MECHANISM OF NONLINEAR BEHAVIOR AND CRACK RESISTANCE OF EXPANSIVE MORTAR

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This paper explains the mechanism underlying the nonlinear behavior of expansive mortar under tensile stress. Through flexural and uni-axial cyclic loading with an unloading phase, it is proved that the tensile stiffness of expansive mortar during unloading gradually decreases with increasing maximum tensile stress, and that expansive mortar exhibits residual tensile strain after unloading. Based on these experimental findings, a new proposal is made for rationally explaining the nonlinear behaviors peculiar to expansive mortar in tension. It is demonstrated that the cracking resistance of chemically prestressed members is greatly enhanced not only by the increased tensile strength added through prestressing but also the large deformability before cracking.

Keywords: *expansive concrete, nonlinear behavior, initial strain distribution, cyclic loading, residual strain, tensile stiffness during unloading*

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1. INTRODUCTION

Expansive agents are known as materials that reduce the cracking of concrete under loading or shrinkage. Expansive concrete is easily produced by the simple procedure of replacing some of the cement with an expansive agent. However, expansive concrete has prevailed little except in the case of precast products. This is mainly because the many advantages of expansive concrete have not been adequately acknowledged and also because it is difficult to quantitatively evaluate the effects of expansive agent.

Many past investigations have reported on the considerable advantages of chemical prestressing, including improved cracking load, reduced crack width, greater shear capacity, and less loss of prestress due to creep compared to mechanical prestressing [1], [2], [10]. The authors themselves have already reported that chemically prestressed members have improved deformability after reinforcement yielding than normal RC members [3]. These past results clearly demonstrate how effectively expansive concrete can improve the structural and durability performance of RC members. However, in order for expansive concrete to be more widely accepted, it is necessary to quantitatively evaluate these merits in advance. In particular, it is considered necessary to develop a method by which to judge with good accuracy whether or not cracking will occur.

Chemical prestress is introduced as a result of chemical reactions involving the expansive agent, and is considerably affected by the amount of expansive agent, the mix proportion, and environmental conditions. For this reason, it is difficult to carry out a quantitative evaluation of chemical prestress in advance of actually implementing it. Tsuji, however, has proposed that the expansion energy of an expansive concrete is constant if the mix proportion and curing method are identical [4]. This rule can be applied except in cases where free expansion occurs or the reinforcement ratio is very low. Consequently, if the expansive strain of the reinforcement in a chemically prestressed member can be predicted in this way, we can calculate the chemical prestress, and from this the cracking load can be estimated. However, there is no evidence that chemically prestressed members, which undergo large volume changes at an early age, exhibit linear behavior up to their tensile limit just like mechanically prestressed members (**Fig. 1**). Actually, Okamura et al. have pointed that expansive concrete exhibits nonlinear behavior in tension, and that crack resistance is improved not only as a result of the prestress but also because deformability is greater [1]. Yet the mechanism of this characteristic has not been clarified at all, and at present the merits of expansive concrete are not adequately acknowledged.

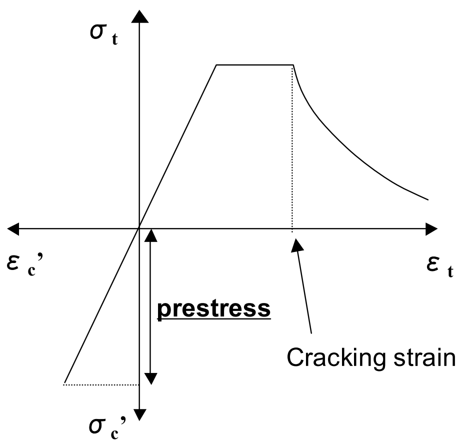

Fig.1 Evaluation of Mechanical Prestress

This research focuses on the nonlinear behavior of expansive concrete in tension and the mechanism of crack resistance. Our future aim is to develop a method for fully and quantitatively evaluating the effects of chemical prestress, and we hope this will lead to effective and wide utilization of expansive concrete in ordinary concrete structures.

2. PAST RESEARCH ON THE BEHAVIOR OF EXPANSIVE CONCRETE IN TENSION

Though an enormous amount of research has been done in relation to expansive concrete, very little has been published about its nonlinear behavior. Concerning behavior in compression, it has been reported that adding an expansive agent causes a decrease in compressive strength and elastic modulus [5], [6], and that compressive creep becomes nonlinearly large as the amount of expansive agent increases [7]. However, research into the nonlinear behavior of expansive concrete in tension is hardly to be found.

Okamura et al. investigated the relationship between load and tensile strain at the tension end of an expansive concrete flexural beam restrained in a uni-axial direction for 28 days after casting and whose restraint by steel was released just before loading [1]. Normal concrete shows almost linear behavior in tension until cracking, but this work showed that in the case of expansive concrete, the increase in tensile strain was considerable before cracking. In other words, expansive concrete exhibits plastic deformability before cracking. This deformability can contribute greatly to the crack resistance of RC members, especially when the reinforcement ratio is high. However, Okamura et al. did not discuss the mechanism governing this nonlinearity. Furthermore, in their experiments, the steel restraint was released immediately prior to loading. There is thus a need for the nonlinear behavior of chemically prestressed members to be investigated under restrained conditions.

Maruyama et al. conducted uni-axial tension tests on expansive concrete at an early age [8], [9]. Direct tension tests were applied to specimens less than 7 days after casting. The specimens were restrained until loading, and the restraint was released immediately prior to direct tension tests. It was proved that the tensile strength of expansive concrete decreased whose restraint had been released and that the tensile strain at cracking became large compared to normal concrete. The effects of concrete age, amount of expansive agent, curing conditions, and curing temperature were also investigated. Again, however, the mechanism behind the nonlinear behavior of expansive concrete in tension was not clarified. The restraint was released before loading, so the behavior of expansive concrete under tension with a restraint was not examined, although this is the most necessary area of research.

The above summarizes past experimental work concerning the nonlinear tensile behavior of expansive concrete. Although nonlinear behavior in tension has been experimentally verified, the mechanism has not been made clear. Furthermore, there are no experimental results regarding the nonlinear behavior of chemically prestressed members under restraint while in tension.

3. EXPERIMENTAL ANALYSIS OF NONLINEAR BEHAVIOR OF EXPANSIVE CONCRETE USING THIN BEAMS

3.1 Objectives

As noted in section 2 above, although the nonlinear behavior of expansive concrete has been demonstrated in a few experiments, the nonlinear mechanism in tension has not been clarified. In this section, experimental results showing the nonlinear behavior of expansive mortar are presented, and the mechanism is discussed. Bending tests on thin beams are conducted for normal mortar, expansive mortar without restraint (free expansion), and expansive mortar with a restraining steel bar (chemically presstressed). Many bending tests of expansive concrete beams have been done in this experiment. The major characteristic feature of this experiment is that cyclic loading — including unloading and reloading — was continued until cracking occurred. Further, bending tests were conducted at several specimen ages. Through a comparison and discussion of these experimental results, the nonlinear behavior of expansive mortar will be analyzed.

3.2 Experimental Procedure

Bending tests including cyclic unloading and reloading were carried out on thin beam specimens. The materials used are shown in **Table-1**. The specimens were made with normal mortar and expansive mortar as shown in **Table-2**. The water-to-binder ratio was 0.5 for all specimens. Three kinds of specimen were prepared; namely, normal mortar (NM), expansive mortar without restraint (FE: free expansion), and expansive mortar with a restraining steel bar (CP: chemically prestressed). In the chemically prestressed members, a D6 deformed

Table 1 Materials

Cement	Ordinary Portland Cement Specific Gravity : 3.15
Sand	Specific Gravity : 2.47 Water Absorption Ratio : 1.60
Expansive Agent	CSA Type : for Structure
Steel	D19 deformed bar Es = $1.93*10^5$MPa

Table 2 Mix Proportions of Mortar

	W/(C+E) (%)	E/(E+C) (%)	Unit Weight (kgf/m^3)			
			W	C	E	S
Normal Mortar	50	0	409	818	0	818
Expansive Mortar	50	11	408	726	90	816

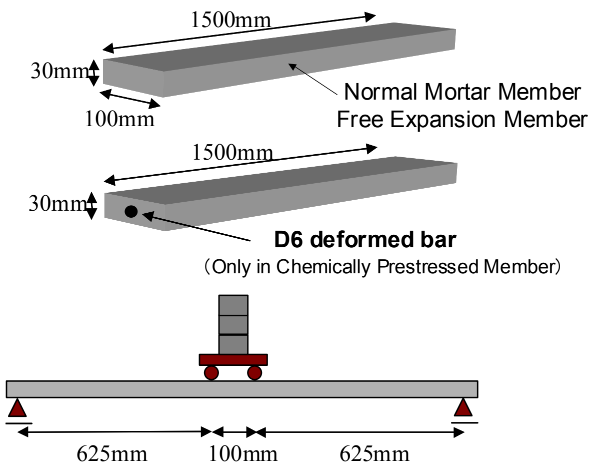

Fig.2 Dimensions of Thin Beams and Loading System

bar was located at the center of the section (neutral axis), and the reinforcement ratio in the section was 1.05%. The beam specimens measured 100 mm in width, 30 mm in thickness, and 1,500 mm in length (**Fig. 2**). Their length was determined in consideration of Tsuji's finding [11] that, in chemically prestressed members, expansive strain can be treated as almost uniform in the section more than 500 mm from the member end. The specimen dimensions were chosen so as to allow application of complicated loading patterns, including unloading and reloading, with comparatively small weights. Mortar was used to make these thin specimens. Mortar with a water-to-binder ratio of 0.5 is prone to bleeding, but these specimens were thin and in fact almost no bleeding was observed. If 11% of cement were to be replaced with expansive agent in the case of concrete with about 300 kg of cement per unit volume, the amount of expansive agent would be less than that required to introduce chemical prestress, though it would approximate the amount needed for shrinkage compensation. However, in this experiment, mortar and not concrete was used, so the amount of expansive agent per unit volume was higher and expansive strain was comparatively greater.

