STUDY ON THE RELATIONSHIP BETWEEN COMPRESSIVE CREEP AND TENSILE CREEP OF CONCRETE AT AN EARLY AGE.

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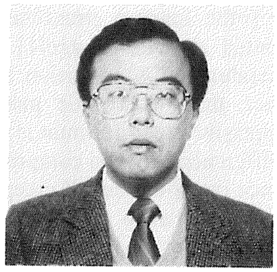

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An investigation of the difference between compressive creep and tensile creep of concrete at an early age is carried out through several creep experiments focusing on the amount of mortar and coarse aggregate. It is noted that the tensile creep strain of the mortar is quite similar to the compressive creep strain of the mortar under the same loading condition. The change in pore size distribution after compressive creep experiments is also quite similar to the change in the tensile creep experiments. The tensile creep strain of concrete is smaller than the compressive creep strain under the same loading condition. The effects of the coarse aggregate are founded to be significant in this study.

Key Words: *thermal stress due to heat of hydration, compressive creep, tensile creep, early age, pore structure*

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1. INTRODUCTION

It is quite important in selecting a suitable construction method to accurately predict the thermal stress resulting from hydration heat in order to avoid thermal cracking. Although 3D-FEM and the Compensation Plane method etc, are available for simulating the mechanism of stress generation, it is difficult to predict thermal stress with good accuracy. Two reasons are considered why the stress can't be predicted. One reason is that no method of the analysis that can simulate the mechanism of cracking has been presented, and the other is that the effects of creep at an early age have not defined in detail.

From the point of view of creep, since thermal stress may change from compression to tension corresponding to variations in temperature, creep behavior from tension to compression should be defined. Further, since the changing of mechanical behavior due to hydration at an early age is significant, effects of degree of hydration should be taken into account in creep models.

Besides, since detective zone may easily generate under loading, the creep strain may be non-linear to the loading stress. Several non-linear compressive creep models taking the effect of the stress-strength ratio (=the loading stress/the compressive strength at loading, described as S/S) into account were presented at matured age[1]. The other compressive creep models taking the effects of loaded age, temperature, mix-proportion and stress-strength ratio into account were presented at an early age [2]. Further, there is a little published literature, although more work has been done recently. Only a compressive creep formula is presented in the JSCE concrete standards and there is no clear definition of the difference between compressive creep and tensile creep.

Since the compressive creep formula is currently adopted for tensile creep, it is very important that the difference between the two creep behaviors is defined by studying tensile creep based on experiments. Although several papers can be found in which tensile creep is similar to compressive creep [3] and tensile creep is larger than compressive creep [4], there are few papers in which a qualitative assessment is carried out by comparing the behavior of tensile and compressive creep.

The authors have pointed out based on creep experiments that tensile creep strain is smaller than compressive creep strain at a 20% stress-strain ratio and with ordinary mix-proportions as used for reinforced concrete [5], [6]. However, the reason why tensile creep strain is smaller was not defined.

A comparison between tensile creep and compressive creep was investigated focusing on the creep behavior of mortar and coarse aggregate separately, since concrete consisted of mortar and coarse aggregate. A pore structural approach was adopted in which the pore size distribution of loaded and unloaded specimens in tensile and compressive creep experiments was measured. The effect of loaded age and stress- strength ratio on tensile and compressive creep was investigated.

2. REVIEW OF CREEP MECHANISM

2.1 Creep Mechanism by flow

Creep can be treated as a flow of pore water and micro cracking. The creep mechanism is by reviewed as described in the published literature.

Concrete consists of cement paste, fine aggregate, and coarse aggregate. Creep strain of the aggregate is smaller than that of cement paste, except in the cases of expanded clay and lightweight aggregates. The creep of mortar, which consists of paste and fine aggregate, and which is concrete less coarse aggregate, is larger than that of concrete. The cement paste consists of CSH gel, portlandite and minerals, evaporable water, and non-evaporable water [7]. Although an authorized theory can not be found, pore water plays as an important role in creep behavior because little creep strain is observed at high temperatures when no pore water exists [8]. Since creep behavior is depended upon movement of pore water and changing pore structure, the creep mechanism might be elucidated by investigating the pore structure before and after creep experiments.

Visco-elastic theory and seepage theory are adopted for explaining creep mechanism in compressive creep [9]. It is assumed that deformation of the hardened cement paste takes place after the load is added and that the radius of pores decreases and pore water is expelled to unsaturated pores. This leads to slow and continuous deformation. Consequently, part of the paste slowly deforms. This deformation is called flow deformation. Although deformation recovers after unloading through a slow return of pore water, the phenomenon is not exactly the same as the deformation during loading. This phenomenon is called delayed elastic deformation.

No literature describes the mechanism of tensile creep. An analytical simulation, in which the suction force

Table-1 Materials of Concrete

Material	Type and Origin	Specific weight
Cement	OPC	3.15
Fine aggregate	Mountain sand at Toyota	2.55
Coarse aggregate	Gravel at Kasugai	2.65 Gmax=20mm
Admixture	Water reducing agency	1.1

Table-2 Mix-proportion

No.	Slump	Air	W/C	S/a	Unit weight (Kg/m^3)				
	(cm)	(%)	(%)	(%)	W	C	S	G	AD
A	8	4	55	100.0	275	501	1221	0	1.9
B				44.6	172	313	787	1015	1.2
C				33.5	155	282	611	1267	1.2
D				55.8	200	364	915	756	1.2

caused by expansion due to tensile loading deformation is taken into account, is able to demonstrate the experimental results of tensile creep [10]. Although the effect of suction force has not been theoretically assessed, it is likely that the reverse phenomenon to compressive creep might occur the radius of pores expands and the proportion of unsaturated pores rises. Equilibrium is reached by the inflow of outside air to compensate for the suction. This means that the mechanism of tensile creep and compressive creep is the same from the point of view of changing pore structures. Creep strain would be the same if the above assumption was proved to be reasonable. Creep due to the movement of pore water is caused by deformation of pores. It is a reversible deformation and has a close relationship to the degree of loading, if deformation of pores is elastic.

