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THE MECHANISMS OF DRYING SHRINKAGE AND CREEP OF CONCRETE

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SYNOPSIS

The objective of the present study is to clarify the mechanisms of drying shrinkage and creep of concrete. The characteristics of drying shrinkage and creep of concretes of various water cement ratios in a wide range from 0.19 to 0.63 are experimentally obtained. The amounts of drying shrinkage and creep of concretes cured in three kinds of conditions at the time of manufacpre and measured in air at 20°C and 50% R.H., and some specimens cured in water at 20 C for 1,250 days. Within the scope of this research, the following conclusions may be drawn : (1) Drying shrinkage is mainly caused by the capillary tension occuring in the gel pores with the radii from 7.5 to 15Å. (2) The total strains of elastic and creep strain due to the stress of capillary tension are apploximately equal to the values of drying shrinkage measured. (3) Drying creep is caused by the stress due to the difference of capillary tension between specimens for both tests. (4) Basic creep is mostly occupied by the delayed elastic deformation, therefore, the mechanism of basic creep can be explained by the visco-elastic theory.

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1. INTRODUCTION

This study discusses the mechanisms of drying shrinkage and creep based on the paper "Properties of drying shrinkage and creep of high strength concrete " previously published (1). Various theories on drying shrinkage and creep mechanisms have been proposed. With regard to drying shrinkage, there are the capillary tension theory, surface adsorption theory and interlayer water theory, while regarding creep, there are the visco-elastic theory, seepage theory and viscous flow theory (2),(3). However, it is said that the individual mechanisms cannot be explained by any single one of the theories (2),(3). The range of relative humidity which plays an important role in drying shrinkage of the ordinary concrete structure is from about 40% to 100%. With regard to the drying shrinkage in this range of relative humidity, the capillary tension theory is dominant. In this theory, it is explained that drying shrinkage is caused by the capillary tension occuring in the moisture existing in the pores in cement gel. This is also recognized at the congress of RILEM in 1968 (3),(4).

It is considered that the stress due to capillary tension in concrete is governed by the pore volume and pore size distribution, however, experimental estimations of the stresses due to capillary tension and the relationship between the stress and the mechanism of drying shrinkage are not sufficientry studied. It is not examined whether the capillary tension theory can be also applied to high strength concrete.

With regard to the mechanism of creep of concrete, it is said that the greater part of the mechanism can be explained by the visco-elastic theory. In this theory, it is considered that cement paste is a composite material which consists of the frame structure and visco liquid filling the pores of cement gel, and that creep is the elastic deformation of the former delayed by the resistance due to viscosity of the latter. Therefore, it is considered that the pore structures in cement paste, manely, pore volume and pore size distribution are closely related to not only drying shrinkage but also creep of concrete. Studies on the creep of concretes widely varying the strength and pore structures are very few. Creep of concrete under drying conditions is hitherto calculated as the difference between the total time-dependent deformation of the loaded specimen and the shrinkage of a similar unloaded specimen cured in the same conditions for the same period. This is a convenient simplification, but drying shrinkage and creep are not independent phenomena to which the principle of superposition can be applied. Drying creep is calculated as the difference between the creep in air and the creep in water, namely, basic creep. In the study on the mechanism of drying creep, it is only said that drying creep is caused by the behavior of moisture in the cement gel (5),(6). Essential studies of the mechanism of drying creep have not been made yet. Therefore, the objective of the present study was to clarify the mechanisms of drying shrinkage and creep of concrete. The characteristics of drying shrinkage and creep of concretes was studied varying water cement ratios in a wide range from 0.19 to 0.63, curing in three kinds of conditions, i.e. standard curing, steam curing and autoclave curing at the time of manufacture, and varying the pore volume and pore-sized distribution of cement paste.

2. OUTLINE OF TESTS

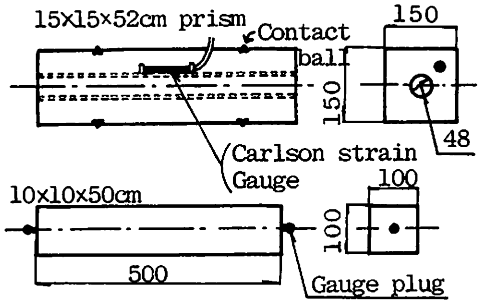
The mix proportions for the experiment shown in Table 1 was used in order to vary pore volume and pore-size distribution in cement paste of concrete in a wide range. As shown in Table 1, there were 14 mix proportions with water-cement ratios varied in a wide range between 0.19 and 0.63 and with unit cement paste volume between 0.236 and 0.423 m^3/m^3 to obtain compressive strengths between 35 and 110MPa. The materials used for the experiments were high-early-strength portland cement, Fuji River sand, Nishitama crushed rock and a kind of

Table 1. Mix proportion of concrete

Water content (kg/m³)	Method of curing	Cement content (kg/m³)					
		300	500	700	300	500	700
		Water-cement ratio (%)			Unit cement paste volume (m³/m³)		
130	N	43.3	26.0	18.6	0.236	0.299	0.363
150	N	50.0	30.0	21.4	0.256	0.319	0.383
170	N,S,AC	56.7	34.0	24.3	0.276	0.339	0.403
190	N	63.3	38.0	27.1	0.296	0.359	0.423
210	N	—	42.0	—	—	0.376	—
230	N,S,AC	—	46.0	—	—	0.399	—

N:Standard curing, S:Steam curing, AC:autoclave c.