Specimens were made in the experimental laboratory at about 20 degrees centigrade, and the formwork was removed one day after casting. Specimens were then cured in water at about 20 degrees centigrade until the bending tests were carried out. Until the removal of formwork, all faces of the specimen were in contact with the formwork and water was unable to either enter or leave the mortar. Loading was conducted at 1, 3, 7, and 21 days. Just prior to loading, the surface of the specimens was coated with very thin epoxy resin in order to avoid water movement during the loading procedure.

As shown in **Fig. 2**, two-point loading was carried out at 1,350 mm centers and with a 100 mm constant moment span. On the top and bottom faces of the specimen within the constant moment span, 60 mm strain gauges were attached, and strain was measured at the compressive and tensile ends of the beam. Instantaneous loading and unloading was repeated using weights. After each loading and unloading cycle, the load was held unchanged for one minute in order to observe time-dependent deformation under constant loading. Expansive strain from one day at the surface of the mortar in the center of the span was 1,000μ (3 days), 1,150μ (7 days), and 1,200μ (21 days) in the case of chemically prestressed members, and 3,100μ (3 days), 3,300μ (7 days), and 3,500μ (21 days) in the case of free expansion members.

3.3 Analysis of Nonlinear Behavior based on Elasto-Plastic and Fracture Model [12]

Experimental results for normal mortar and chemically prestressed members at three days are shown in **Fig. 3**. These are the relationship between load and tensile strain at the bottom face. Compared to normal mortar, which exhibits almost linear behavior until cracking, the chemically prestressed member demonstrates remarkable nonlinear behavior. Three significant characteristics can be noted.

First, in the case of the chemically prestressed member, stiffness during unloading gradually decreases as the maximum experienced load increases. It is well known that stress-strain relations are close to linear during unloading and reloading. Therefore, the gradual reduction in unloading stiffness means that the volume of the constituent materials of the mortar gradually decreases, thus giving it the ability to take up the elastic strain energy [12]. View quantitatively in **Fig. 4**, the data shows that in the case of NM, the deformation per unit weight during unloading is almost constant, while in the case of CP and FE, the deformation per unit weight gradually increases. This clearly means a reduction in stiffness.

The second notable characteristic is that considerable residual strain remains after unloading. As **Fig. 3** shows for the case of CP at three days, about half of the total deformation before cracking is plastic tensile strain. **Fig. 5** shows the relationship between maximum experienced load and residual tensile strain at the bottom face after unloading (60 seconds after unloading). Residual strain is very small in NM, but remarkable residual strain was observed in CP.

The third characteristic is that remarkable deformation was observed under constant load. In the case of CP at three days, deformation as great as 160 μ in one minute was observed near the cracking load. However, it should be noted that deformation on this scale occurred because the reinforcing bar was placed near the neutral axis. It is thought that in a normal chemically prestressed member, with reinforcing bars on the tension side, deformation under constant load would not be as large as in this experiment. This will be explained further in section 4.

The tendencies seen at the tensile end of a chemically prestressed member were observed also at the compressive end. **Fig. 6** shows the deformation per unit weight during unloading at the compressive end. The change in stiffness of CP and FE was also observed at the compressive end. However, according to past research by the authors [13], the behavior of expansive mortar in compression differs little from that of normal mortar at the levels of compressive stress experienced around the cracking stress in flexural members. For this reason, we deduce that behavior peculiar to chemically prestressed members appears on the tension side, and this has an effect on behavior on the compression side. A detailed discussion of how expansive concrete exhibits nonlinearity under pure tensile stress will be presented later in section 4.

The type of nonlinearities seen, which include reductions in stiffness and plastic deformation, are similar to those of concrete in compression. Consequently, the nonlinear behavior of expansive concrete is going to be analyzed with reference to the Elasto-Plastic and Fracture (EPF) Model, which express the complex nonlinear behavior of normal concrete under compressive stress.

In the EPF Model, concrete nonlinearity is expressed in terms of fracturing and plasticity. A fracture is defined as the disappearance of a volume of the constituent material which reserves the strain energy, while plasticity is an irreversible deformation obtained as the total strain in the zero stress state. It is assumed that fractures originate as a result of the accumulated mechanical damage to the concrete, such as the appearance of micro cracking, microscopic buckling, and collapse of the mortar and aggregates. On the other hand, it is thought that plasticity originates from the collapse of fine voids in the concrete, and from mechanical slippage between coarse aggregate and mortar. The fracturing and plasticity in the EPF Model do not depend on each other, but both phenomena are considered to occur at the maximum experienced stress. In virgin loading, fracturing and plasticity both arise, and thereafter the concrete exhibits nonlinearity. However, in unloading and reloading, the stress-strain relationship is almost linear, and fracturing is seen as a reduction in stiffness. Plasticity is treated as a residual strain (**Fig. 7**). In the EPF Model, concrete in uni-axial compressive stress is modeled from micro constituent elements arranged in parallel. It is further assumed that the fracture strength of a constituent element is not constant but has a strength distribution. Because each constituent element loses its ability to support the stress when the stress level applied to it reaches the fracture strength, unloading stiffness gradually decreases as the maximum experienced stress increases. However, according to Maekawa et al., this assumption of a strength distribution includes the effects of the stress distribution in the concrete due to variations in the properties of the materials of which it is composed, and this is rather dominant.

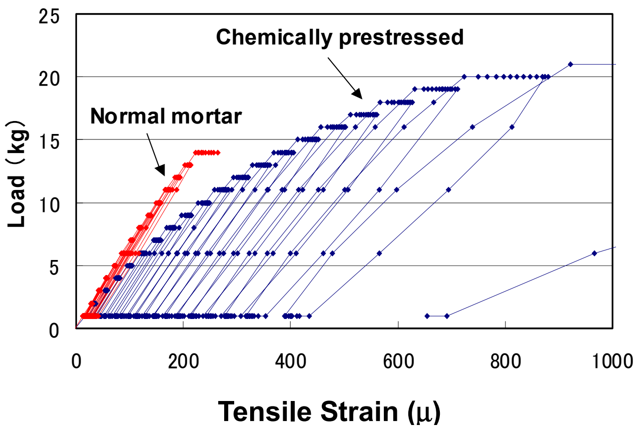

Fig.3 Load and Strain at the Tensile End (3days)

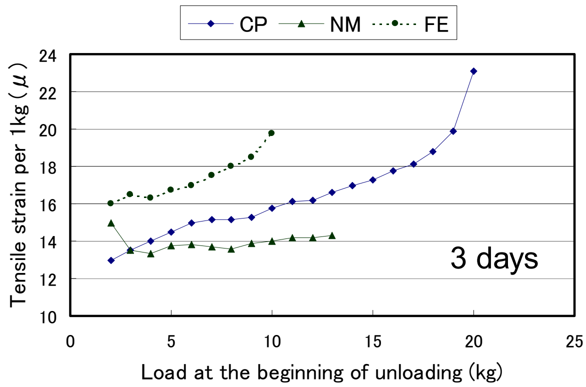

Fig.4 Deformation per Unit Load in Unloading (Unloading Stiffness, Tensile End, 3 days)

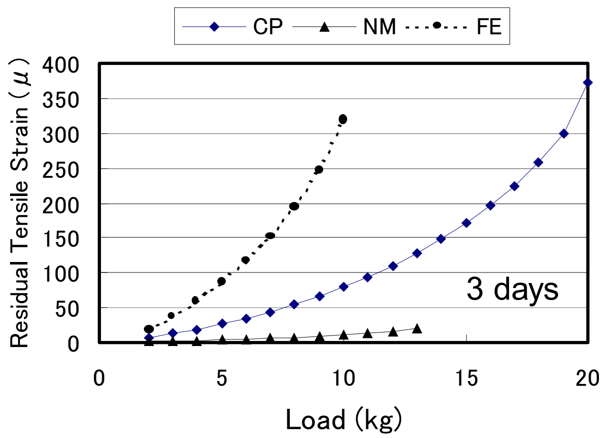

Fig.5 Residual Strain after Unloading (Tensile End, 3 days)

Referring to the EPF Model, we assume that expansive concrete in uni-axial tension is modeled as a parallel arrangement of micro constituent elements. Further, we have reached the understanding that the initial strain of each constituent element is distributed.