2.2 Micro cracking

It is assumed that creep strain is increased if micro cracking takes place due to the tensile stress exceeding strength of the cement paste. This type of creep is influenced by the stress-strength ratio and is irreversible since it is not an elastic but a plastic strain. The mechanism of this type of creep is different from that of plastic flow. Little experimental work on this type of micro cracking was found, probably because it is difficult to monitor the process. The authors have investigated the relationship between stress-strength ratio and unrecovered creep strain and pointed out that unrecovered creep strain increases corresponding to an increment in stress-strength ratio [11]. A rise in unrecovered creep strain means that plastic strain remains as a result of increased micro cracking.

2.3 Method of comparison

No available published data was found to contribute to a theoretical consideration of the difference between compressive creep and tensile creep. The three investigations below described below were carried out to study the creep of concrete at an early age.
-Tensile and compressive creep experiments in which parameters were the amount of coarse aggregate carried out to investigate the effect of material factors.
-Measurement of pore size distribution changes after creep experiments.
-Tensile and compressive creep experiments under identical conditions, such as loaded age and stress-strength ratio to investigate the effect of loading and age.
The effect of micro cracking on creep strain was investigated by measuring the permanent strain after unloading, since it could not directly be scanning.

3. CREEP EXPRIMENTS

3.1 Materials and mix-proportion

The mix-proportion was selected from among actually used mix-proportions in reinforced concrete construction work. The design compressive strength was 30N/mm^2 at 28 days. Detail of materials is shown in Table-1, and the mix-proportions are described in Table-2. The basic mix-proportion is type B which has water cement ratio of 55% and sand ratio of 44.6%. Three mix proportions, which changed amount of coarse aggregate with the same mortar, were used to investigate the effect of coarse aggregate. Since some

Table-3 Mechanical behavior of concrete

Age (Day)	Sand ratio (%)	Compressive Strength (N/mm^2)	Tensile Strength (N/mm^2)	Young's Modules ($\times 10^4 N/mm^2$)
3	33.45	17.52	1.90	3.01
	44.60	17.59	1.48	2.87
	55.75	17.13	1.42	2.12
5	100.00	20.96	1.93	2.03
	44.60	21.53	2.12	3.50
	100.00	19.31	2.76	2.54

Table-4 Test case

case No.	Direction	W/C (%)	Mix proportion	S/S (%)	Loaded age (day)	Loaded stress (N/mm^2)
1		55	A	4.4	3	1.0
2		55	A	20.0	3	4.8
3		55	B	4.3	3	1.0
4		55	B	20.0	3	4.1
5		55	C	4.7	3	1.0
6		55	C	20.0	3	3.5
7		55	D	4.1	3	1.0
8	Compression	55	A	29.0	3	4.5
9		55	A	49.0	3	7.7
10		55	A	60.0	3	9.4
11		55	B	40.0	3	6.0
12		55	B	50.0	3	7.7
13		55	B	70.0	3	11.0
14		55	B	20.0	5	3.4
15		55	B	40.0	5	7.3
16		55	B	50.0	5	10.1
17		55	B	70.0	5	13.4
18		55	A	48.5	3	1.0
19		55	A	20.0	3	0.4
20		55	B	49.6	3	1.0
21		55	B	20.0	3	0.4
22		55	C	53.2	3	1.0
23	Tension	55	C	19.9	3	0.3
24		55	D	49.1	3	1.0
25		55	B	40.0	3	0.7
26		55	B	60.0	3	1.2
27		55	B	20.0	5	0.5
28		55	B	40.0	5	0.9
29		55	B	60.0	5	1.4

segregation was observed in the case of high aggregate proportions, an amount of cement paste was added to avoid segregation.

3.2 Experimental conditions

The age at loading was 3 days and 5 days in most cases when changes in mechanical behavior due to hydration had stabilized according to the earlier research [2,5,6,11] This was varied somewhat according to the purpose of the experiments.

Part of mortar was used to measure pore size distribution in every case.

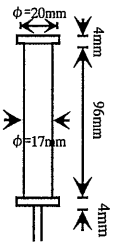
The test results of compressive and tensile strength (which was obtained by splitting test) and compressive young's modulus at 3 days and 5 days of age, as tested under the same conditions as the creep specimen, are shown in Table-3.
The experimental cases and parameters used are shown in Table-4. Only unknown parameter was changed in the parameter study, since the effects of the parameter was quantifiably assessed.

3.3 Procedure of creep test

Compressive and tensile creep specimens, which were 10cm in diameter and 20cm in height, were immediately stored in a curing room at 30℃ after concreting at 20℃. They were demolded in the room after 24 hours and sealed with an aluminum membrane in order to avoid drying. They were stored in the curing boxes at temperature-controlled 30℃ and a humidity of 98%. The strain due to creep was measured by embedded creep strain meters alongside the thermocouples used to control temperature. A schematic figure of an embedded strain meter is shown in Fig.-1. The creep test equipment, which is shown in Fig.-2, was of the lever type with a lever ratio of 1/40 and it was enclosed in a temperature and humidity controlled box where the humidity was controlled at 98% and temperature at 30℃. Basic temperature of this experiment was 30℃, since the humidity could be controlled under the atmospheric temperature. Other strains generated in specimens during creep tests, such as aoutohomogeneous shrinkage, were compensated by measuring the strain of an unloaded specimen in the same box and by subtracting it from the measured creep strain. The tensile stress was directly loaded by embedded several bolts, which has little risk of changing load. Schematic of the connecting bolts is shown in Fig.-3. Two specimens were tested after a preliminary creep test in which no significant error was observed if the uniformity of specimens was maintained, as in a laboratory test.

Measurement of pore size distribution.

