature, for example to 90°c was 1.5 times as much as the elastic strains at the normal temperature of 20°c.

(4) When the prestressed specimens were exposed to cycles of temperature change, very rapid increases of creep strain were found during elevating of temperature in the first cycle, while they were not found in the second cycle or thereafter. If the specimens were exposed to new cycles of higher temperature range, however, the rapid increases of creep were found again. This indicates that creep of concrete exposed to temperature change within the range of 20°c to 90°c is remarkably affected by the highest temperature rather than by the history of temperature change.

Temperature conditions to be considered in design of prestressed concrete for nuclear reactor will be such as the highest value of temperature in concrete to be expected, temperature gradient and history of temperature. However, in this paper the authors mainly discussed on the properties of concrete in which the elevated temperatures are uniform. In design of prestressed concrete for nuclear reactor it seems proper that required compressive strength of concrete is determined to be 15 percent higher than that used in ordinary temperature, considering the undesirable effects of elevated temperature, and the value of creep of concrete is determined on the basis of creep test at the expected highest temperature. In the design, besides the creep of concrete, the relaxation of steel is also important because of its larger amount at elevated temperature.. On this problem, the results of Japanese research(3) show that use of chrome-silicon steel as a prestressing tendon materials is a practical method to reduce the relaxation of stress in tendons at elevated temperature.

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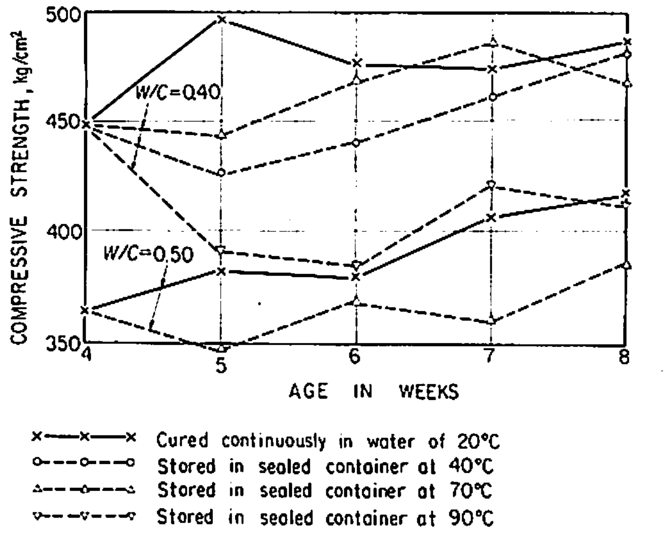

Fig. 1 Compressive strength of concrete stored in sealed containers at elevated temperatures after curing in water of 20°c for 28 days

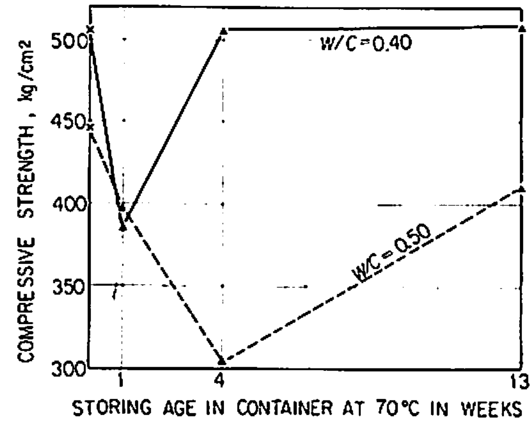

Fig. 2 Compressive strength of concrete stored in sealed container at 70°c after curing in water of 20°c for 300 days

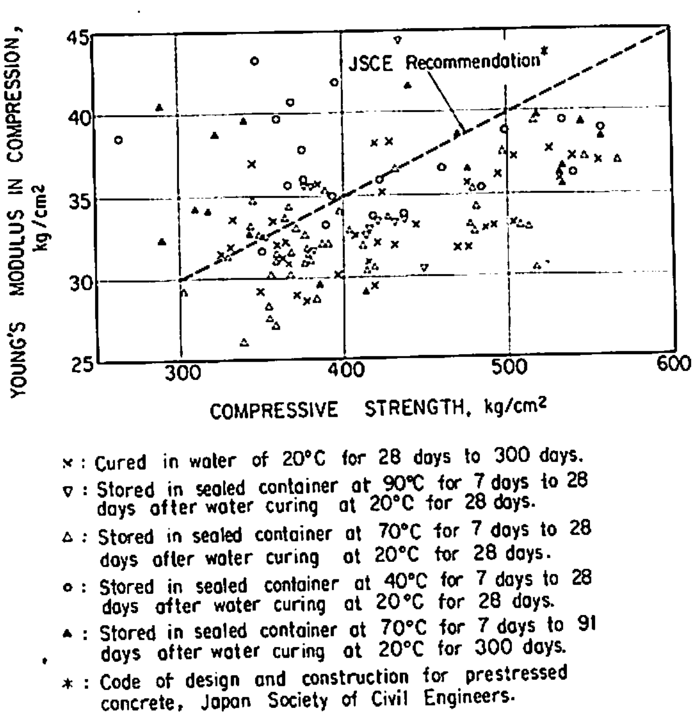

Fig. 3 Relation between compressive strength and Young's modulus (Young's modulus is culculated at stress of one third of compressive strength)