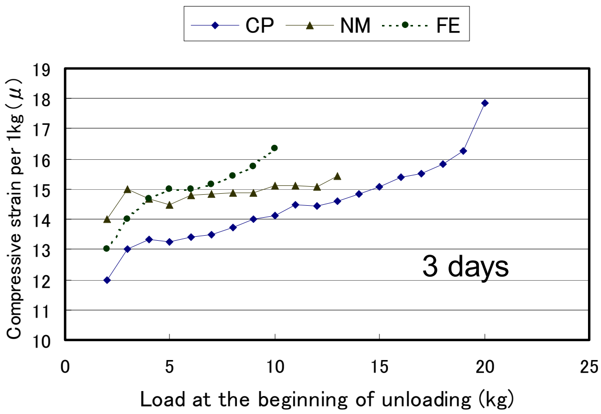

Fig. 6 Deformation per Unit Load in Unloading (Unloading Stiffness, Compressive End, 3 days)

3.4 Concepts underlying Explanation of Nonlinear Behavior of Expansive Concrete in Tension

In order to explain the phenomena by which unloading stiffness decreases as the maximum tensile stress increases, each micro constituent element needs to exhibit different properties. In the EPF Model, element strengths are assumed to be distributed, but in the case of expansive concrete in tension, we assume that each micro constituent element has its own initial strain before tensile force is applied (even though they have the same material properties). Here, it is assumed that the micro constituent elements are gradually produced as hydration of the cement proceeds, and that a fist-sized piece of concrete is represented by a group of constituent elements. Weak points near aggregate and paste matrix boundaries, micro damage around the expansive agent (as discussed later), and the large compressive strain introduced into the paste matrix are represented by the assumption that initial strain of each element is distributed (**Fig. 8**).

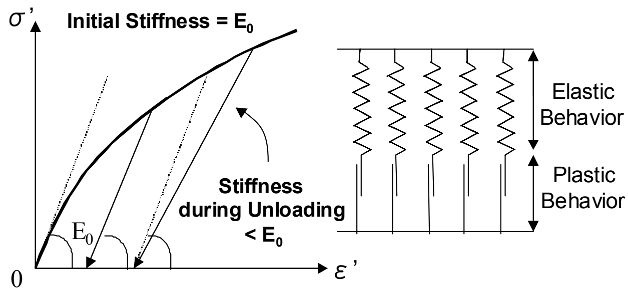

Fig.7 Elasto-Plastic and Fracture Model

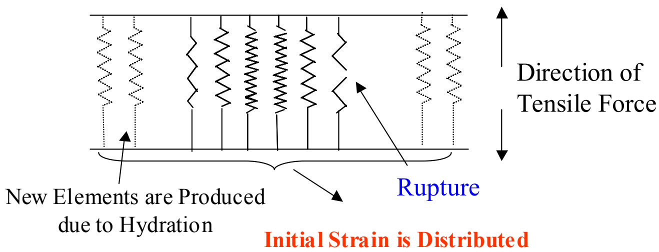

Fig.8 Micro Constituent Elements and Initial Strain Distribution

The hydration of the expansive agent is considered to be a topo-chemical reaction, so expansive reaction products around the agent force the cement matrix and aggregate outward [14]. It has been reported that, in the case of free expansion, micro cracks can be observed around the expansive agent with an optical microscope [15]. This means that tensile stress acts at a microscopic level on some parts, and micro cracks may result from this tensile stress. In the case of free expansion without an external restraint, a tensile force corresponding to the compressive force due to expansion acts on the internal structure of the concrete, and the compressive force and tensile force are in equilibrium. On the other hand, in the case of expansive concrete with an external restraint such as a steel bar, most of the tensile force is carried by the steel, so the corresponding compressive force accumulates in the concrete. In this situation, the averaged compressive force acts on concrete, but it is considered that at the microscopic level there is a distribution of internal stress. In fact, in our observations of uni-axially restrained expansive mortar using a microscope, micro cracks were found in the direction normal to the restraint, though they were rare and very small. This means that even under restrained condition, tensile stress acts on some localized sections. Based on these considerations, we arrive at the understanding that in expansive concrete, the initial strains of micro constituent elements are in some kind of distribution.

Adopting the assumption that expansive concrete under uni-axial tension comprises parallel micro constituent elements, along with certain other assumptions, it becomes possible to qualitatively explain nonlinear behavior. Here, taking into account the smoothness of stress stream under tensile stress, it is assumed that when tension is applied to expansive concrete then the tensile strain uniformly acts on each constituent element. A further assumption is that a micro constituent element has a uniform rupture criterion in tension, which is not affected by concrete age. **Fig. 9** illustrates a group of micro constituent elements whose initial strain is distributed due to expansion of the expansive agent. Here, the horizontal axis represents the initial strain introduced into the constituent elements, while the vertical axis shows the number of elements. The zero point on the horizontal axis means the point where the initial strain is zero. For example, if we consider expansive concrete in free expansion, each micro constituent element has its own initial strain distributed from compression to tension, and the total force of all the elements is zero.

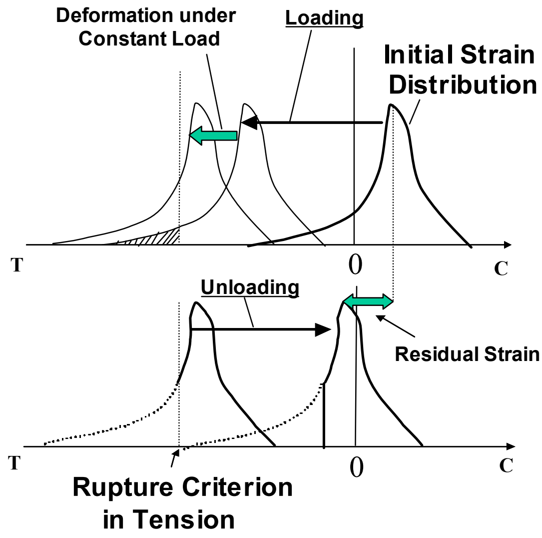

Fig.9 Mechanism of Nonlinear Behaviors of Expansive Concrete

When uni-axial tensile force is applied, a uniform tensile strain is applied to each element, and this is represented by a uniform shift of the strain distribution to the tension side in **Fig. 9**. As the strain distribution shifts, any elements whose tensile strain exceeds the rupture criterion suffer rupture. And if some elements do fail, the volume which reserves the strain energy decreases, and leads to a decrease in unloading stiffness. And since some elements rupture, in unloading, the total force is balanced before returning to the original position. The difference between the new balanced position and the original position is the residual post-unloading strain. Furthermore, if a small deformation of expansive concrete occurs under constant load within a short time, elements near the rupture criterion will fail. In such a case, with elements that should be carrying tensile force ruptured, further deformation occurs in order to achieve a balance (re-distribution of stress). In this way, as noted above, the concept of strain distribution can be used to qualitatively explain behavior peculiar to expansive concrete.

The initial strain distribution introduced into constituent elements is largely dependent on the restraint conditions, the age of the concrete, the mix proportion, and environmental conditions, etc. Here, in order to discuss the essential role of the expansive agent, we discuss in particular the effects of restraint conditions and concrete age on initial strain distribution.

In the case of normal concrete, micro constituent elements will be formed with little initial strain, because the action of the expansive agent is missing. As the concrete becomes old, only the number of constituent elements increases, while the shape of the strain distribution does not change so much from its initial state, which is a very sharp peak at the zero position.

Next, we look at the case of expansive concrete in free expansion. At a very early age, when the reaction of the expansive agent is proceeding very rapidly, the initial strains introduced into the elements have a wide distribution. Elements whose strain exceeds the rupture criterion will fail. However, no significant compressive strain accumulates because the compressive force of elements must be balanced only against the tensile force introduced into the concrete, which is not very large. As the concrete gradually ages, the reaction rate of the expansive agent falls, and a large number of constituent elements will appear near the zero position. Ultimately, therefore, the shape of the strain distribution is thought to be similar to that of normal concrete, with a large, sharp peak near the zero position.

Finally, we look at the case of expansive concrete with an external restraint. At a very early age, when the reaction of the expansive agent is active, large compressive strains accumulate in some elements, and this corresponds to the large tensile force carried by the restraining steel bars. During this process, the total volume of expansive concrete is increasing, so the tensile strain acts locally on some sections. It can be considered that some elements have tensile strain, and that the initial strain is distributed widely from tension to compression. As the concrete ages, the reaction rate falls, and newly produced elements have a smaller distribution of initial strain. However, the compressive strain introduced at an early age remains, so it is considered that the strain distribution of total elements is maintained for a long time.

In the next section, the experimental results for thin beams will be analyzed in light of the ideas described above.