The change in pore size distribution was investigated by comparing the results of loaded specimens with unloaded specimens after the creep test. Samples were prepared for pore size distribution tests by carefully slicing the specimen. The preparation procedure was as follows. The specimen was sliced into several cubes 1cm on a side with a cutter. The cubes were stored in D-dry apparatus for 72 hours in order to



type	KM-100B
Max.	±5000μ
Min.	1μ
Length	100mm

Fig.-1 Embedded strain meter

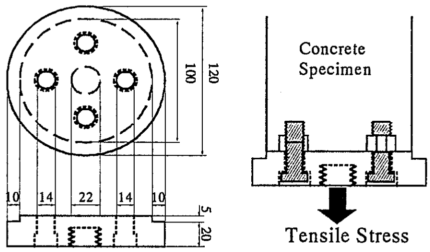


Fig.-2 Loading apparatus

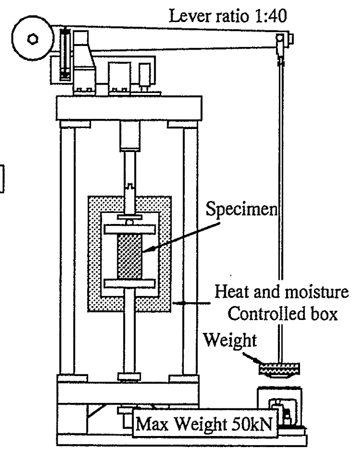


Fig.-3 Creep test apparatus

extract free water from the pores. Pore size distribution tests were then immediately carried out by mercury intrusion porosimetry.

Loading pattern and creep strain

The loading pattern and creep strain in this study were as shown in Fig.-4. Each strain generated by loading was defined as Fig.-4. Loading period was mainly 5 days. Creep strain at 5 days was defined as the final creep strain, since it was the final creep strain during this experimental study. Although the creep strain was increasing, the ratio of increase stabilized and it was noted that the effects of the parameters could be assessed by 5 day of loading. The velocity of loading was 1.0N/mm^2/min in compressive creep tests and 0.1N/mm^2 in tensile creep tests.

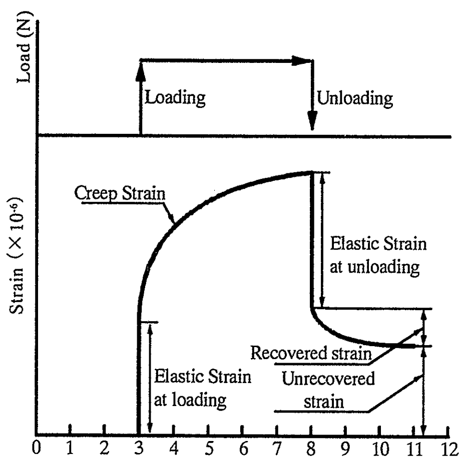


Fig.-4 Loading pattern and strain

4. COMPARISON OF CREEP STRAIN BETWEEN COMPRESSION AND TENSION

4.1 Compressive creep of mortar

Effect of stress-strength ratio for the creep strain

The total strain, which was obtained by subtracting the strain of unloaded specimens from the strain of loaded specimens, is shown in Fig.-5. The strain of unloaded specimens is shown in Fig.-6. The relationship between final creep strain and stress-strength ratio is shown in Fig.-7. The final creep strain was calculated by subtracting the elastic strain at loading from the total strain. Since it was noted that the final creep strain was proportional to the stress-strength ratio below a stress-strength ratio at 20% [3,5], the creep strain was defined proportional to the ratio below 20%. It was noted that the final creep strain was proportional to the stress-strength ratio until about a stress-strength ratio of 35%. The linear relationship was not observed above a stress-strength ratio of 35% and creep strain increased immediately beyond that value. The formula for creep strain and stress-strength ratio can be written as follows.

$$\varepsilon_{cr}=109.91\exp(0.038S/S) \quad (20\leqq S/S\leqq 60) \qquad (1)$$
$$\varepsilon_{cr}=11.95(S/S) \quad (S/S\leqq 20)$$

ε_{cr} : Final creep strain S/S : Stress strain ratio

The effect of micro cracking was investigated as possible reason for creep strain increasing with an increment in stress-strength ratio. A preliminary estimate for the generation of micro cracking is shown below. It is assumed that micro cracking is generated by shear deformation of the pores in compressive creep, and the stress-strength ratio at crack generation in the pores was estimated.

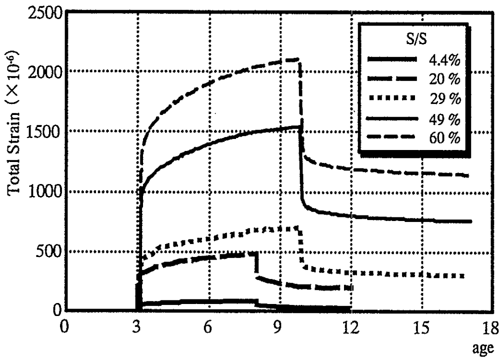


Fig.-5 Change of total strain (mortal)

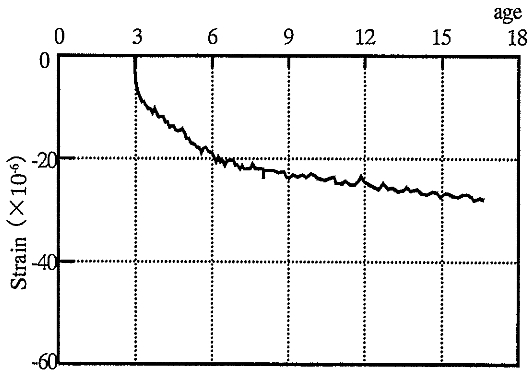


Fig.-6 Strain of unloaded specimen

$$\varepsilon_{t\,lim} = \nu \cdot \sigma_{c\,lim} / E \qquad (2)$$

$$\sigma_{c\,lim} / \sigma_c = \sigma_t / \sigma_c / \nu$$

$\varepsilon_{t\,lim}$: Horizontal tensile strain at crack generation crack (N/mm^2)

ν : Poisson ratio

$\sigma_{c\,lim}$: Compressive stress at micro cracking

σ_c: Compressive strength (N/mm^2)

E: Young's modulus (N/mm^2)

σ_t : Tensile strength(N/mm^2)

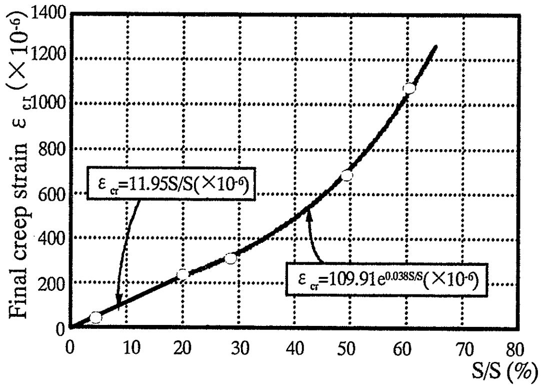


Fig.-7 Relationship between S/S and final creep strain (mortal)

Since the compressive strength at 3 days was 17.60N/mm^2, Young's modulus was 2.87N/mm^2 and the tensile strength was 1.48N/mm^2, the stress-strength ratio at the generation of micro cracks was 50% as obtained by formula (2). This value is a little bigger than the limit below which creep strain increases linearly with stress-strength ratio. It can be calculated that the creep strain increases by generation of localized micro cracking at stress-strength ratios below the value obtained by formula (2).

