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Tensile behavior of restrained expansive mortar and concrete

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ABSTRACT

Effect of restraint on the tensile behavior of expansive mortar was investigated by testing specimens with concentrically un-bonded restraint, chemically prestressed mortar (CPM), and chemically prestressed concrete (CPC). The deformation under flexural load is measured by a series of strain gages. In the test of specimens with un-bonded restraint, the restraining steel was removed and the expansion, chemical prestress, and rebound strain are measured before the flexural test. Tensile strength, cracking strain capacity as well as the plastic deformation was quantitatively investigated. The results show that the restrained expansive mortar has unique tensile properties, i.e., larger cracking strain capacity, non-linearity, and more plastic deformation. The effects of bonding between rebar and mortar, curvature, and the presence of coarse aggregate on the tensile properties of CPM and CPC were also experimentally investigated.

1. Introduction

Expansive concrete has been introduced as an efficient way to prevent cracking or improve some structural behaviors of concrete structures [1,2]. Based on the formation of ettringite or calcium hydroxide, a considerable expansion of concrete at early age can be produced. The application of expansive concrete can be classified into shrinkage-compensating concrete and chemically prestressed concrete according to its expansive energy [3]. Shrinkage-compensating concrete is defined as a concrete that, when restrained properly by reinforcement or other means, expands an amount sufficient to prevent shrinkage cracking. Recently, a shrinkage-compensating concrete with a special PA/SRA superplasticizer was successfully applied in the construction of outside industrial floors in the absence of wet curing and construction joints [4].

In the design and construction of shrinkage-compensating concrete, ACI 223 committee [5] recommends that the expansion must be equal to or slightly greater than the anticipated drying shrinkage. The concept ignores tensile strain capacity of concrete and gives conservative design; however, it limits the application of structural member under higher restraint. This is because high restraint usually limits expansion during curing period and thus less shrinkage compensating capability but creates more tensile stress in the shrinkage phase of the same mix proportion of expansive concrete. Following current guidelines, in such cases, may result in the requirement of more expansive additive and thus higher cost of material than necessary. However, by considering the cracking capacity of concrete, the design can be more efficient.

The cracking strain capacity of concrete has been investigated by many researchers. The measurement of cracking strain can be done by flexural test or direct tension test [6–8]. The state of stress and test methods considerably affect the cracking strain of concrete. The cracking strain obtained from flexural test is larger than the value obtained from direct tension test [8]. Thus, the testing method should be selected according to application of the data. In the case of drying shrinkage, the shrinkage strain is greatest at the surface where moisture lost is fastest and, as a result, the induced stress is not uniform across the section [9]. Therefore, the cracking strain obtained from the flexural test seems to be more

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suitable when shrinkage cracking or cracking of flexural member is under consideration.

Since the microstructure of expansive concrete is highly dependent on restraining stress [10–14], the cracking strain of restrained expansive concrete can be largely different from that of normal concrete or unrestrained expansive concrete in same condition and may be influenced by other factors, for instance, age of concrete and loading rate [14]. The information on the tensile properties, especially the cracking strain of restrained expansive concrete, is thus very important for the efficient field application of expansive concrete. This research is thus an attempt to experimentally investigate the cracking of expansive mortars and expansive concrete with and without restraint. Three experiments were conducted in this study. The objective of the first experiment – tensile properties of expansive mortar with unbounded restraint (Section 2) – was to observe the effect of restraint on tensile properties of expansive mortar while the effects from bonding between reinforcement and mortar, as well as presence of the interface between coarse aggregates and cement paste, are excluded. The second experiment – chemically prestressed mortar with concentric reinforcement (Section 3) – focused on the effect of longitudinal reinforcement and curvature on the tensile properties of restrained mortar. The last experiment – chemically prestressed concrete with concentric reinforcement (Section 4) – was conducted to investigate the tensile behaviors when coarse aggregate is embedded in the matrix.

2. Tensile properties of expansive mortar with un-bonded restraint

In the normal situation where reinforcing bars are provided in RC structures, it is difficult to clarify the cracking strain capacity of concrete from the prestress effect caused by restraint. The cracking strain capacity of concrete is usually merged with the prestress effect. In this research, however, a clear separation between cracking strain capacity, which is a material property, and the prestress effect is done by eliminating bonding of the reinforcing bar so that the rebar can be removed from the specimen before measurement of cracking strain by a flexural loading test.

Test on mortars was selected to inspect the effect of restraint on tensile properties, which is dependent on amount of cement paste in the mixture. Testing the mortars also allows the use of easy-to-handle size of specimen and limits the unwanted failure caused by weak interface between the matrix and coarse aggregate. The effect of coarse aggregate on tensile properties of restrained expansive concrete is investigated in Section 4.

2.1. Specimens and materials

Special mortar prisms with concentric, longitudinal un-bonded reinforcement were used in this study (see Fig. 1). Three types of specimens, namely, normal mortar (NM), expansive mortar (EM), and restrained expansive mortar (REM) were tested. The specimens were designed so that the reinforcing bar can be removed from the specimens before loading. Un-bonded condition between mortar and rebar was achieved by providing transparent sheath around the reinforcement before pouring concrete. Low friction tape was wrapped around reinforcement with 3 mm-thickness at an interval of approximately 500 mm to ensure that rebar will be at the center of the sheath and friction-free condition was achieved. The reinforcing bars were connected with a restraining steel plate at the ends of the specimens. These steel plates were placed and locked to the rebar by nuts in order to restrain the expansion of restrained expansive mortar. For normal mortar and free expansive mortar, however, these steel plates will be used only as formwork and the nuts were removed as soon as the pouring of concrete was finished.