3.5 Experimental Results and Discussion

(a) Decrease in Unloading Stiffness

It can be considered that the changes in unloading stiffness shown in **Fig. 4** are brought about by the distribution of initial strain, which causes gradual rupture of constituent elements and a consequent decrease in unloading stiffness. **Fig. 10** to **12** show the differences in unloading stiffness at the tensile end at 1, 7, and 21 days. At any age, the stiffness of normal mortar (NM) varies little because there is almost no initial strain distribution. In contrast, the change in unloading stiffness of a chemically prestressed member (CP) is considerable, because the initial strain distribution is large at an early age. As time passes and the age of 21 days is reached, the unloading stiffness of CP changes less, but compressive strain due to the restraint is maintained. As a result, a decrease in unloading stiffness can be seen especially near cracks. In other words, even at 21 days, the effects of the initial strain distribution can still be seen in the experimental results. In the case of free expansion (FE), the unloading stiffness changes up to around 3 days, because there is an initial distribution of strain. But by 7 or 21 days, the number of elements whose initial strain is has little distribution increases, and the unloading stiffness does not change very much. In this sense, it is similar to NM.

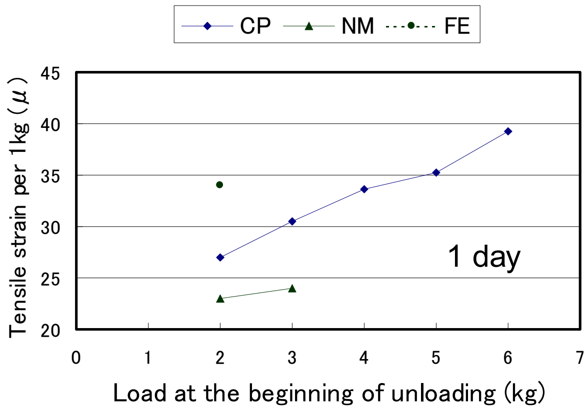

Fig.10 Deformation per Unit Load in Unloading (Unloading Stiffness, Tensile End, 1 day)

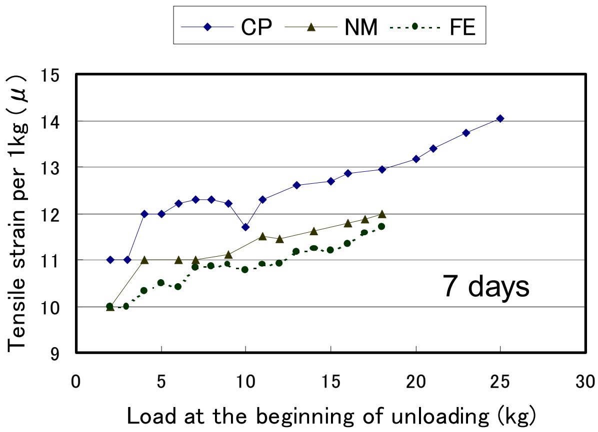

Fig.11 Deformation per Unit Load in Unloading (Unloading Stiffness, Tensile End, 7 days)

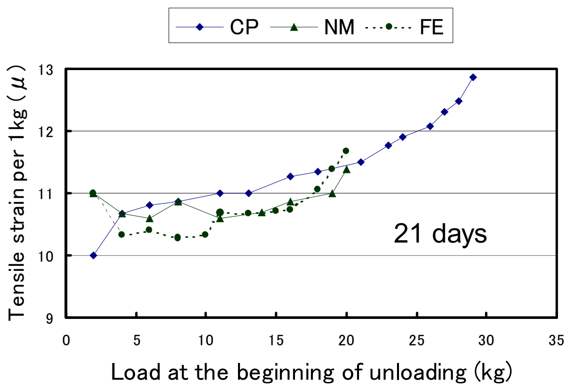

Fig.12 Deformation per Unit Load in Unloading (Unloading Stiffness, Tensile End, 21days)

(b) Plastic Deformation and Time-Dependent Deformation Peculiar to Expansive Mortar

As shown in **Fig. 13**, large deformation of CP is observed under constant load, and a large residual strain remains after unloading. In particular, just before cracking, as much as 150μ of strain is observed in only one minute at the tensile end under constant loading. Considerable nonlinearity is also observed in the case of FE, though not as much as in the CP case. In **Fig. 13**, the relationship is given between load and deformation at the tensile end after one minute when each load is applied at 3 days. For example, in the case of CP, in the minute following application of 15 kg, a deformation of 40μ was observed. As can be seen in the figure, the relationship is almost linear in the case of NM, while for CP and FE the deformation increases nonlinearly. Deformation near cracking is particularly large. When the applied tensile force approaches the tensile strength, it can be considered that the number of the elements whose strain exceeds the rupture criterion suddenly increases, and extremely large deformation occurs. Actually, cracking occurred when 21 kg was applied to CP, and in the minute following application of 20 kg deformation of more than 150μ was observed. It appeared that rupture of elements in tension prevented balancing of the forces.

As seen in **Fig. 13**, when 20 kg was applied to CP, tensile strain at the tensile end was around 800μ, so it can be considered that a large number of elements ruptured in tension, and suddenly the balance of forces was lost.

Fig. 14 shows the deformation after a minute under constant load at the tensile end, and the recovery deformation in the minute following unloading for CP at 3 days. **Fig. 15** shows the same results for NM at 3 days.

In **Fig. 14**, it is evident that even in the range of small loads, deformation of CP under constant loading includes irreversible deformation. In particular, near cracks, irreversible deformation is much greater than the reversible deformation. The time-dependent deformation shown here is the deformation after one minute under each load, and the total sum of the irreversible deformations at all loads is almost equivalent to the residual strain at the tensile end. On the other hand, in **Fig. 15**, very little deformation is seen in NM, and almost all of it recovers in the minute after unloading. As a result, almost no residual strain is observed.

(c) Plastic Deformation and Time-Dependent Deformation at Each Age

As time passes, the initial strain distribution changes, and this affects plastic deformation and time-dependent deformation. **Fig. 16** to **18** show the deformation after a minute under constant load and the recovery deformation a minute after unloading both at the tensile and compressive ends of CP at 3, 7, and 21 days. **Fig. 19** to **21** show the same data for NM at 3, 7, and 21 days. **Fig. 22** to **23** show the same for FE at 3 and 21 days.

As **Fig. 16** shows for the case of CP at 3 days, irreversible deformation occurs at both the tensile and compressive ends. Irreversible deformation in the small load range means that a certain amount of micro constituent elements fail even at small tensile strains. In other words, before loading, a certain number of elements were already in tension and their tensile strains were close to the rupture criterion. As also seen in **Fig. 16**, when the load is near the cracking load, the deformation after one minute rises, and the ratio of irreversible deformation increases. This is considered to be because a considerable proportion of the elements have failed.

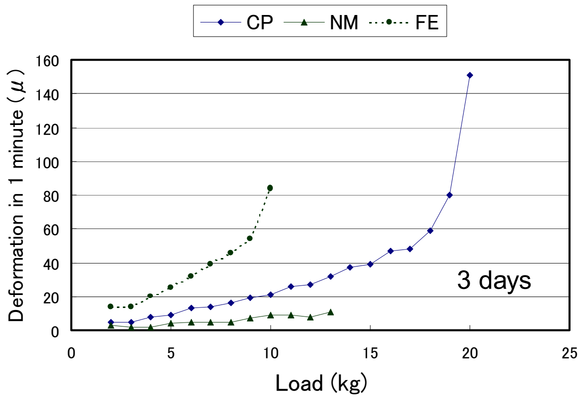

Fig.13 Deformation under Constant Load (Tensile End, 3 days)

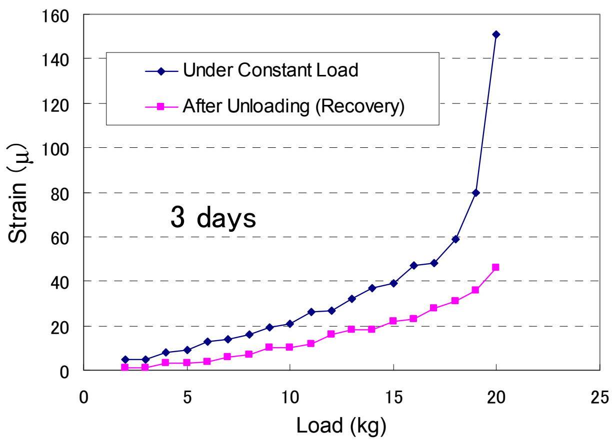

Fig.14 Deformation under Constant Load and Recovery after Unloading (CP, Tensile End, 3 days)

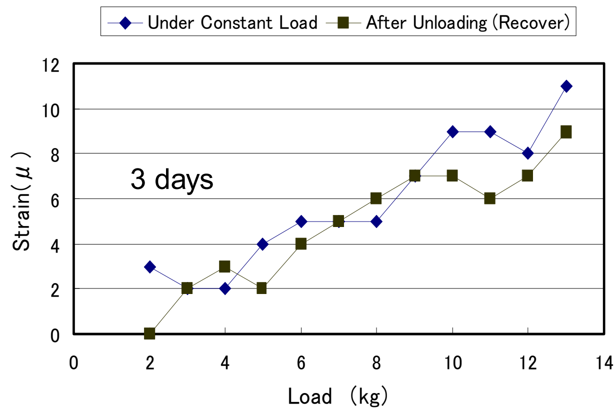

Fig.15 Deformation under Constant Load and Recovery after Unloading (NM, Tensile End, 3 days)

As time passes, as shown in **Fig. 17** and **18**, little irreversible deformation is observed in the small load range. This is thought to be because the initial strain distribution changes. The reaction of the expansive agent slows, and thereafter as a result of active cement reactions the ratio of elements with small initial strain distributions becomes greater. In this situation, when a small load is applied, the ratio of failed elements to the total is so small that no re-distribution of stress occurs. However, when the applied load is high, the ratio of failed elements increases, and then deformation after one minute of loading and the irreversible deformation become greater. This means that even at 21 days, when the reaction of the expansive agent has just about stopped, the initial strain distribution is maintained. This is because the large compressive strain introduced at a very early age, while the reaction of the expansive agent remains active, accumulates in many elements, and this strain is maintained for a long time by the steel restraint.