(a) Specimen for drying shrinkage test



(b) Specimen for creep test

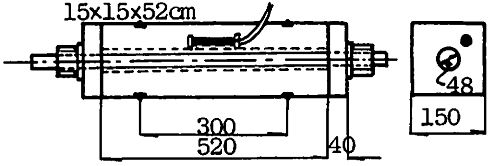


Fig 1. Specimens for drying shrinkage and creep tests

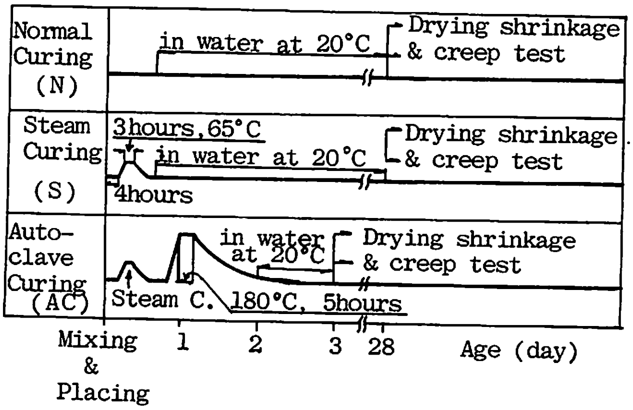


Fig 2. Methods of manufacturing specimens

superplasticizer of napthalene sulfonate type. Fig. 1 shows the specimens for drying shrinkage and creep tests. Drying shrinkage specimens were two kinds of prisms of 15×15×52cm and 10×10×50cm. In order to provide identical drying conditions for the specimens for creep tests, a sheath of Φ48mm was arranged at the centroid, and coats were applied to the two end surfaces to prevent evaporation of moisture, and drying was allowed from the other four surfaces. In case of the 10×10×50cm specimens, drying was permitted from all six surfases. The specimens for creep tests were prisms of 15×15×52cm and were prestressed by steel rods. Retensioning to compensate the reduction of prestress due to the shrinkage of concrete was not performed, and results were adjusted by corrective calculations.

As shown in Fig. 2, these specimens were cured in three kinds of conditions i.e. standard curing (in water at 20°C), steam curing (precuring time 4 hr., rate of temperature rise 20°C/hr., 65°C maintained 3 hr. followed by natural cooling) and autoclave curing (after steam curing, rate of temperature rise 60°C/hr., maintained at 180°C for 5 hr. followed by natural cooling). Reference lengths were measured after standard curing up to the age of 28 days in cases of standard curing and steam curing, and after standard curing up to the age of 3 days in case of autoclave curing, upon which drying shrinkage and creep tests were started. The specimens for the drying shrinkage test were left indoors at the temperature of 20°C and the relative humidity of 50%. The creep test specimens were left in air of 20°C and 50% R.H. or in water of 20°C after measuring reference lengths. The respective length changes were measured for 1,250 days. In case of drying shrinkage specimens of 10×10×50cm, weight mesurements were made at the the same time. After drying for 1,250 days, the quantity of remaining water and length changes of the specimens before and after oven drying were measured.

The pore-size distributions of mortar obtained from the concrete were measured by the mercury porosimetry method.

3. MECHANISM OF DRYING SHRINKAGE IN CONCRETE

According to the paper previously published (1), it is considered that drying shrinkage of concrete is affected not only by the unit cement paste volume but also the concentration of cement paste, namely, water-cement ratio(W/C), and not only by the pore volume but also the pore-size distribution. Therefore, the stresses due to capillary tensions occuring in pores of the specimens are estimated, and the adaptation of the capillary tension theory to the mechanism of drying shrinkage is studied.

3.1 The stress due to capillary tension

The stresses due to capillary tension are estimated by following methods, that is, at first, the pore volume and pore-size distribution are measured by mercury porosimetry method, and the pore volumes which can not be measured by this method are estimated by the measurement of evaporable water and remaining water after drying for 1,250 days. The ranges of pore-size measured by the mercury porosimetry method, as shown in Fig.3, are from about 40 Å to 30,000 Å (=3μ) in radius of pores. Therefore, gel pores which is said to be with the diameter of 15~30 Å (namely, pore radius of 7.5~15 Å), shown in Fig. 4, capillary pores of radius larger than 3μ and bubbles of diameter from 0.1 ~1.0 mm are not measured. Accordingly, the pore volumes which can not be measured by the mercury porosimetry are estimated as follows. It is assumed that the structure of hydrated cement is like the model as shown in Fig. 4 or Fig.5 (7),(8). If such porous material is dried, menisci are formed by water existing in pores as shown in Fig. 6. When water surface retreats to the smaller capillary tubes, the curvature of meniscus is greter. With regard to

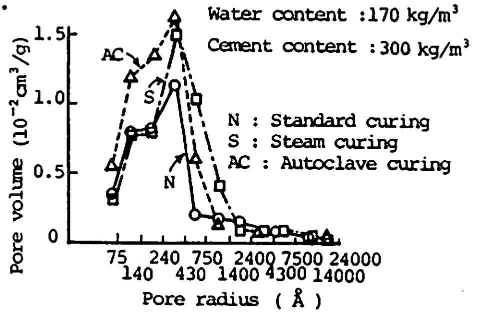


Fig 3. Pore-size distribution

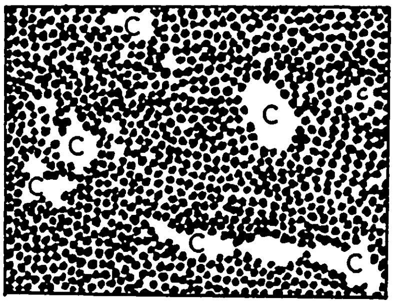


Fig 4. Simplified model of paste structure (Solid dots represent gel particles ; interstitial spaces are gel pores ; spaces such as those marked C are capillary cavities.

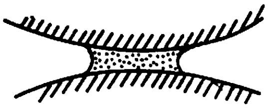


Fig 6. Meniscus in a pore

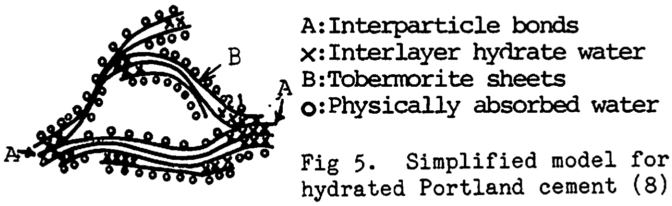


Fig 5. Simplified model for hydrated Portland cement (8)

the evaporation of moisture, the relation between the radius of curvature of meniscus and the relative humidity is expressed by the following equation.

$$\ln\frac{P}{P_0} = -\frac{2\gamma M}{RT\rho}\,\frac{1}{r} \qquad \text{----------(2.1)}$$

where, ln:natural logarithms, P:existing vapour pressure, P_0:saturated vapour pressure at temperature T, P/P_0:relative humidity, γ:surface tension (72.75×10^{-5} N/cm at 20°C), M:molecular weight of water (18.02g/mol), R:gas constant (8.315×10^7erg/°K·mol), T:absolute temperature (°K), ρ:density of water (g/cm^3), r:radius of curvature of a water surface (cm).