Effects of recovered creep strain.

The relationship between stress-strength ratio and the recovered creep strain and unrecovered creep strain is shown in Fig.-8. The unrecovered creep strain increased with an increment in stress-strength ratio. However the recovered creep strain did not increase like the unrecovered creep strain but was linear to the stress-strength ratio. It was considered that the unrecovered creep strain was caused by the deformation of gel particles and micro cracking based on seepage theory, and that recovered creep strain was caused by transportation of pore water by deformation of pore (12). It was noted that the ratio of unrecovered creep strain to creep strain was high. Since the unrecovered creep strain increased beyond a the stress-strength ratio of 35%, which was the value at which cracks were generated according to formula (2), the increase can be attributed to micro cracking. The recovered creep strain, which was caused by transportation of pore water, linearly increased with the stress-strength ratio. This means that pores were elastically deformed under stress causing transport of pore water, and that creep strain was recovered. This is supported by visco-elastic theory.

The amount of strain is investigated below. The creep strain, which were shown in Fig.-7, were similarly changed to unrecovered strain in Fig.-8. Each type of strain, which was generated before and after unloading, was compared to the stress-strength ratio in Table-5. It was noted from the results that the creep strain was roughly equal to the unrecovered creep, and the creep strain increased as much as the increment in elastic strain due to the changing of Young's modulus. Since the change of strain after unloading consisted of the recovered creep and unrecovered creep, and most creep strain was attributed to unrecovered creep, the recovered part of the strain was small and the process of unloading was different from loading. Consequently it is proposed that super-positioning theory can not be adopted, and the

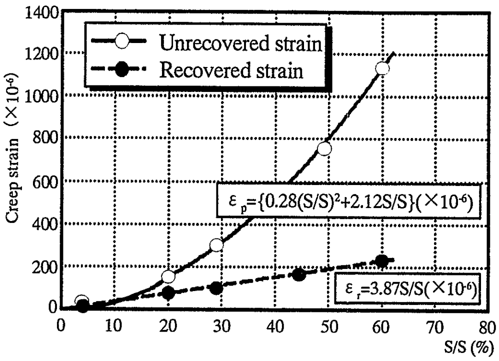


Fig.-8 Relationship between recovered and unrecovered strain

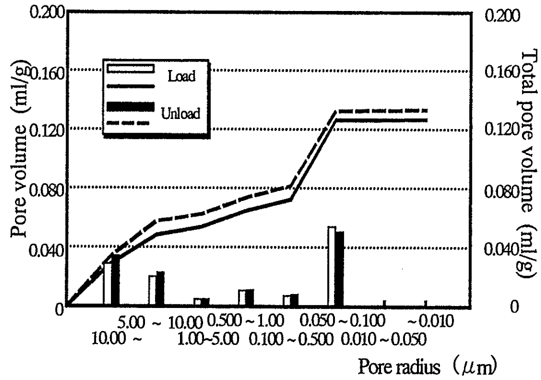


Fig.-9 Pore size distribution (Compressive creep)

Table-5 Elastic strain and recovered strain

S/S (%)	Loaded elastic strain	Creep strain	Total strain	Recovered strain	Unrecovered strain	Unloaded elastic strain
4.4	45	45	90	6	41	43
20	241	240	481	48	235	197
29	388	336	724	107	314	303
49	806	705	1511	190	757	563
60	1051	1087	2138	254	1147	736

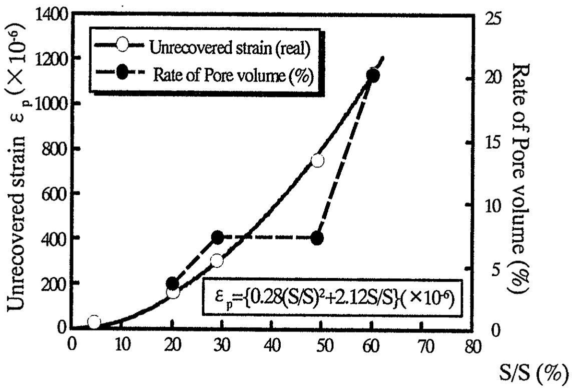


Fig.-10 Unrecovered strain and rate of pore volume

process of unloading should be theoretically modeled if the process of unloading needs to be taken into account, such as in thermal stress analysis

Pore structure and unrecovered strain

The change of the pore size distribution and total pore volume of the mortar, which was obtained under 1N/mm^2 of compressive and tensile stress, are shown in Fig.-9. It is noted that a change in total pore volume indicates a change in the micro pore structure, which affected unrecovered creep, since the measured value was obtained after unloading. It was noted that the total pore volume decreased by loading under compressive stress, and that pore of diameter 5μm or greater significantly decreased. Calculation in which the change in total pore volume was translated into a change in strain was carried out. It was assumed in the calculation that the change in total pore volume was concentrated into the top of a cube of 1cm and that strain was the ratio of change, in the cube edge length. The calculated value was 190μ, which was much smaller than the measured strain, at only about 17%. It was consequently noted that the pore structure was little changed or that it recovered.

The relationship between unrecovered creep and the ratio of change in total pore volume at each stress-strength ratio is shown in Fig.-10. Although the unrecovered creep strain increased corresponding to the stress-strength ratio, the change in the total pore volume was insignificant until a stress-strength ratio of 50%. However the change in total pore volume increased at a stress-strength ratio of 60%. It was pointed out that the change in micro pore structure became greater at high stress-strength ratios.