As shown in **Fig. 19** to **21**, NM shows the same tendency regardless of age. The deformations after one minute at the tensile and the compressive ends are almost the same, and almost all of them recover within one minute of unloading. This can be explained by our understanding that, in the case of NM, the initial strain barely has any distribution, so little rupturing of elements occurs before the cracking load.

Next, the results for FE are discussed with respect to **Fig. 22** and **23**. At 3 days, the irreversible deformation is large in the range of small load, while the deformation under loads near the cracking load is very large. This is similar to the behavior of CP at 3 days. In the case of FE, however, the initial element strain has a distribution due to the reaction of the expansive agent, but there is no restraint so the compressive force is balanced only against the tensile force in the concrete. As a result, the strain distribution is different from that of CP, and is very wide and on the compression side on average. However, at around 3 days, the expansive agent is still very active, so the initial strain distribution is comparatively large; thus the behavior of FE is similar to that of CP at this time. At around 21 days, the reaction of the expansive agent has dwindled, and elements with almost no initial strain become dominant. The FE then performs more like NM. At loads near the cracking load, however, irreversible deformation is observed due to the strain distribution. At around 3 days, the cracking load of FE is much smaller than that of NM, but by around 21 days they are almost the same. This can also be explained by our understanding that the strain distribution of FE becomes similar to that of NM at around 21 days.

To summarize the discussions in this section, an attempt has been made to rationally explain behavior peculiar to thin beams made with expansive mortar. Referring to the EPF Model, expansive concrete in tension was modeled as a series of parallel micro constituent elements. As a result of the expansion energy resulting from reaction of the expansive agent, it was assumed that there is a distribution of initial element strain. The nonlinear behavior seen in the experimental results can be explained qualitatively by adopting this interpretation.

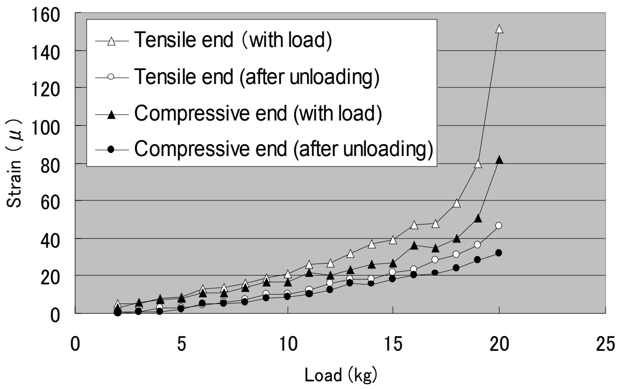

Fig.16 Deformation under Constant Load and Recovery after Unloading (CP, 3 days)

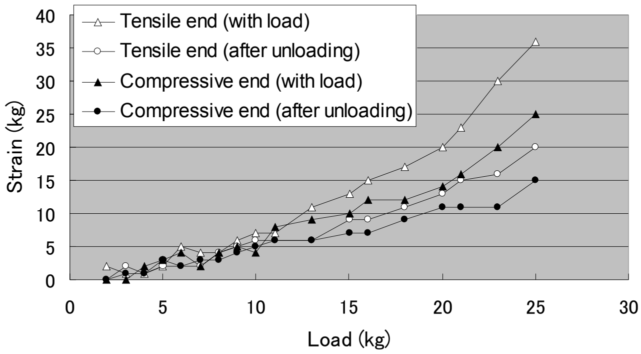

Fig.17 Deformation under Constant Load and Recovery after Unloading (CP, 7 days)

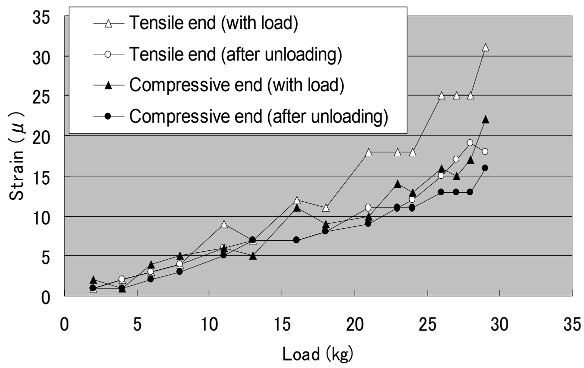

Fig.18 Deformation under Constant Load and Recovery after Unloading (CP, 2 1days)

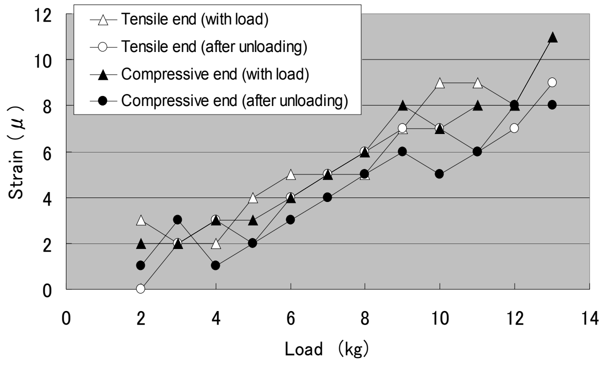

Fig.19 Deformation under Constant Load and Recovery after Unloading (NM, 3 days)

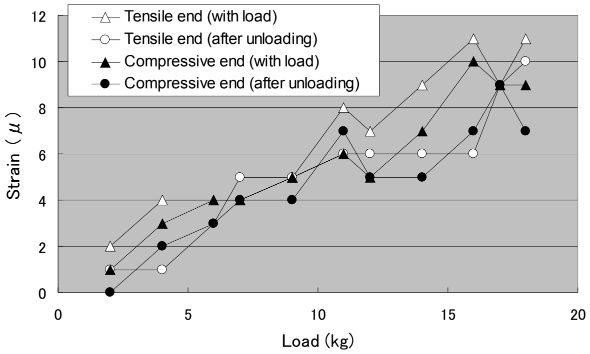

Fig.20 Deformation under Constant Load and Recovery after Unloading (NM, 7 days)

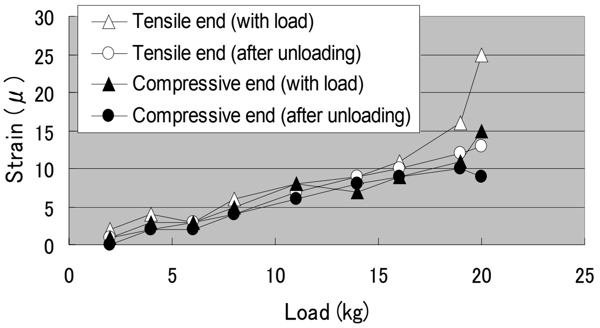

Fig.21 Deformation under Constant Load and Recovery after Unloading (NM, 21 days)

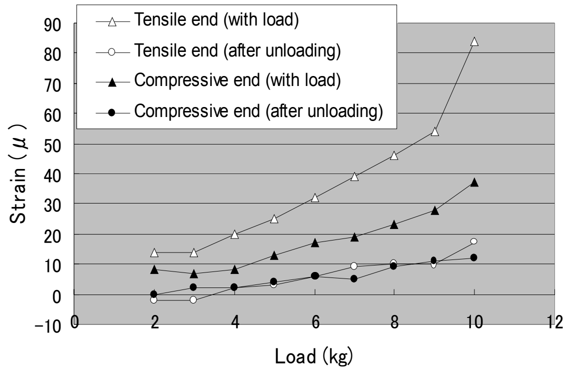

Fig.22 Deformation under Constant Load and Recovery after Unloading (FE, 3 days)

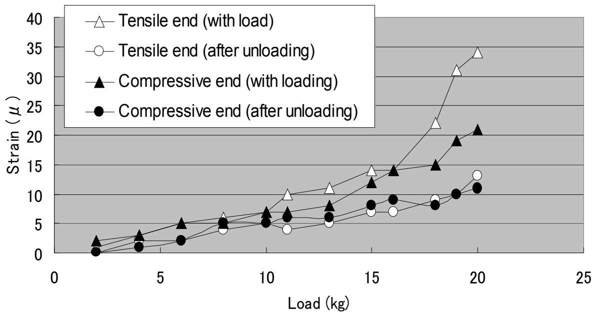

Fig.23 Deformation under Constant Load and Recovery after Unloading (FE, 3 days)

4. UNI-AXIAL TENSION TEST (EXPANSIVE MORTAR RESTRAINED BY STEEL)

4.1 Objectives

In section 3, the mechanism of nonlinear behavior by expansive concrete in tension was discussed based on experimental results using thin beams. However, the explanation given is simply based on some ideas by the authors, and there is no clear evidence that expansive concrete in tension exhibits nonlinear behavior as a result of the mechanism we suppose. In this chapter, uni-axial tension tests are carried out as a way to obtain more direct evidence.