The relations between the relative humidities P/Po and the radii of capillary tubes which are calculated by equation (2.1) are shown in Table 2. According to this table, as it is considered that the moisture existing in the pores of radius larger than 16 Å is evaporated at 20°C and 50% R.H., it is assummed that the total evaporable water at the age of 1.250 days of drying is the moisture evaporated from the pore of radius larger than 16 Å under this drying condition. It is considered that the remaining water obtained by oven drying the drying shrinkage specimens after drying for 1,250 days is the gel water existing in the pores of radii from 7.5 Å to 15 Å.

Fig. 7 shows the relation between the evaporable water or remaining water and the compressive strength of concrete. According to this figure, in case of high strength concrete, the evaporable water is small and the remaining water is larger than that of normal concrete, although unit cement paste volume is larger than that of normal strength concrete. This shows that the compressive strength of concrete is higher, the percentage of fine pores is increased.

The stresses due to capillary tension in each radius of pores are calculated by the equation (2.2), and these values are shown in Table 3.

$$\sigma_{cp} = \frac{v}{\rho}\times\Delta P \qquad \text{----------(2.2)}$$

where , δ_{cp}:the stress in concrete due to capillary tension in the pores of a certain range of radius, (MPa), v:pore volume in the pore of a certain range of radius (measured by mercury porosimetry, evaporable water and remaining water after drying for long time)(m^3), ρ:unit cement paste volume (m^3), Δp:capillary tension in the average pore of a certain range of radius (Δp is the pressure difference due to capillarity).

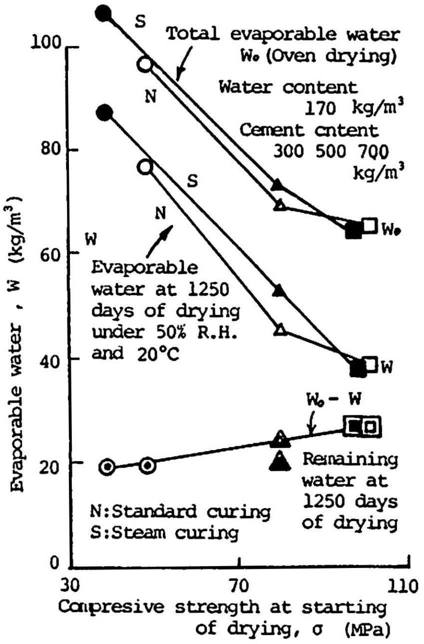


Fig 7. Relationship between W and σc

Δp is given by the following equation.

$$\Delta p = \gamma\left(\frac{1}{r_1}+\frac{1}{r_2}\right)$$

where, r_1 and r_2 are the principal radii of curvature of the water surface. If the surface of the water is spherical,

$$\Delta p = \frac{2\gamma}{r} \qquad \text{----------(2.3)}$$

Hence, from Eq. (2.1) $\Delta p = \frac{2\gamma}{r} = -\frac{RT\rho}{M}\ln\frac{P}{P_0}$ ----------(2.4)

Table 2. shows the relation between the capillary tension and the relative humidity or radius of capillary tubes (2).

Table 2. Relation among relative humidities, radii of pores and capillary tensions

P/Po	1	0.98	0.95	0.90	0.8	0.7	0.6	0.5	0.4	0.3	0.11
r (Å)	∞	550	217	105	50	31	22	16	12	9	5
-p (MPa)	0	2.5	6.5	13.3	27.9	45.1	63.4	87.2	116.6	154.8	279.3

Table 3. shows the stress due to capillary tension calculated from Eq.(2.2), and the evaporable water and remaining water shown in Fig 7. According to Table 3, the stresses due to capillary tension occuring in the gel pores of radii of 7.5~15 Å are 3.7~11.1MPa. These values are considerably larger than those of the pores of 40 Å~3μ, namely, 0.1~0.9MPa and the pores larger than in 3μ radius, namely, 0 MPa . Furthermore, the streses due to capillary tension in the pores less than 15 Å in radius continue during the drying of long time at 20°C and 50% R.H.. Therefore, it is concluded that the most part of drying shrinkage is caused by the stresses due to capillary tension occuring in the pores of 7.5~15 Å.

Table 3. Stress due to capillary tension, evaporable water and remaining water

Cement content (kg/m³)	Method of curing	Stress due to capillary tension (MPa) ( ): Evaporable or remaining water (kg/m³) Pore radius >3μ	 40Å~3μ	 7.5~15Å	Total evaporable water in cement paste (kg/m³)
300	N	0 (25.9)	0.6 (24.0)	11.1 (19.7)	68.9
	S	0 (30.1)	0.6 (30.6)	10.9 (19.3)	80.0
	AC	0 (31.1)	0.9 (27.3)	5.9 (10.5)	68.9
500	N	0 (6.4)	0.1 (15.4)	10.9 (23.7)	45.5
	S	0 (16.2)	0.4 (13.4)	9.0 (19.7)	49.3
	AC	0 (--)	- (--)	6.5 (14.1)	46.3
700		0 (8.4)	0.1 (9.6)	10.3 (26.7)	44.7
	S	0 (--)	0.1 (24.4)	10.1 (26.3)	43.6
	AC	0 (--)	- (--)	3.7 (9.3)	51.6

The stresses due to capilary tension of autoclave cured specimens (AC) are smaller than those of standard cured or steam cured ones, and these values are 1/2~1/3 as much as those of standard cured specimens. This proves that the drying shrinkage per unit cement paste volume (ε_s/ρ) of autoclave cured concrete is approximately 1/2 as much as that of standard cured concrete as shown in previous paper (1).

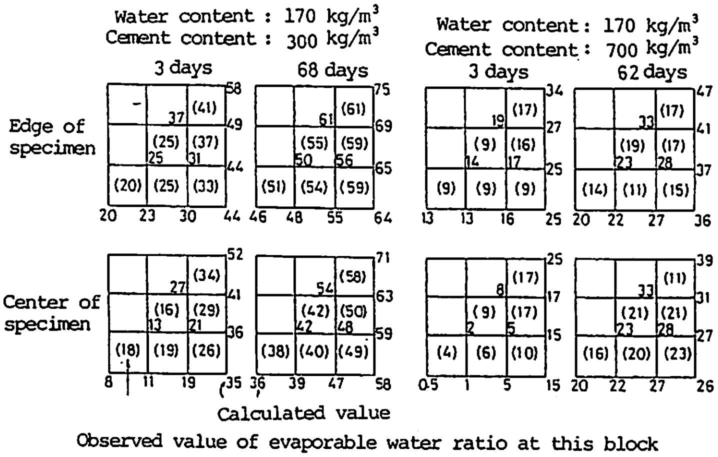


Fig 8. Evaporable water ratio of concrete specimens

2.2 Change of stress due to capillary tension during drying with time

The stresses due to capillary tension shown in Table 3 are the final values after drying for long time. Therefore, the changes of stress due to capillary tension with time are calculated by following methods. At first, the quantities of evaporable water are mesured by oven dried pieces at the end and the center of broken specimens at several drying times. The distributions of the ratios of evaporable water at a certain drying time to total evaporable water obtained by oven drying at the end and center of the specimens are shown in Fig. 8.