The following items are noted from the investigation of micro pore structure:

- Although the total pores volume after unloading decreased with compressive creep, the calculated strain of based on change of pore volume was relatively small comparing to the unrecovered creep strain.
- The change in the total pore volume increased at a stress-strength ratio of 60%. It was considered that the progress of micro cracking affected the increment.

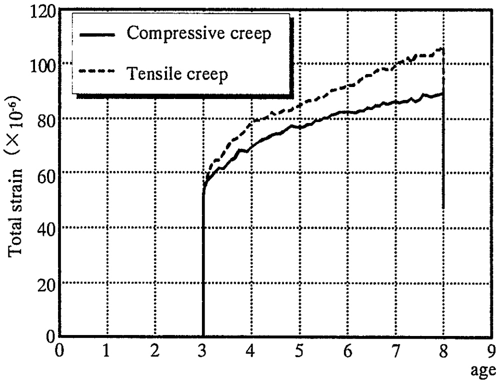


Fig.-11 Total strain (Mortal at 1N/mm^2)

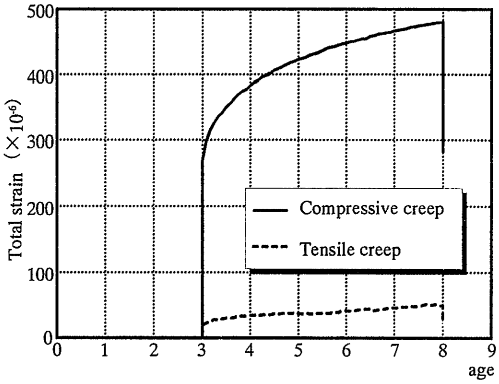


Fig.-13 Creep strain (Mortal at S/S=20%)

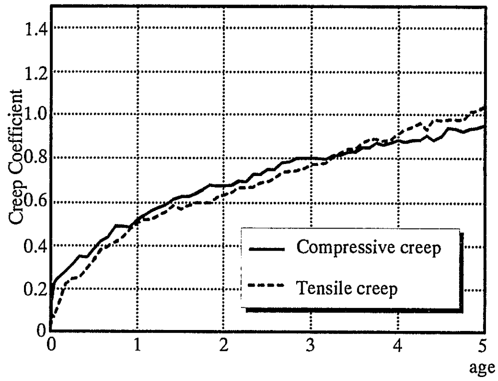


Fig.-12 Creep Coefficient (Mortal at 1N/mm^2)

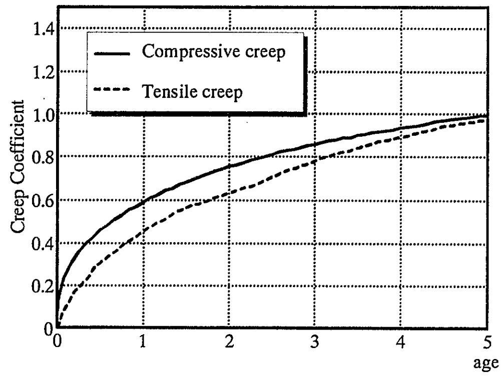


Fig.-14 Creep Coefficient (Mortal at S/S=20%)

4.2 Comparison of compressive and tensile creep

Effect of loaded stress and stress-strength ratio

A compressive and tensile creep test, in which the loading condition was equaled and 1 N/mm^2 of stress was loaded for the mortal specimen, was carried out. A comparison of total creep strain is shown in Fig.-11. The tensile creep strain was 19 μ (23% larger) larger than the compressive creep strain in the mortar. A comparison of creep coefficient is shown in Fig.-12. The tensile creep coefficient was 0.05 (5%) larger than the compressive one. Although the tensile creep strain was larger than the compressive one, both creep coefficients were quite similar and little difference was observed in creep behavior according to the test results.

A comparison of creep strain at 20% of stress-strength ratio is shown in Fig.-13. The tensile creep strain was 60 μ , which was about 1/6 of the compressive creep strain, and tensile creep strain was smaller than the compressive one at the same stress-strength ratio. A comparison of both creep coefficients at the same stress-strength ratio is shown in Fig.-14. Both creep coefficients at 5 days at the same stress-strength ratio were similar, although the change with loading period was different. It is noted that the compressive creep behavior of mortar in creep coefficient was the same as the tensile creep and that in creep strain it was a little smaller than the tensile creep. It is considered that the tensile creep strain was larger than the compressive creep strain, since the stress-strength ratio of tensile creep was larger in case of the same stress as the compressive creep and it potentially caused micro cracking. Since the changing process of creep strain was different for both creep behaviors in the same stress-strength ratio, it is concluded that the mechanism of creep is not the same for both types of creep. However, it can be pointed out that both creep behaviors of mortar until 5 days are quite similar.

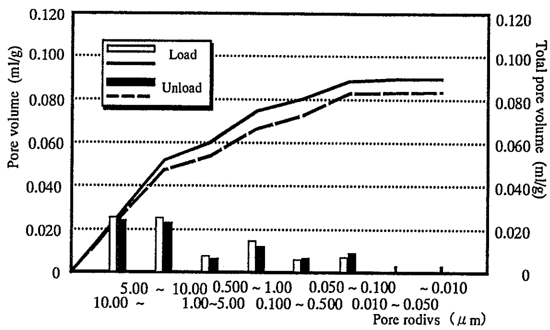


Fig.-15 Pore size distribution of tensile creep

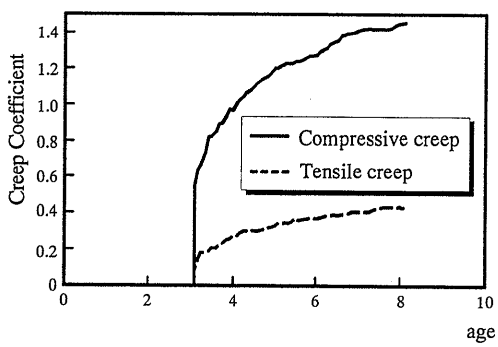


Fig.-17 Creep Coefficient (Concrete at 1N/mm^2)