Almost all tension tests carried out on expansive concrete in the past were implemented with no restraint (free expansion) or after the restraint had been released. However, expansive concrete really exhibits its advantages in restrained conditions, so we really need more information about the tensile properties of restrained expansive concrete. Here, uni-axial tension tests on expansive mortar with an internal restraint consisting of a steel bar are carried out. Cyclic loading with an unloading procedure is carried out until cracking, as in section 3.

4.2 Experimental Procedure

Uni-axial tension tests were carried out. The specimens were made with expansive mortar and normal mortar. The material properties were as shown in Table-1, and the mix proportion as in **Table-3**. The water-to-binder ratio is different in this experiment from that of the thin beams in section 3. In this section, the water-to-binder ratio is made smaller in order to restrain the effects of bleeding, taking into account the larger size of the specimens. As shown in **Picture-1**, the center of the specimen section is penetrated by a D19 deformed steel reinforcing bar to restrain expansion, and tensile force is directly applied to the rebar for loading. The section of the specimen is square, measuring 100 mm x 100 mm, and it is 1,000 mm long. Screw-shaped D19 reinforcing bars are used, and their Young's modulus is 1.93x x 10^5 MPa. Formwork was removed at 3 days. Confirmation was obtained that bonding was sufficient over the whole section, in that the strain of the rebar and that at the specimen surface was almost the same. The specimens were cured under wet conditions after removal of the formwork, and loaded at 3 days or 7 days. Cyclic loading was applied, with the inclusion of an unloading phase one of the main characteristics of this experiment. Expansive strain after casting was measured using strain gauges (gauge length = 5 mm) attached to the rebar at 10 cm spacing. During cyclic loading, the load applied to the rebar, the rebar strain, and the mortar/paste strain were measured. The mortar/paste strain was measured using strain gauges measuring 60 mm and attached to the surface of the specimen over a continuous length of 50 cm. During testing, almost all strain gauges on the steel and the mortar/paste indicated close to the same values just before cracking. The steel strain at the strain gauge nearest the crack and the mortar strain obtained from the strain gauge under the crack were picked up for use as experimental results, and it is these that are discussed in the next section. The loading rate was about 0.1 MPa/minute, but unloading was instantaneous. Reloading was again at the rate of 0.1 MPa/minute from near the maximum experienced load.

Table 3 Mix Proportions of Mortar

	W/(C+E)	E/(E+C)	Unit Weight (kgf/m^3)			
			Water	Cement	Expansive Agent	Sand
Normal Mortar	0.4	0	356	891	0	891
Expansive Mortar	0.4	0.11	355	791	98	889

Picture 1 Uni-axial Tension Test

4.3 Experimental Results and Discussion

Post-casting expansive strain is shown in **Fig. 24**. The relationship between load and tensile strain of the mortar is shown in **Fig. 25** both for normal mortar (NM) and expansive mortar (CP) at 3 days. This figure clearly shows that the normal mortar member exhibits almost linear behavior until cracking, whereas nonlinearity is predominant in the case of the expansive mortar member while the cracking load is much higher than for normal mortar. This relationship between load and tensile strain includes the effect of steel in the elastic range. Therefore, the stress-strain relationship of the mortar alone was calculated, and this is shown in **Fig. 26**. This was accomplished by calculating the tensile force carried by the steel and subtracting it from the total tensile force; the remaining tensile force — that is, the force carried by the mortar — was divided by the sectional area of mortar. As **Fig. 26** demonstrates, the stress-strain relationship of expansive mortar exhibits notable nonlinearity. As will be discussed later, it was proved that the unloading stiffness gradually decreases as the maximum experienced stress increased, and that residual strain is observed after unloading. These tendencies were not seen for normal mortar members. We believe the experimental results given in this section support our explanation of the experimental results for thin beams in section 3.

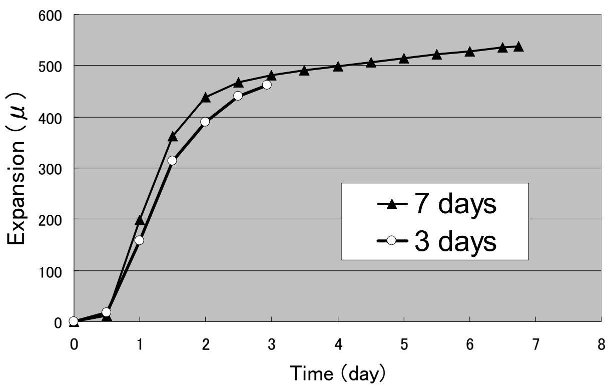

Fig.24 Expansive Strain after Casting

Fig. 27 shows the unloading stiffness; that is, the stress carried by the mortar during unloading divided by the deformation of the mortar. The horizontal axis represents the stress carried by the mortar during unloading. The unloading stiffness of CP was, from the beginning, smaller than that of NM, and it was shown that the unloading stiffness of CP clearly decreases as the applied tensile stress rises. However, it should be noted that as long as the tensile stress is below about 0.5 MPa, the unloading stiffness is calculated with less accuracy because the measured tensile strain was small. Based on the explanation developed in section 3, it is possible to explain these experimental results. The stiffness of CP was smaller than that of NM from the beginning, because some of the micro constituent elements of CP had already failed prior to loading. Further, the unloading stiffness gradually decreased as elements failed in order when their tensile strain exceeded the rupture criterion.

Fig. 28 shows the residual strain after unloading. The horizontal axis is the same as that in **Fig. 27**. In the case of NM, even when the applied tensile stress approaches the tensile strength, the residual strain remains very small. On the other hand, in the case of CP, the residual strain increases nonlinearly in the range of tensile stresses up to 2.0 MPa and beyond. Here, the residual strains measured both with a steel strain gauge and a mortar strain gauge are shown.

At around 3.5 Mpa, where the unloading stiffness begins to decrease notably, residual strain starts to increase rapidly. This coincidence of observations seems to support our explanation for the nonlinearity of expansive concrete.

However, the nonlinearity seen here is rather small compared to that of the CP thin beam at 3 days, as discussed in section 3, though the water-to-binder ratios are only slightly different. This is mainly because the reinforcement ratio is much larger (2.9%) and the loading was conducted in a uni-axial direction in the test described here. In the thin beam experiment, deformation of more than 100μ was observed after just one minute of loading near the cracking load (at 3 days). On the other hand, in the case of this uni-axial tension test, deformation was hardly noted under constant load. When micro constituent elements fail due to the application of tensile strain, deformation occurs so as to balance the forces. But minimal deformation is enough to secure a balance, because the reinforcing bar carries a large part of the tension. Under the conditions used for this uni-axial experiment, deformation to be balanced under constant load is very small to happen. Thus, in chemically prestressed members in which the tensile reinforcing bars are well arranged, time-dependent deformation over the short term under constant load is not very great.

Fig. 29 to **32** show the experimental results at 7 days. Compared to the 3-day case, CP nonlinearity is somewhat less, but clear nonlinearity can be seen especially around cracks. The unloading stiffness of CP gradually decreases, and again near cracking the decrease is particularly notable. It is deduced that a considerable number of elements fail near cracks, and this led to macro cracking. In the case of NM, a slight decrease in stiffness can be seen just before cracking. Even in the case of NM, the initial strain is not

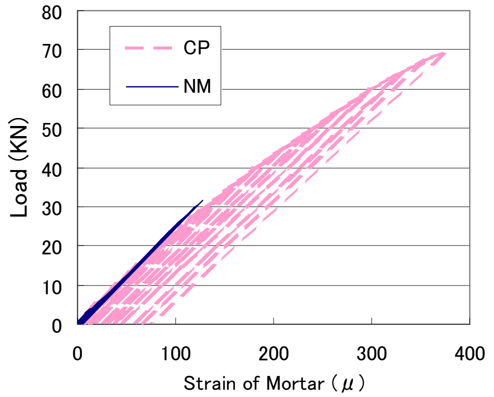

Fig.25 Load-Tensile Strain Relationships (3 days)

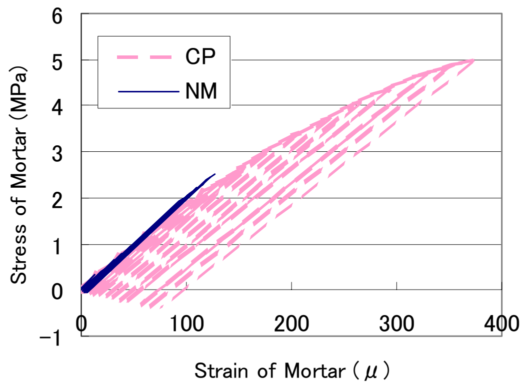

Fig.26 Stress – Strain Relationships of Mortar (3 days)

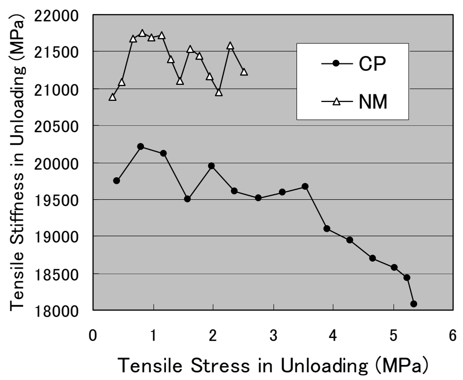

Fig.27 Change of Unloading Stiffness (3 days)

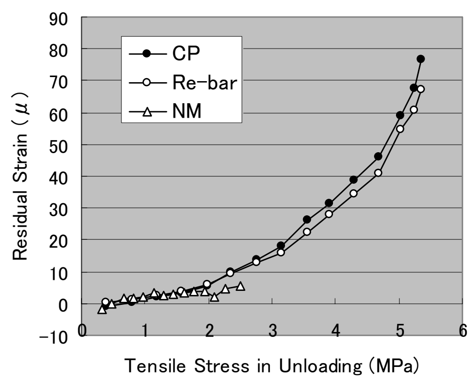

Fig.28 Residual Strain after Unloading (3 days)

perfectly uniform, so it is possible that slight nonlinearity is possible, especially near cracks.