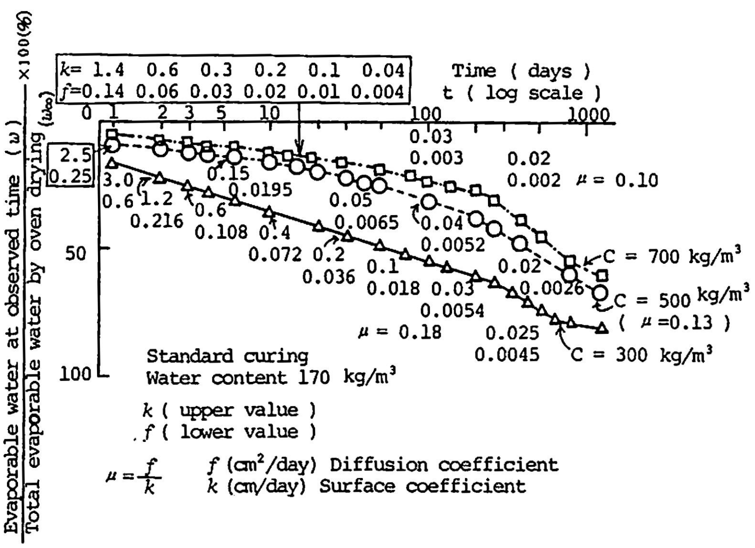


Fig 9. Relation between w and t, and change of diffusion coefficient and surface coefficient

Next, the distributions of the ratios of evaporable water in the sections of concrete specimens are calculated by using the three-demensional diffusion equation as shown in Eq. (2.5).

$$\frac{\partial w}{\partial t} = k\left(\frac{\partial w}{\partial x^2} + \frac{\partial w}{\partial y^2} + \frac{\partial w}{\partial z^2}\right) \text{-----(2.5)}$$

where,

w:evaporable water content

k:diffusion coefficient

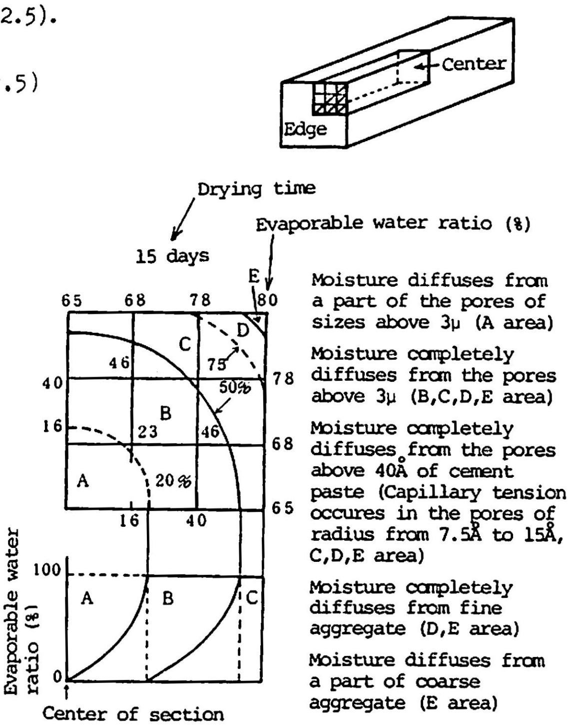


Fig 10. Region in which capillary tension occurs in the pores 7.5 to 15 Å

The solution to this equation is calculated by using the finite element method. The calculation results are shown in Fig 8. and Fig 9. In Fig. 9. curved lines tie between observed volues, and calculated values are plotted on the lines in relation to evaporable water and drying time. In order to match the calculated values with the observed values of evaporable water, diffusion coefficients (k) and surface coefficients (f) are decreased exponentially with the decrease of moisture content of the specimens. The values of k and f are properly selected. Therefore, there are no physical meaning in the values. But, the distributions of evaporable water calculated by using such k and f approximately agree with the observed values in case of normal strength concretes as shown in Fig. 8.

Therefore, the stresses due to capillary tension are calculated by using the values of evaporable water obtained from the diffusion equation at each day of drying. Fig. 10 shows the region in which capillary tension in the pores with the radius of 7.5 Å to 15 Å occurs. The boundary lines of B and C regions shows the quantity of evaporable water (w/w_∞) completely diffused from the pores with the radii of above 40 Å, where, w_∞ is the total quantity of evaporable water obtained by oven drying and w is the quantity of evaporable water at a certain drying time. In case of line B-C, w shows the evaporable water of the pores with the radii of above 40 Å in Table 3.

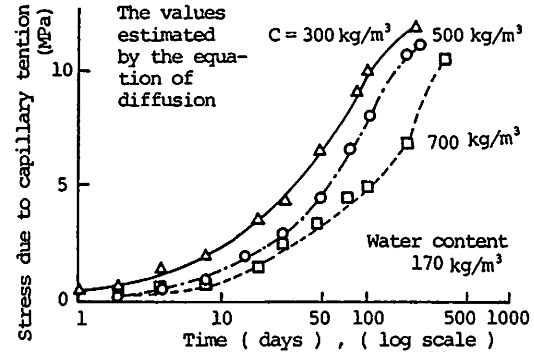


Fig 11. Development of capillary tension with drying

Therefore, under the assumption that the capillary tensions occur in the pores with the radius of 7.5 to 15 Å in the regions of C, D and E, the stsresses due to capillary tension are calculated with the drying time. The results of the above calculation are shown in Fig. 11.

2.3 Relation between drying shrinkage and stress due to capillary tension

L'Hermite offered the following equation on the length change of porous materials due to capillary tension.

$$\frac{\Delta L}{L} = \gamma\left(\frac{1}{r_1} + \frac{1}{r_2}\right)\frac{e}{v}\,x \quad \text{----------(2.6)}$$

where,

L:length of a body, ΔL:the amount of deformation,$\Delta L/L$:strain, e:volumes of liquid, V:total volume of porous body, X:contraction factor, $\gamma(1/r_1 + 1/r_2)$:capillaly tension.