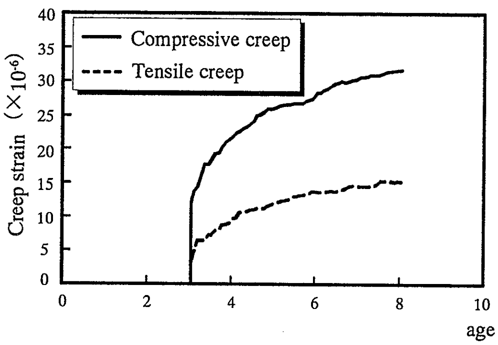


Fig.-16 Creep strain (Concrete at 1N/mm^2)

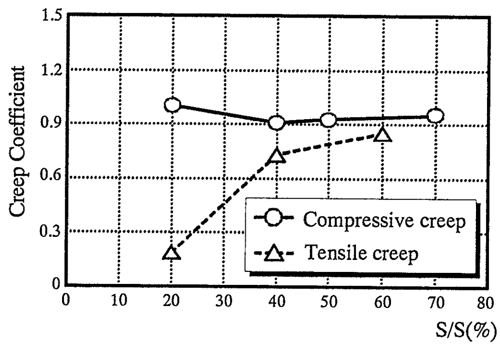


Fig.-18 Creep Coefficient and S/S of Concrete (Loading age was 3days)

Comparison of pore structure

The change in pore size distribution before and after tensile creep tests is shown in Fig.-15. It is observed that the pore volume of relative bigger diameter increased. It is pointed out that the same change in absolute value of pore size distribution is generated in tensile and compressive creep. The change in the total pore volume in tensile creep increased by about 10% at stress-strength ratios of 20% and 50%. This tendency was quite similar to compressive creep.

5 COMPARING TENSILE CREEP AND COMPRESSIVE CREEP IN CONCRETE

5.1 Influence of loaded age and loaded stress

Comparison at same stress

The relationship between the creep strain and creep coefficient, as measured at 3 days loading and 1 N/mm^2 with mix proportion A, is shown in Fig.-16,17. The calculated stress-strength ratio was 5.7% in the compressive creep test and 50% in the tensile creep test. Change of creep strain in the tensile creep was different from change of compressive creep in an early age, and the compressive creep strain was larger than the tensile creep strain, although a similar process was observed in mortar with the same mix proportion. Since the stress-strength ratio of tensile creep was higher than that of compressive creep, the creep coefficient of tensile creep was about 80% of the compressive value.

Influence of the loaded age and stress-strength ratio

The relationship between creep coefficient and stress-strength ratio, in which the compressive creep is quite similar to the tensile creep in mortar, is shown in Figs.-18,19. The tensile creep coefficient was smaller than the tensile one at a stress-strength ratio of 20%. Although it was also smaller than the compressive creep coefficient, the difference between creep coefficients became small as the stress-

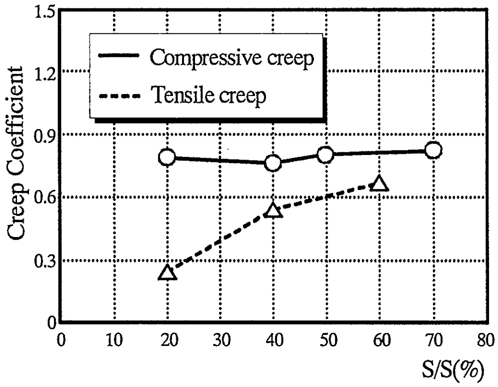


Fig.-19 Creep Coefficient and S/S of Concrete (loading age was 5days)

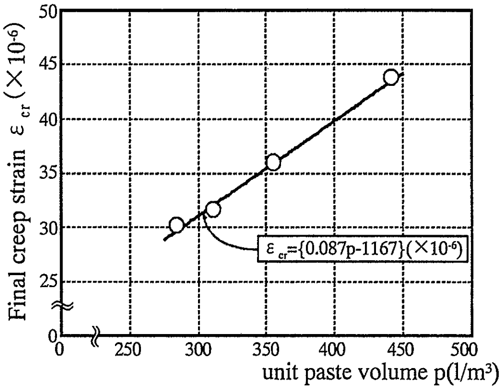


Fig.-21 Relationship between unit paste volume and creep strain (compressive creep)

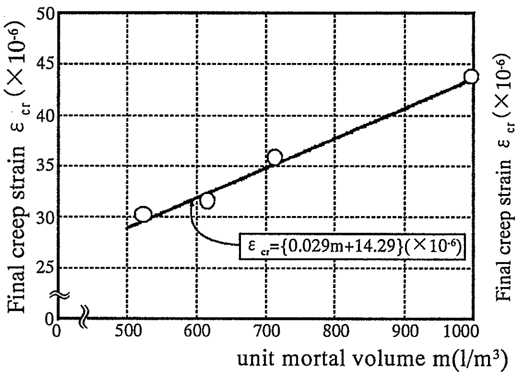


Fig.-20 Relationship between unit mortal volume and creep strain (compressive creep)

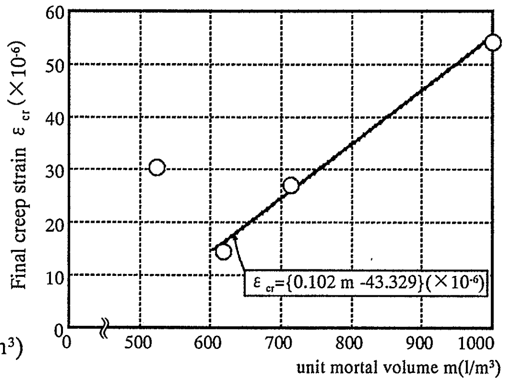


Fig.-22 Relationship between unit mortal volume and creep strain (tensile creep)

strength ratio rose. The difference in compressive and tensile creep coefficients in 3 day loading was larger than that in 5 day loading for the same loading condition at a stress-strength ratio of 20%. Above, it was noted that the tensile creep was smaller than the compressive creep, however, it was strongly observed at early age and at a low stress-strength ratio.