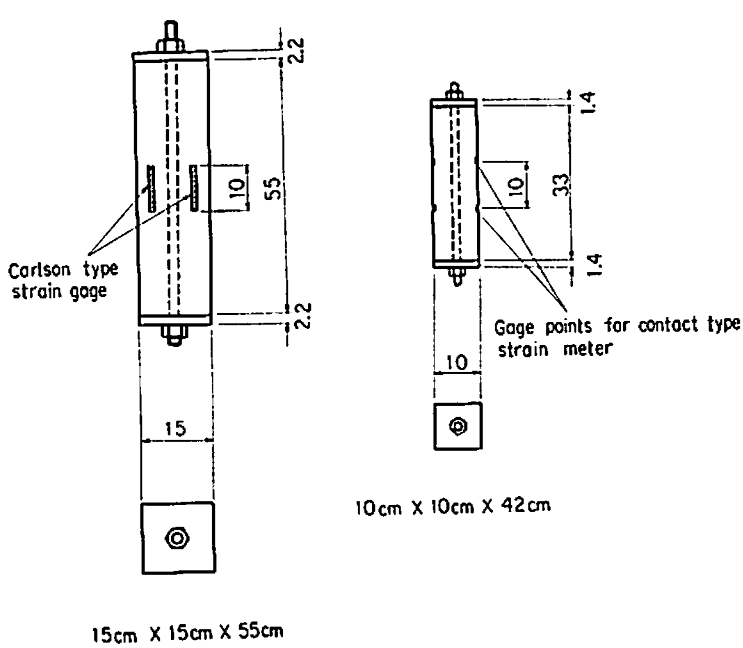

Fig. 4 Specimens for creep tests

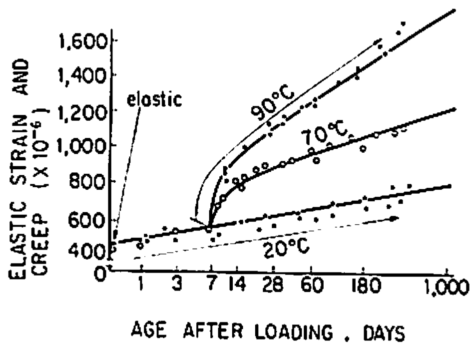

Fig. 5 Creep of sealed concrete exposed to elevated temperatures

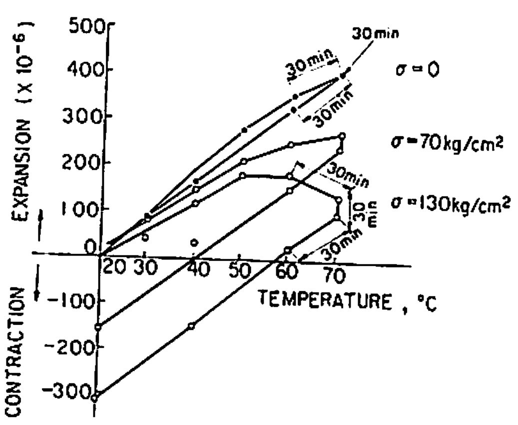

Fig. 6 Strains in concrete put into hot water

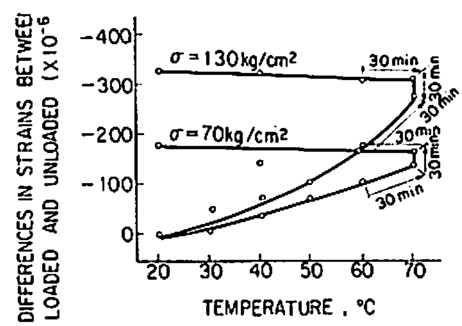

Fig. 7 Remained contractive strains subtracted unstressed strains from stressed ones.

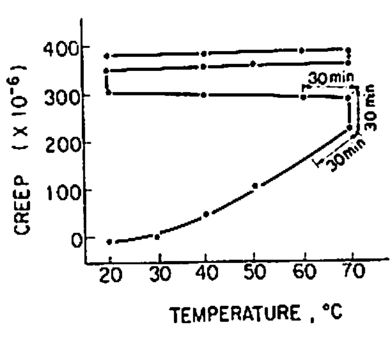

Fig. 8 Creep of concrete in water exposed to cycles of temperature changes

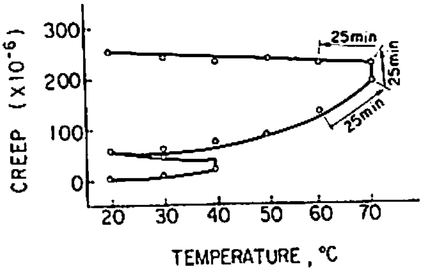

Fig. 9 Creep of concrete in water exposed to cycles of temperature changes with different maximum temperatures

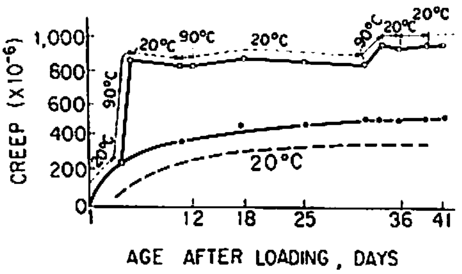

Fig. 10 Creep of concrete in air exposed to elevated temperatures

Table 1 Mixes for experiment of strength, Young's modulus and Poisson's ratio

Mix	A	B
Max. size of coarse aggregate (mm)	40	40
Water cement ratio	0.40	0.50
Sand percentage	31.5	34
Water content (kg/m^3)	137	135.5
Cement content* (kg/m^3)	342.5	271
Air content (%)	2.5	2.5
Slump (cm)	5	5
Required compressive strength (kg/cm^2)	450	365

* Normal portland cement

Table 2 Properties of concrete used in creep tests

Cement	Normal	High early strength
Max. size of coarse aggregate (mm)	25	12.5
Water cement ratio	0.40	0.45
Sand percentage	36.5	44
Water content (kg/m^3)	151	151
Cement content (kg/m^3)	377	335
Air content (%)	3.8	3.0
Slump (cm)	8	3
Age at loading (days)	28	14
Compressive strength (kg/cm^2)	459	499
Size of specimens for creep test (cm)	15x15x55	10x10x42