4.4 Initial Strain Distribution and Crack Resistance

Here, the effects of initial strain distribution on the crack resistance of chemically prestressed members are discussed. As shown in **Fig. 3** and **Fig. 26**, the wide initial strain distribution of expansive mortar means that it has considerable deformability, though its stiffness gradually decreases. Here, the experimental results at 3 days are again taken up for discussion. The chemical prestress in the mortar section can be calculated from the expansive strain before loading, the reinforcement ratio, and Young's modulus of the steel. At 3 days, the calculated chemical prestress was 2.67 MPa. In **Fig. 26**, the difference in cracking stress between CP and NM appears almost equal to the calculated prestress. Thus, in general, the effect of adding an expansive agent seems to be to increase the tensile strength through prestressing, as long as we evaluate it in terms of stress. But, actually, the expansive agent contributes more than this to crack resistance, because deformability before cracking is significantly enhanced. With the mortar or concrete exhibiting greater deformability, the reinforcing bars carry an additional burden of tensile force. As a result, the crack resistance of chemically prestressed members is much improved. That is, the effects of an expansive agent cannot be rationally evaluated only in terms of stress.

Here, again we look at the experimental results at 3 days so as to discuss the effect of expansive mortar deformability on cracking in a quantitative manner (**Fig. 33**). The tensile strength of normal mortar at 3 days was 2.52 MPa, and that of expansive mortar at the same age 4.98 MPa. As is shown in **Fig. 33**, if we assume that expansive mortar has the same stiffness as normal mortar and that expansive mortar is elastic until cracking, the cracking load of CP member evaluates to about 60 kN. But, actually, expansive mortar exhibits nonlinear behavior and the cracking strain in fact reaches about 370μ, so the equivalent cracking load is 70 kN (**Fig. 33**). This enhanced cracking load arises because the steel is able to sustain additional tension force while the mortar deforms. This effect is considered to be much greater in flexural members than in uni-axial tension members.

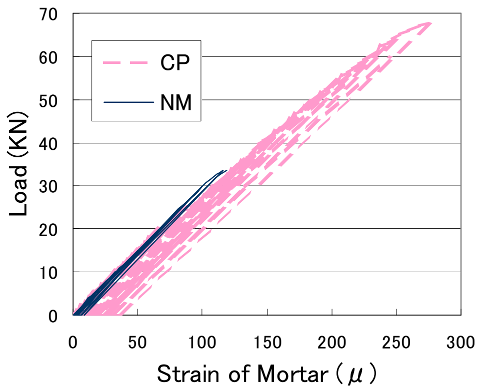

Fig.29 Load-Tensile Strain Relationships (7 days)

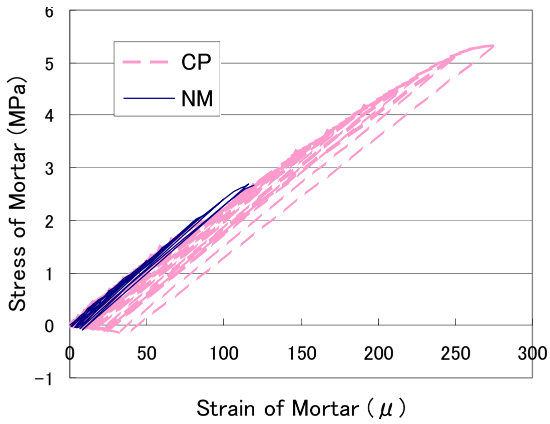

Fig.30 Stress – Strain Relationships of Mortar (7 days)

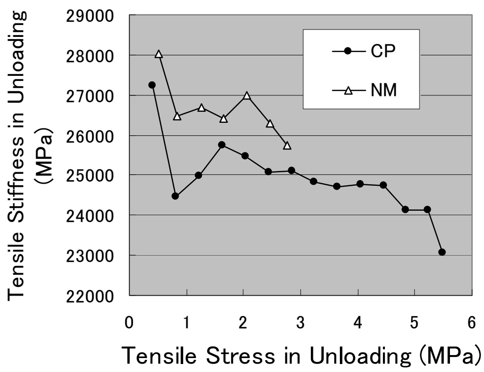

Fig.31 Change of Unloading Stiffness (7 days)

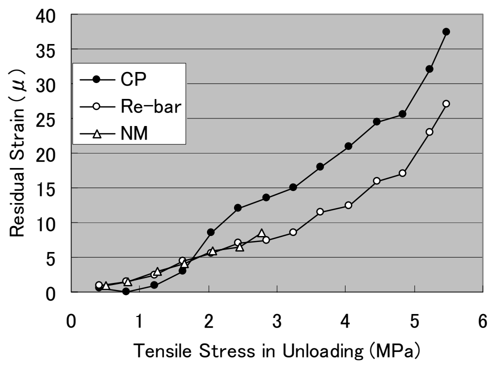

Fig.32 Residual Strain after Unloading (7 days)

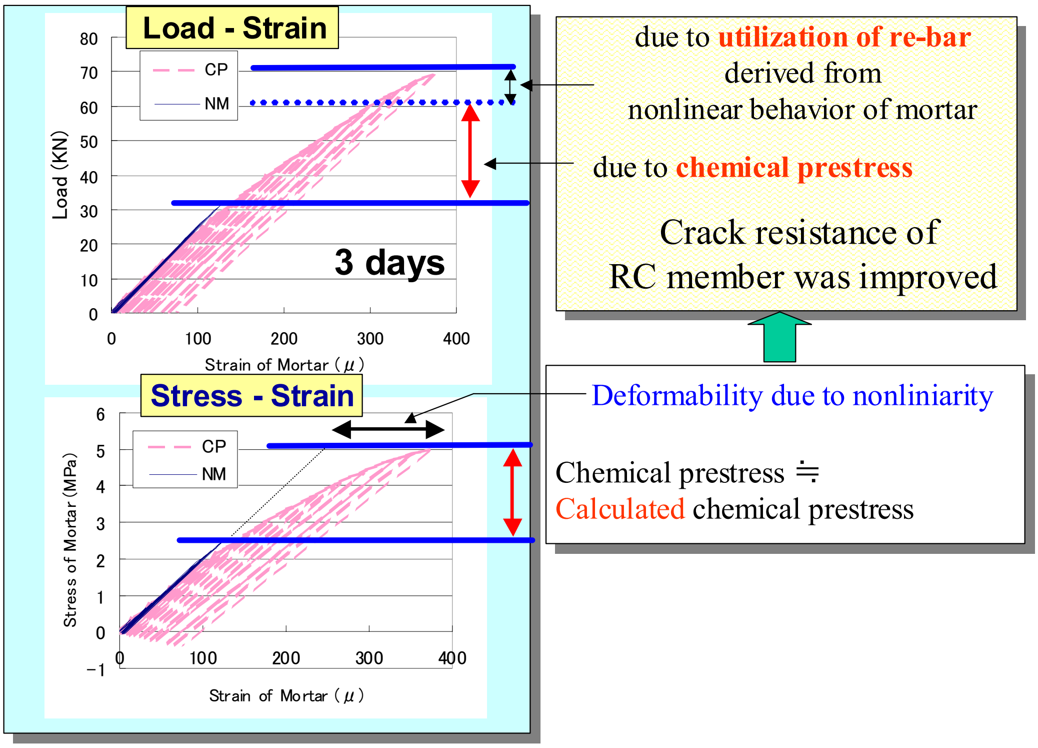

Fig.33 Deformability of Expansive Mortar and Crack Resistance (Uni-axial Tension, 3 days)

5. DIFFERENCE BETWEEN NONLINEARITY OF THIN BEAMS AND UNI-AXIAL MEMBERS

Bending tests on thin beams were described in section 3, and uni-axial tension tests in section 4. Here, we discuss why the nonlinear behavior of thin beams is more notable than that of uni-axial members.