In drying shrinkage of concrete, as the capillary tensions gradually increase with drying, and applied for a long time, concrete is considered to creep. Therefore, assuming that the drying shrinkage is the sum of elastic and creep deformations due to capillary tension, the relation between the streses and the sum of their deformations is expressed by Eq. (2.7).

$$\varepsilon_{st} = \frac{\sigma_t}{E_c} + \Sigma\sigma_t(\varepsilon_{spt} - \varepsilon_{spt-1}) \quad \text{----------(2.7)}$$

where,

σ_t:the stress due to capillary tension at a certain drying time, (MPa)(refer Fig.11), E_c:Young's modulus of concrete,(Mpa) ε_{spt}, ε_{spt-1}:specific creeps of concrete cured in water at the age of t days

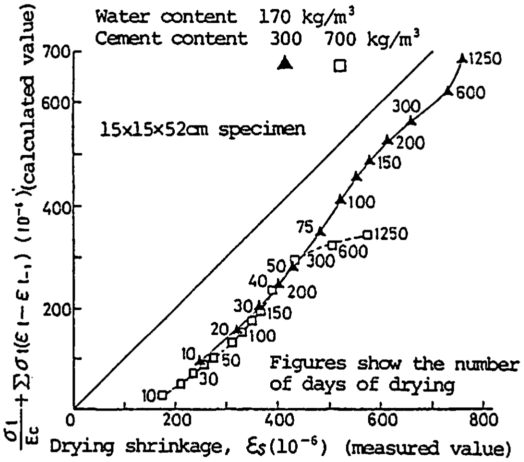


Fig 12. Relation between measured values and calculated values of drying shrinkage

and t-1 days at the loading,(10^{-6}/Mpa) (15×15×52cm specimen), ε_{st}:drying shrinkage calculated by Eq. (2.7)

The relation between the values calculated by Eq. (2.7) and the observed values of strains due to drying shrinkage are shown in Fig. 12. In this figure, the calculated values do not agree with the observed values well at the initial stages of drying, but do well as the drying time goes on. Such a tendency is due to the following reason. As shown in Fig. 8, the values of evaporable water calculated by the diffusion equation are smaller at the initial stages of drying than those observed. In Eq. (2.7), it is assumed that Young's modulus is constant for all the time of drying, and that the stress due to capillary tension is uniformly distributed in all the parts of the sections. But, as different intensity of capillary tensions actually occur between the surface parts and inner parts of the same section, the tensile stresses in the surface parts and the compressive streses in the inner parts of section should be totally considered. Although the above problems are involved in Eq. (2.7), it is said that the values calculated by Eq. (2.7) agree very well with observed values of drying shrinkage as shown in Fig. 12. This shows the reasonableness of considerations that the drying shrinkage is the sum of elastic deformations and creep deformations due to capillary tension. It is recognized that the length change between before and after oven drying for the specimens dried by the oven after drying for a long time is expansion in case of high strength concretes, but contraction with the decrease of compressive strength of concretes, as shown in Fig. 13. Up to this time, although, it may be said that the capillary tension theory for the mechanism of drying shrinkage is strong among many theories, but the length change between before and after oven drying are not explained by the capillary tension theory. However, in this study, it is first recognized that the expansive deformation occur by the extinction of capillary tension due to oven drying in case of high strength concrete. This is considered to be a very strong data when the mechanism of drying shrinkage is studied by using the capillary tension theory.

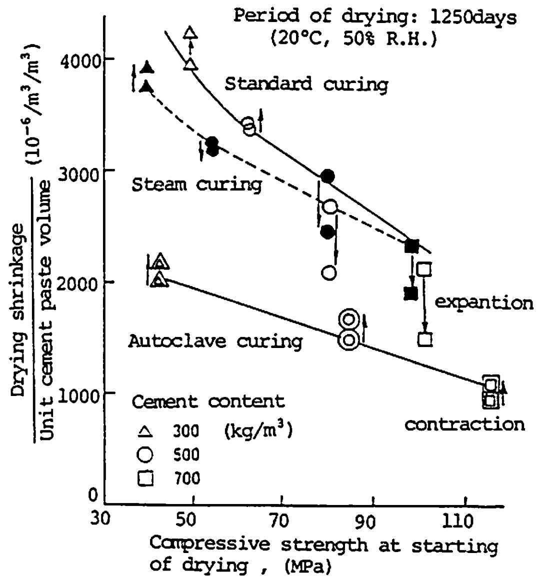


Fig 13. Length change of specimen after oven dry

3. MECHANISM OF CREEP IN HIGH-STRENGTH CONCRETE

3.1 Investigations on the mechanism of drying creep

The relation between the values (ε_{sp}/ρ) of specific creep divided by the unit cement paste volume and the loading time is shownin Fig. 14, and the relation between ε_{sp}/ρ and the compressive strength of concrete at loading is shown in Fig. 15. The ratios ε_{sp}/ρ of concretes with the cement content of 700kg/m^3 and the compressive strength of above 100MPa cured in air are smaller than that of concrete cured in water after a long load time. This fact is quite different from the normal strength concrete. The drying creep, namely, the difference between creeps of concretes cured in air and in water, are smaller with the increase of compresive strength in the range of strength less than

100MPa. These facts shows that the total contractions of loaded specimens in air are not simple superposition of creep strains and drying shrinkage strains. It is considered that this total strains are affected by stresses due to capillary tensions. Therefore, at first, drying shrinkage strains are divided into elastic strain and creep strain due to capillary tensions, and it is assumed that the strains of remainder subtracted the elastic strains due to capillary tensions from the total contractions of the creep specimen are the creep strains which are the sum of the stresses due to capillary tensions and loads. According to this assumption, the specific creep considering capillary tensions in case of concretes stored in air is derived as Eq. (3.1).

$$\varepsilon_{sp} = \Sigma \frac{\{(\varepsilon_{cj} - \sigma_{sj}/E_c) - (\varepsilon_{ci} - \sigma_{si}/E_c)\}}{1/2(\sigma_i + \sigma_j)} \text{ ----------(3.1)}$$

$$\sigma_i = \sigma_{ci} + \sigma_{si}, \qquad \sigma_j = \sigma_{cj} + \sigma_{sj}$$

where,

ε_{sp}: specific creep considering the stress due to capillary tensions (MPa)

$\varepsilon_{ci}, \varepsilon_{cj}$: the total contraction of creep specimens after i days and j days under loading (10^{-6})

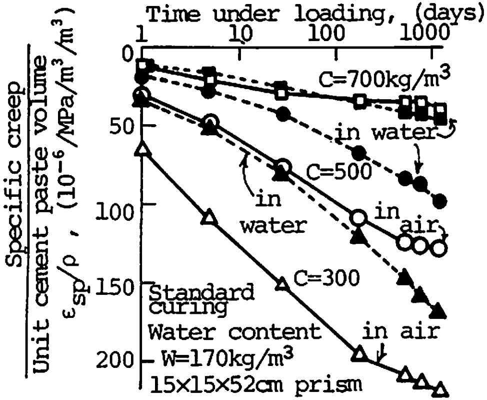


Fig 14. Relation between ε_{sp}/ρ and log t.