6 INFLUENCE OF COARSE AGGREGATE

6.1 Influence of coarse aggregate on compressive creep

The influence of the coarse aggregate was investigated in order to find the reason why tensile creep is smaller than compressive creep at an early age and for the low stress-strength ratio. A creep test was carried out with several mix proportions in which amount of mortar was equal to the basic concrete and several amount of coarse aggregate was added to the mortar. The relationship between unit volume of mortar and the final creep strain at $1N/mm^2$ in compression is shown in Fig.-20. The relationship between unit paste volume and final creep strain is shown in Fig.-21.

The relationship between final creep strain and unit mortar volume or unit paste volume is defined by a linear formula. This means that the effect of fine aggregate in compressive creep can be neglected, since the relationship can be defined by the same linear formula in both paste and mortar.

6.2 Influence of coarse aggregate in tensile creep

Tensile creep test was carried out under the same condition as the compressive creep test. The relationship between final creep strain and unit mortar volume is shown in Fig.-22, and the relationship between unit paste volume and final creep strain is shown in Fig.23. The creep strain increased

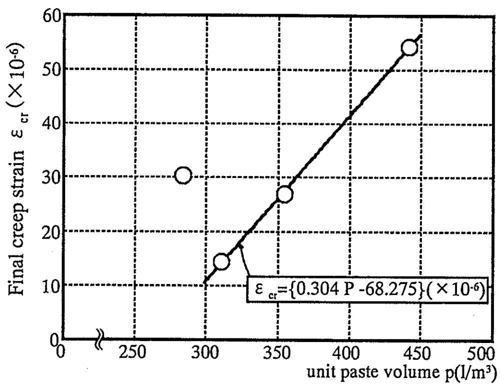


Fig.-23 Relationship between unit paste volume and creep strain (tensile creep)

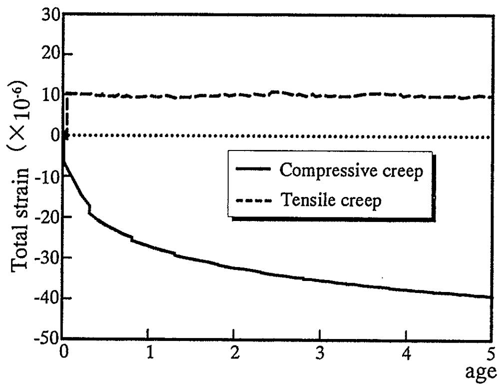


Fig.-24 Creep of Coarse aggregate

corresponding to the amount of mortar in its rich area in which the ratio of fine aggregate was more than 44.6% that was the most suitable ratio.

The creep strain was increased at a ratio of fine aggregate of 33.75%, which was smaller than the most suitable ratio. It was assumed that segregation occurred and that a defective zone was generated by short of mortar to fill with the void. Influence of this defective zone was significant in tensile creep. The tensile creep strain was proportional to the volume of mortar and paste as the compressive creep within workable concrete.

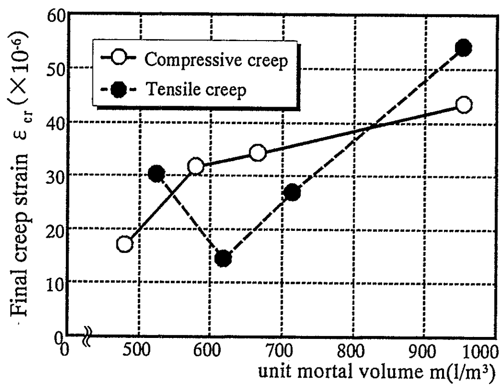


Fig.-25 The effect of coarse aggregate

Although concrete consists of paste, fine aggregate, and coarse aggregate, a simple model has creep strain consisting of creep strain of the mortar and coarse aggregate.

6.3 Comparing tensile creep to compressive creep of coarse aggregate

It was noted that the influence of the volume of mortar was significant in the creep behavior of concrete. However the effect of mechanical behavior of coarse aggregate had not been investigated in former studies. The influence of the mechanical behavior of coarse aggregate was investigated by measuring the creep behavior of the coarse aggregate. Creep tests using the rock specimens, which were cored from the mother rock of the coarse aggregate and which were 5 cm in diameter and 10cm in height were carried out. The testing procedure was the same as for the compressive creep test of the concrete and the stress level was $1N/mm^2$. A pair of gauges 30 mm in length and 1μ in minimum measurement, were attached to the surface of the rock specimen to measure deformation by stress. The surface was sealed with aluminum membrane in the same way as the concrete specimens. The temperature was controlled at 30℃ but the humidity was not controlled. Although the strain of unloaded specimens was measured to compensate for other strains, no strain was observed. The equipment for tensile creep was attached to the specimen by epoxy resin and was the same as used in the concrete creep tests. The change in creep strain corresponding to loaded period is shown in Fig.-24. A compressive creep strain was observed, but no tensile creep strain was observed. This tendency of the rock was similar to that of concrete, in which tensile creep was smaller than compressive creep.

6.4 Influence of volume of coarse aggregate on the tensile and compressive creep

The relationship between final creep strain and unit mortar volume is shown in Fig.-25. The creep strain

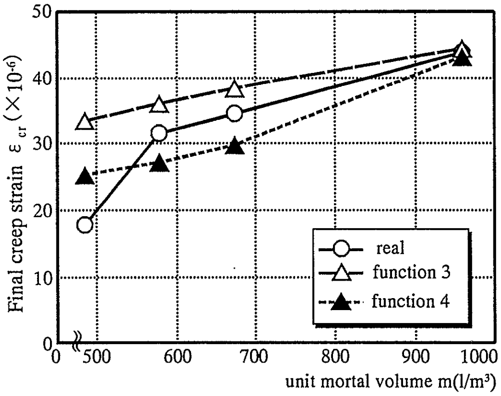


Fig.-26 Calculated creep strain
(Compressive creep)

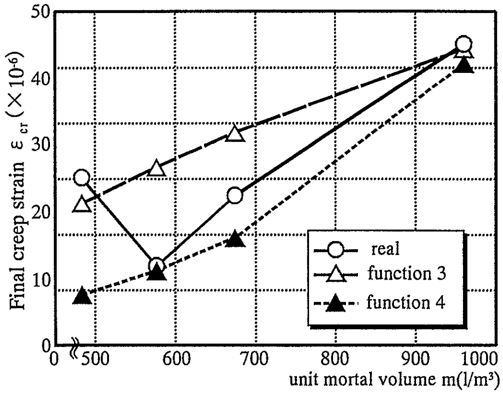


Fig.-27 Calculated creep strain
(Tensile creep)

was relatively smaller than the compressive one in actually used workable concrete. Since the difference became small with an increment of the volume of mortar, it was noted that the tensile creep was significantly influenced by the volume of coarse aggregate. The creep behavior of the coarse aggregate influenced the creep behavior of concrete in tensile creep. Although the tensile creep was equal to compressive creep in the mortar, the tensile creep of concrete became smaller than compressive creep due to creep behavior of coarse aggregate. This tendency for the tensile creep to be smaller than compressive creep in concrete became significantly with an increment of volume of coarse aggregate.