It is considered that there are several reasons for this behavior, but one of the main ones is the function of the reinforcing bars. As already noted in section 4, the reinforcement ratio in the uni-axial tests was very large (2.9%), so it was difficult for time-dependent deformation under constant load to occur; slight deformation would introduce large tensile force to the reinforcing bars, compensating for the lost tensile force due to rupture of micro constituent elements. On the other hand, in the bending tests on thin beams, the reinforcing bar restraint was located near the neutral axis of the section, so the strain of the reinforcing bar would be much smaller than that at the tensile end. Due to rupturing of the micro constituent elements on the tension side of the beams, further deformation occurred. However, the slight deformation was not enough to introduce a great tensile force to the reinforcing bar, and considerable deformation was required for balancing to occur. If reinforcing bars had been incorporated near the tensile end, the nonlinearity would not have been as large as seen in our experiments described in section 3.

Another important reason for the difference is thought to be the difference in strain gradient between flexure and uni-axial tension, and this can be expected to affect the cracking criterion. It is generally known that the flexural strength of concrete is greater than its tensile strength. It is worth pointing out that, in bending, the propagation of crack is prevented at points distant from the tensile end and near the neutral axis, since tensile stress falls in these locations [16], [17]. The thin beams studied here had particularly large strain gradients (3 cm thickness), so it is thought that macroscopic flexural cracks did not occur easily. In other words, in the flexural case, the strain gradient prevents the sudden localization of damage at the tensile end, and the result is good deformability before macroscopic cracking. Even in the case of normal mortar, cracking strain at the tensile end of thin beams is larger than that of uni-axial members. But in the case of CP, a considerable number of micro constituent elements have initial compressive strain, and this initial strain is widely distributed, so considerable deformation is allowable until flexural cracking.

In summary, in the experiment on thin beams, the effects of initial strain distribution were particularly significant due to the large strain gradient and the arrangement of the reinforcing bar. In the case of the uni-axial tests, nonlinearity until cracking was minimal as early as 7 days of age, whereas in the case of the thin beam tests, even at 21 days the chemically prestressed members still showed significant nonlinearity and deformability (**Fig. 34**). Thus, expansive concrete offers good crack resistance in the case of flexural members that have a suitable reinforcement arrangement, because deformability due to initial strain distribution is well utilized.

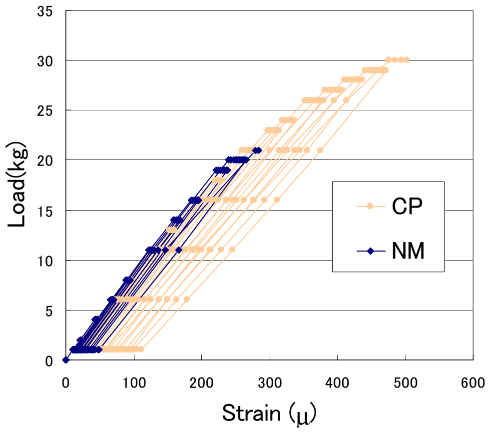

Fig.34 Load-Tensile Strain Relationships of Thin Beam (Tensile End, 21 days)

6. CONCLUSIONS

In order to clarify the mechanism of nonlinear behavior of expansive concrete under tensile stress, cyclic flexural loading with an unloading phase was applied to thin beams. A form of nonlinearity prior to cracking that is peculiar to chemically prestressed members was demonstrated in the experimental results. This nonlinearity was quantitatively analyzed in terms of residual strain after unloading and unloading stiffness. By reference to the Elasto-Plastic and Fracture Model, which can be used to model the nonlinear behavior of normal concrete under compression, a new explanation was proposed for the nonlinear behavior of expansive concrete in tension. Using this understanding, we were able to explain the nonlinear behavior of expansive mortar thin beams with and without restraining rebars. Next, cyclic tension tests on chemically prestressed members were conducted under uni-axial tensile stress. The nonlinear behavior of these members in pure tension was clearly seen in the experiments, and its mechanism was explained using the same methodology.

The following are the main conclusive results of this research.

1) Chemically prestressed members exhibit nonlinearity under tensile stress before cracking. Through cyclic loading tests with an unloading phase, it was demonstrated that residual tensile strain occurred after unloading, and that the unloading stiffness gradually decreased as the maximum experienced tensile stress rose.

2) The nonlinearity exhibited by chemically prestressed members under tensile stress is more notable at a very early age (3 days) than at 21 days. However, even at around 21 days, nonlinearity was particularly noteworthy near cracks.

3) Expansive mortar without a restraining rebar exhibited nonlinear behavior similar to that of a chemically prestressed member at around 3 days. But by around 21 days, such specimens behaved like normal mortar.

4) Expansive concrete under uni-axial tension was modeled in the form of individual micro constituent elements in parallel. It was assumed that these elements gradually formed as hydration of the cement proceeded, and that the initial strain of each element was in the form of a distribution due to hydration of the expansive agent. It was also assumed that all elements had the same rupture criterion in tension, and that ruptured elements could not sustain tensile force any longer. Based on these assumptions, the nonlinear behavior of expansive mortar members with and without a restraining rebar were rationally explained.

5) The role of an expansive agent in expansive concrete is thought to be that it causes a non-uniform distribution of stress and variation in quality at the micro level to the surrounding cement matrix and aggregate through expansive energy. When expansion is restrained in a localized region of the concrete, damage such as micro cracking occurs, while in other regions very large compressive strains accumulate. This variation in microscopic quality leads to improvement of the deformability of the concrete, which in turn increases the crack resistance of chemically prestressed members.

6) Chemically prestressed members show remarkable nonlinear behavior before cracking, and this gives them very good deformability. The crack resistance of chemically prestressed members is considerably better than that of normal members, not only because of the increase in tensile strength due to prestressing but also because of the improved deformability which arises from better distribution of the tensile force to the reinforcing bars.

References

[1] Okamura, H. and Tsuji, Y., “Behavior of Chemically Prestressed Concrete Member” (in Japanese), Transactions, Japan Society of Civil Engineers (JSCE), No.225, pp.101-108, 1974.5.
[2] Okamura, H. and Ikeuchi, T., “Effects of Creep in Flexural Members with Expansive Concrete” (in Japanese), Annual Report of Cement Association of Japan (CAJ), Vol.31, pp.225-227, 1977.
[3] Kishi, T., Hosoda, A., Gurung, B. and Kittiwuttichusinp, S., “Effect of Drying/Autogenous Shrinkage on Ductility/Fracture Mode of Beam and Self-Repairing Function of Expansive Agent”, Annual Report of Japan Concrete Institute (JCI), Vol.22, No.3, pp.511-516, 2000.
[4] Tsuji, Y., “Fundamental Study on the Use of Chemical Prestress in Concrete” (in Japanese), Transactions, JSCE, No.235, pp.111-124, 1975.3.
[5] Kokubu, M., Kobayashi, M., Nagataki, S., Okamura, H., and Machida, A., “Study on Standard Tests for Concrete with Expansive Components” (in Japanese), Transactions, JSCE, No.225, pp.93-99, 1974.5.
[6] Okamura, H., Tsuji, Y., and Goto, K., “Strength of Expansive Concrete restrained in Uni-axial Direction” (in Japanese), Annual Report of JCI, pp.85-88, 1979.
[7] Nagataki, S., and Goto, Y., “Creep Characteristics of Expansive Cement Concrete” (in Japanese), Transactions, JSCE, No.207, pp.93-105, 1972.11.
[8] Sasatani, T., Maruyama, K., Sakimura, R., and Tsuji, Y., “Tension Behavior of Expansive Concrete at Early Ages” (in Japanese), Annual Report of JCI, No.7, pp.261-264, 1985.
[9] Sakimura, R., Maruyama, K., and Tsuji, Y., “Study on Tension Properties of Expansive Concrete at Early Ages” (in Japanese), Abstracts of 40th Congress, JSCE, Vol.5, pp.64-64, 1985.
[10] Okamura, H., Tsuji, Y., and Maruyama, K., “Application of Expansive Concrete in Structural Elements”, University of Tokyo, 1977.
[11] Okamura, H. and Tsuji, Y., “Structural Performance of Chemically Prestressed Concrete Member” (in Japanese), Annual Report of CAJ, Vol.26, pp.494-498, 1972.
[12] Okamura, H. and Maekawa, K. “Nonlinear Analysis and Constitutive Models of Reinforced Concrete, Gihodo-Shuppan, Tokyo, Japan, 1991.
[13] Hosoda, A. and Kishi, T., “Compressive Behavior of Expansive Concrete whose Restraint Conditions in Uni-axial Direction are Varied” (in Japanese), Abstracts of 54th Congress, CAJ, pp.266-267, 2000.
[14] Yamazaki, Y., “Mechanism of Expansion of Concrete with Expansive Component” (in Japanese), Cement and Concrete, No.352, pp.10-18, 1976.6.
[15] Nakamura, T. and Fukaya, Y., “Expansive Deformation of Hardened Cement Paste due to Expansive Agent” (in Japanese), Annual Report of CAJ, NO.26, 1972.
[16] A.M. Neville, “Properties of Concrete” (in Japanese), Gihodo-Shuppan, pp.408-410,Tokyo, Japan, 1979.
[17] Committee Report on Fracture Mechanics, JCI, 1993.10.