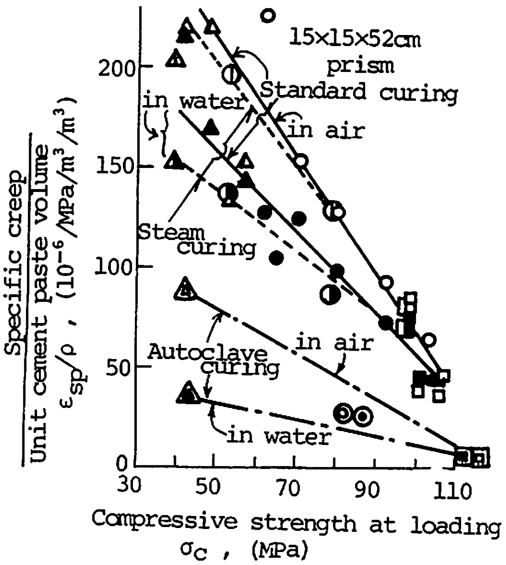


Fig 15. Relation between ε_{sp}/ρ and σ_c

σ_{ci}, σ_{cj} : stress due to load after i days and j days of loading (MPa)

σ_{si}, σ_{sj} : stress due to capillary tension after i days and j days under drying, (MPa)

E_c : Young's modulus of concrete, (MPa)

σ_{si}/E_c : elastic strain due to capillary tension after i days under drying.

The results of the values of specific creep calculated by substituting the stresses due to capillary tensions calculated by the diffusion equation shown in Fig. 11 into Eq. (3.1) are larger than those of the specific creep of dry-stored specimens obtained by the ordinary method, namely, by substracting the strains of drying shrinkage from the total contractions of creep specimens. Particularbly, at the initial stages of loading, the calculated values of specific creep are extremely larger than observed values. This is due to the reasons that as seen in Fig. 12, the stresses due to capillary tensions is not grasped well at the initial stages of loading, and the stresses due to capillary tensions calculated are smaller than observed values. Therefore, the stresses due to capillary tensions, in which the values of drying shrinkage calculated by Eq. (2.7) agree with observed values. In Fig. 12, the calculated values plotted on the straight line of 45° are obtained by the reverse calculation of Eq. (2.7) The observed values of the concrete stored in water at each stage of loading time are used as the values of specific creep in Eq. (2.7) The results of calculations are shown in Fig. 16. According to Fig. 16 the stresses due to capillary tensions are from two to three times as large as those calculated by the diffusion equation up to the initial month of drying.

Figs. 17 and 18 show the relation between the specific creep of concretes with the water content of 170 kg/m^3 and the cement content of 500 and 700 kg/m^3 respectively and the loading time, in case of the ordinary method (the total contraction of creep specimen — drying shrinkage) and the method taking capillary tensions (Eq.(3.1)) into account. According to these figures, the specific creeps taking capillary tensions into account are smaller than those of those of the observed values by the ordinary method for basic creep, in case of the cement content of 300 and 500 kg/m^3. While, in case of the cement content 700kg/m^3, although the specific creep in air by the ordinary method are smaller than that of basic creep. The specific creep where capillary tensions are taken into account nearly equal to basic creep, and the variation of specific creep due to stress-strength ratios are also diminished. According to such results, it is considered that the streses due to capillary tensions occuring in creep specimens are different from those of drying shrinkage specimens in some cases.