6.5 Influence of volume of coarse aggregate, loaded age, and stress-strength ratio

The effects of the volume of coarse aggregate, loaded age, and stress-strength ratio on creep behavior were investigated. It was noted from Figs.-18,19 that the tensile creep coefficient was smaller than the compressive one. Although the difference became little at 5 days, tensile creep was smaller than compressive creep up to 3 days. The reason for this was investigated from the view point of the micro pore structure. The 20% point of stress-strength ratio was the area where the recovered creep strain based on seepage theory was large and where the defective zone was relatively small. Since the coarse aggregate rigidly bonded to the paste, coarse aggregate strongly constrained mortar. It can't be denied that the mechanism of transportation of pore water based on seepage theory was different in both creep behaviors, since the change in tensile creep coefficient corresponding to loading period was smaller than that in compressive creep at a stress-strength ratio of 20%.

However, it was concluded that the difference in creep behavior of the coarse aggregate was strongly influenced at 20%, since the difference between both creep behaviors in concrete was larger than in mortar. Considering the decrement of the difference between the both creep strains, it was noted that the constraint would be reduced by micro cracking at the interface between coarse aggregate and mortar in both creep behaviors. Besides, it was noted that the Young's modulus increased and the effect of the coarse aggregate decreased upon the decrement of difference between both creep strains. It was also noted that the creep strain of mortar decreased and the effect of the coarse aggregate decreased.

7. MODELING OF CREEP IN CONCRETE

The creep strain of concrete was modeled based on the creep behavior of mortar and coarse aggregate. Two models, taking into account the stiffness of the mortar and the coarse aggregate, and the volume of the both materials, were adopted based on the theory in which creep strain consists of strain of mortar and coarse aggregate with constraint, although strain was generated in each material by loading. The basic balance of each stress in the materials was kept in the stiffness model, although stress did not increase corresponding to creep increment. A simple model was defined such that creep strain was obtained by multiplying each volume of concrete and coarse aggregate by each creep strain corresponding to the loaded stress. The formula of the simple model is shown in (3). A stiffness model, which was based on the stiffness of mortar and coarse aggregate and the balance formula, is defined as formula (4).

$$\varepsilon_{cr} = V_m \cdot \varepsilon_{mcr} + V_a \cdot \varepsilon_{acr} \qquad (3)$$

$$\varepsilon_{cr} = \frac{E_m \cdot \varepsilon_{mcr} \cdot V_m + E_a \cdot \varepsilon_{acr} \cdot V_a}{E_m \cdot V_m + E_a \cdot V_a} \qquad (4)$$

ε_{cr} :Final creep strain (μ)
V_m :Volumetric ratio of mortar (%)
ε_{mcr}: Creep strain of mortar (μ)
E_m :Young's modulus of mortar(N/mm^2)
V_a :Volumetric ratio of coarse aggregate (%)
ε_{acr}: Creep strain of coarse aggregate (μ)
E_a :Young's modulus of coarse aggregate (N/mm^2)

A comparison between the calculated values based on the two formulas and the results of experiments is shown in Figs.-26, 27. The results of compressive creep tests are plotted within calculated results of the both formulas, and the tensile creep strain is plotted near to the formula (4).

It was noted that tensile creep was smaller than compressive creep strain as a result of the constraint of the coarse aggregate, and that the effect of coarse aggregate could be modeled based on the stiffness model.

8. CONCLUSION

The process of creep and recovery in the mortar was investigated. The creep behavior of mortar and concrete was also compared. The following conclusions were obtained:

1) Since the effect of stress-strength ratio on mortar is significant, the creep strain is proportional to stress-strength ratio up to only 35%.
2) The unrecovered creep strain increases as a secondary function corresponding to the increment in stress-strength ratio. However, the recovered creep strain is proportional to stress-strength ratio and the unrecovered creep strain increases corresponding to the ratio.
3) A part of the creep strain comprises unrecovered creep strain at an early age. The creep strain is approximately equal to the unrecovered creep strain. The recovered creep strain is equal to the elastic strain caused by the difference in Young's modulus between loading and unloading.
4) A decrement in total pores is observed in compressive creep, but it accounts for only a small part of the creep strain. The total pore volume increases in tensile creep, but it occupies a small part of compressive creep.
5) Tensile creep strain is a little larger than compressive creep in mortar at the same loading stress. Both creep coefficients of mortar are similar. The coefficient of compressive creep is a little larger than the tensile creep coefficient at the same stress-strength ratio, and it is concluded that the tensile creep behavior is equal to the compressive behavior in mortar.
6) Since the creep strain of concrete closely relates to the volume of mortar, the creep strain becomes small corresponding as the volume of mortar.
7) The tensile creep strain of concrete with normal coarse aggregate is smaller than compressive creep strain at low stress-strength ratios such as 20%. However the difference becomes small in 5 day loading.
8) The tensile creep strain is smaller than compressive creep strain in creep tests on rock from which the coarse aggregate is made. The effect of the coarse aggregate is significant at an early age and with low stress-strength ratios, when the constraint of the coarse aggregate is superior to that of mortar. Consequently the tensile creep strain of concrete is smaller than compressive creep.
9) The tensile creep increases in case of lack of mortar to fill the void between aggregates.
10) A creep model consisting of the creep of mortar and coarse aggregate and in which the stiffness is taken into account, is able to predict the creep of concrete.

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