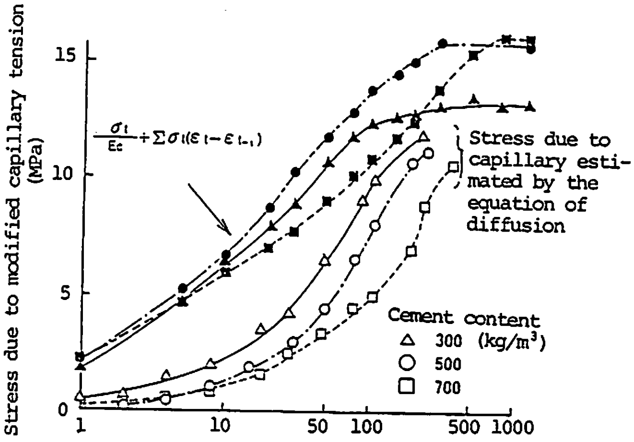


Fig 16. Stress due to capillary tension estimated by strains of drying shrinkage

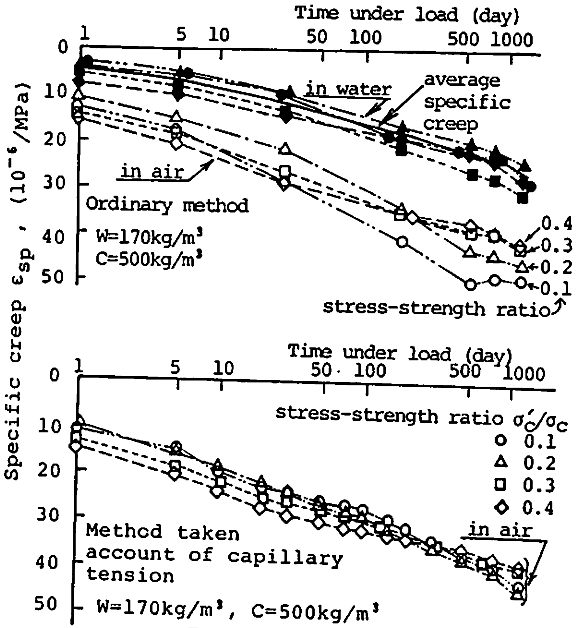


Fig 17. Specific creep

Fig. 19 shows the relations between the drying time and the evaporable water in cement paste and mortar of the creep and drying shrinkage specimens. In case of cement paste, the differences of evaporable water between the creep specimen and the drying shrinkage specimen at the same drying time are extremely large in case of the water-cement ratio(W/C) of 50% and are scarcely recognized in case of W/C=30%. Such a tendency is also recognized in case of mortar, although the differences are smaller than those in case of cement paste. In case of concrete specimens, as the volume of cement past occupying in concrete is small, the difference cannot be recognized in all the concrete mixes. The behavior to evaporable water in cement paste in concrete is considered to be similar to that of cement paste specimens. According to the above, it is considered that the developments of capillary tensions of creep specimens are earlier than that of drying specimens in case of the normal strength concrete, while, in case of high strength concrete, the developments of capillary tensions are almost same in the both specimens. Therefore, the stresses due to capillary tensions are correctly calculated. It is said that the specific creeps cured in air calculated by Eq. (3.1) agree with the specific creep cured in water, i.e. the basic specific creep regardless of concrete strength. It seems that the ordinary method of calculation for the creep strains can be expressed by Eq.(3.2).

$$\varepsilon_0 - \varepsilon_s = \varepsilon_{c(air)} \quad \text{-----}(3.2)$$
$$\varepsilon_0 = \varepsilon_{sp(water)} \cdot (\sigma_0 + \sigma_1) + \sigma_1 / E_c$$
$$\varepsilon_s = \varepsilon_{sp(water)} \cdot \sigma_2 + \sigma_2 / E_c$$

where, ε_0: total contraction of creep specimen (10^{-6}), ε_s: drying shrinkage strain (10^{-6}), $\varepsilon_{c(air)}$: creep strain in air (10^{-6}), $\varepsilon_{sp(water)}$:basic specific creep (in water)(10^{-6}/MPa), σ_0: loading stress (MPa), σ_1: stress due to capillary tensions occured in creep specimen (MPa), σ_2:stresses stresses due to capillary tensions occured in drying shrinkage specimen (MPa). From this equation, it is said that, the same values as basic creep are obtained by Eq. (3.1) or (3.2) in case of the specific creep of high-strength concrete stored in air. In case of normal strength concrete, as the capilly tensions of creep specimens are larger than that of drying shrinkage specimens, drying creep arises.

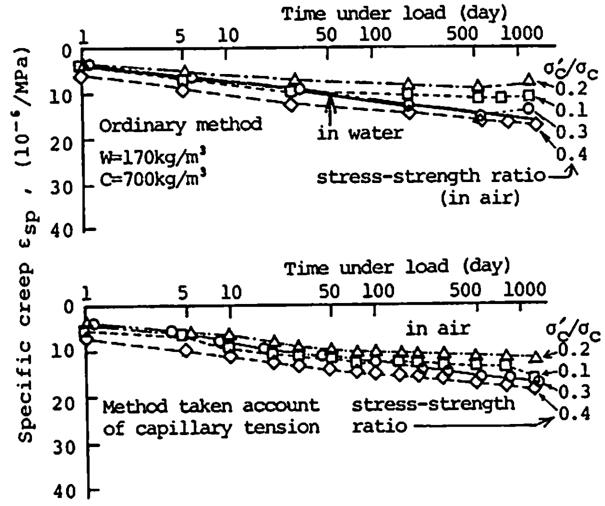


Fig 18. Specific creep (Specific creep taken account of capillary tension is compared with that of ordinary method) (W=170kg/m³, C=700kg/m³)

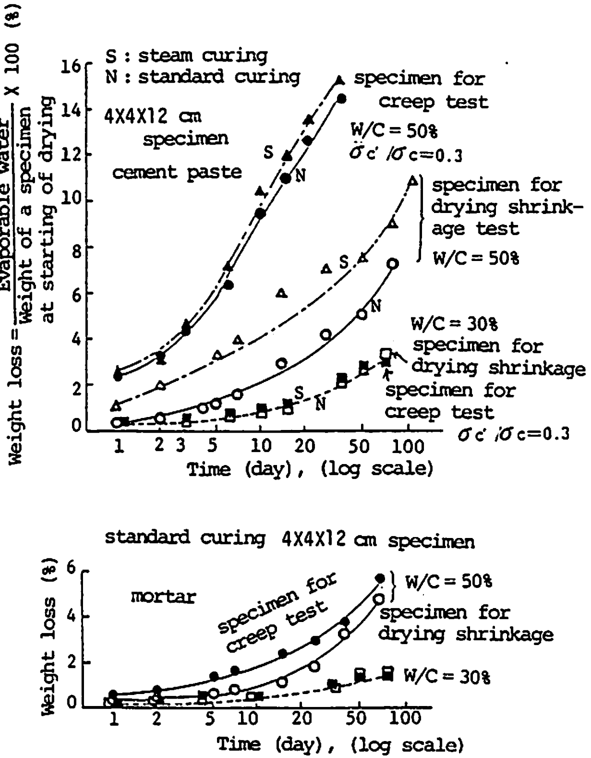
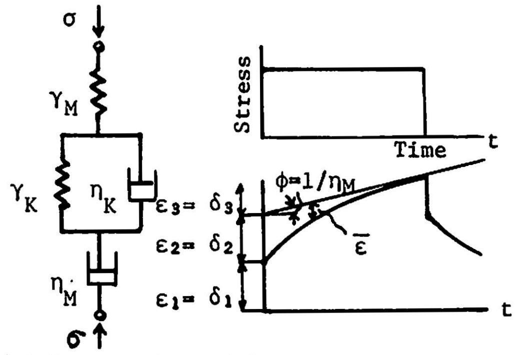


Fig 19. Weight los of specimen for drying shrinkage and creep test

3.2 Rheological study on the creep mechanism of concretes

In this section, the influences of the strength of concrete and curing method on the development of creep with loading time are discussed by using a rheological model. It is considered that the rheological analysis for creep is very effective in discussing. It is said that both of the elastic and viscous deformation are caused in stressed concrete. In the visco-elastic theory for the mechanism of creep, it is said that cement paste is a composite material which consists of the elastic frame structure and viscous liquid filling the pores of cement gel, and the deformation of concrete can be expressed by a Burgers body (model) as one of basic built-up rheological models for creep. The deformational response of Burgers model is a combination of Kelvin and Maxwell models as shown in Fig. 20. Thus, when a sustained load is applied to a Burgers model, instantaneous deformation take place, followed by time-dependent deformation increasing at a decreasing rate and tending asymptotically to an inclined straight line on a deformation-time diagram (Fig. 20). Thus, the behaviour of a Burgers model is qualitatively similar to that of concrete. Therefore, the observed values of creep deformations may be expressed by the equation for Burgers model, and the rheological coefficients of Maxwell model (γ_M, η_M) and Kelvin model (γ_K, η_K) are calculated. According to Fig. 21, the values of γ_M and γ_K is are of the order of 10^4MPa, and the value of η_M is of the order of 10^{19}Pa·S, and η_K is of the order of 10^{17}Pa S. These values agree apploximately with the Oogishi's experimental results (9), and it seems that these values are adequate. The compliance of spring in Maxwell model γ_M is related to an instantaneous deformation δ_1 (reffer Fig. 20), and γ_M is not related to the creep after loading. The quantity of creep deformations is expressed by $\delta_2 + \delta_3$ as shown in Fig. 20.



(a) Burgers body (b) Creep curve for Burgers body

Fig 20. Burgers body

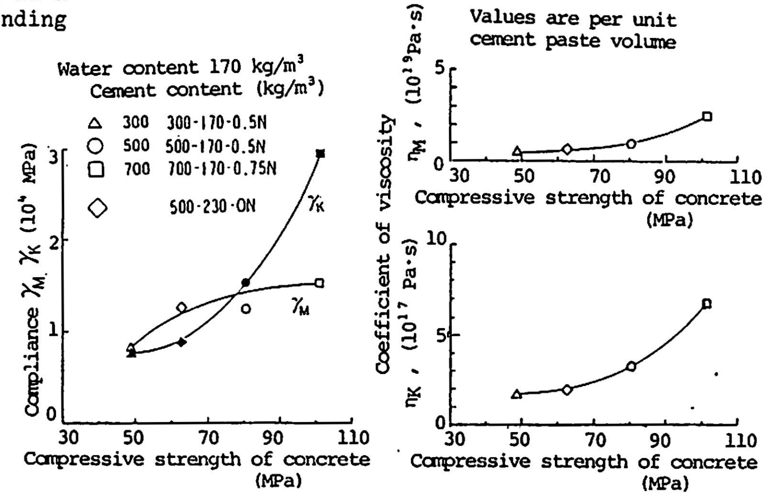


Fig 21. Relation between rheological coefficients and compressive strength of concrete (standard curing)

The values of η_M which is related to permanent deformation is as large as 100 times as much as η_K. Therefore, it can be said that the greater part of the creep deformation occurs in the component of Kelvin element i.e. the part of δ_2. According to the above, it can be said that the mechanism of creep can be approximately explained by the visco-elastic theory besides the parmanent deformation. In case of the creep of concrete, the phenomenon of delayed elasticity is very strong. The values of η_K and γ_K of high strength concrete are about two times and four times as much as that of normal strength concrete, respectively. The ratios of γ_K of high strength concrete to that of normal strength concrete agree completely with the ratios of values of creep as shown in Fig. 15. The values of ε_{sp}/ρ of water-cured concrete produced by standard curing is about 40×10^{-6}/MPa in case of high strength concrete, and about 160×

10^{-6}/MPa in case of normal strength concrete. In case of delayed elasticity, the ultimate deformation is expressed by $1/\gamma_K$. Therefore, the above descriptions that the values of $1/\gamma_K$ is the same ratio as of the experimental results, show that the greater part of creep deformation is explained by the visco-elastic theory.

4. CONCLUSIONS

The present study is made with the objective of clarifing the mechanisms of the drying shrinkage and creep of concrete. The characteristics of the drying shrinkage and creep of concretes varying compressive strength in a wide range from 35 to 110 MPa and curing method are experimentally obtained. Within the scope of this research, the following conclusions may be drawn:

(1) Drying shrinkage and creep are affected not only by unit cement paste volume, but also by the concentration of the paste. Drying shrinkage per unit cement paste volume (ε_s/ρ) and specific creep per unit cement paste volume (ε_{sc}/ρ)in the range of compressive strength of concrete from 35MPa to 110MPa, are smaller for high-strength concrete, and a linear relationship exists with compressive strength of concrete from low strength to high strength. Evaporable water from concrete at drying is smaller for high-strength concrete, but, for equal evaporable water, ε_s/ρ is larger for high-strength concrete. The above facts show that drying shrinkage and creep of concrete are closely related to the pore volume and pore-size distribution of cement paste in concrete.

(2) The stresses occured in concrete in the pores with the radii of 7.5Å to 15Å by capillary tensions obtained from remaining water after drying time, are as large as from 50 to 100 times as much as that of the pores with the radii of more than 15Å. According the above, it can be said that drying shrinkage is mainly caused by capillary tensions occuring in gel pores with the radii of 7.5 to 15Å.

(3) Based on the concept that drying shrinkage of concrete is the sum of elastic and creep strains caused by the stresses due to capillary tensions, the values of drying shrinkage calculated by using observed Young's modulus and basic specific creep agree fairly well with the observed values of drying shrinkage. Therefore, the mechanism of drying shrinkage of concretes of low to high strength in the range of medium to high relative humidities can be explained by the capillary tension theory.

(4) Drying creep becomes smaller with the increase of compressive strength of concrete, and is caused by the stress due to the differenc of capillary tension between drying shrinkage specimens and creep specimens.

(5) Drying creep of high-strength concrete is about zero, because the difference of capillary tensions between drying shrinkage specimens and creep specimens does not arise. Drying creep is larger for lower-strength concrete because the capillary tensions of creep specimens are larger than that of drying shrinkage specimens.

(6) The creep of concrete cured in water, namely, basic creep is mostly occupied by the delayed elastic deformation, therefore, in case of stress-strength ratio less than 0.4, the greater parts of basic creep can be explained by the visco-elastic theory.

5. AFTERWORD

In this study, the calculated values of drying shrinkage and creep based on the assumption that drying shrinkage and creep can be explained by the elastic and creep deformations due to capillary tensions, agree with the observed values fairly well. It is considered that this shows a direction of study on the mechanisms of drying shrinkage and creep of concrete. This study was performed

at Tokyo Institute of Technology and Hiroshima University and was a part of the dissertation of one of authors. Experiments were conducted with the cooperation of members of the above Institute and University. To all the gentlemen who gave the authors advice and suggestion or assisted the analysis or experiment, the authors owe their sincerest gratitude.

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