Cross-section of the specimen is 100 × 100 mm (including a hole) and net length of specimens is 900 mm. In the case of restrained expansive mortars, restraining levels (defined as a ratio of nominal cross-sectional area of rebar and net cross-sectional area of concrete) were varied by changing the sizes of the reinforcement; i.e., D13 (1.3%), D16 (2.0%), and D19 (3.0%), respectively. The external diameter of the employed transparent sheath was 26 mm for both D13 and D16, and 29 mm for D19. The flexural tests were conducted at 7 days and 28 days. Effect of drying is also investigated by comparing the tensile properties of normal mortar and restrained expansive mortar with 2.0% reinforcement (D16) subjected to drying after 7 days. In this case, the force will gradually diminish when shrinkage takes place and the stress will not be induced in specimens when specimen returns to its original length

Table 1
List of specimens (un-bonded specimen).

Name	Reinforcement ratio (%)	Type of mortar	Curing method	Ages of loading
N-7		Normal	Moist curing	7 days
FE-7		Expansive		
E13-7	1.3			
E16-7	2.0			
E19-7	3.0			
N-28		Normal		28 days
FE-28		Expansive		
E13-28	1.3			
E16-28	2.0			
E19-28	3.0			
N-D1M		Normal	Dry condition after 7 days	28 days
E16-D1M	2.0	Expansive		28 days
N-3M		Normal	Moist curing	84 days
E16-3M	2.0	Expansive		
N-D3M		Normal	Dry condition after 7 days	84 days
E16-D3M	2.0	Expansive		84 days

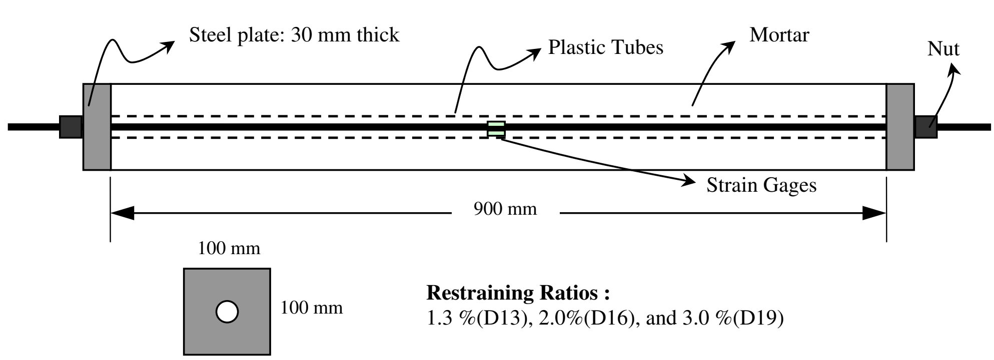


Fig. 1. Profiles of specimens (un-bonded specimen).

Table 2
Mix proportion of mortars.

	W/(C + E)	Unit content (kg/m^3)				
		W	C	E	S	AE (303A)
Normal	0.5	257.30	514.6	0	1366	1.98
Expansive	0.5	255.76	421.52	90	1366	1.98

because the restraining system will restrain only expansion but not shrinkage. The flexural test of specimens in dry conditions was conducted at 28 days (approximately 1 month) and 84 days (approximately 3 months), respectively. Table 1 summarizes the specimens in this experimental program. Three duplicate specimens were made for each case. Mix proportions of the mortars are given in Table 2. Compressive strengths of the mortars at different ages are shown in Table 3. Properties of cement, expansive agent and sand are given in Table 4 and the mechanical properties of steel are given in Table 5.

2.2. Experimental procedure

Two strain gages were attached to reinforcing bar before inserting the reinforcing bar into the transparent sheath (Fig. 2a). The reinforcing bar and sheath are then placed concentrically before the casting of the restrained expansive mortar (Fig. 1). The expansions of restrained expansive mortars were monitored by measuring the strain of the reinforcing bars. After casting of mortar, the formworks on both sides were removed at 24 h to minimize friction while the specimens were left on the bottom formwork until 3 days in order to avoid any defect which may be caused by the early movement. This early removal of side formworks is to minimize the effect of friction and transverse confinement from the formworks which cannot be quantitatively evaluated; however, it should be noted that the friction and transverse confinement are beneficial and should be provided in real practice in order to ensure sufficient confinement to expansive concrete. The specimens were cured in moist condition until 7 days and subsequently cured in the decided condition (see Table 1) until a few hours before loading. The chemical prestress can be calculated from the strain of the reinforcing bar and force equilibrium equation. For specimens subjected to a drying condition, additional strain gages were attached on each specimen, at the time of exposure to the drying condition (7 days), in order to monitor their length change.

In the preparation for the loading, ten 30-mm long strain gages were continuously attached to the bottom surface to measure the deformation of concrete (Fig. 3). The restraining end plates and reinforcement were then removed. The deformation of restrained expansive mortar during removal of restraint was measured and called ‘rebound strain’. This rebound strain is a result of a sudden removal of compressive stress. The concrete was allowed to recover from the restrained condition for 20 min. The rebound strain was measured during this period. The loading were conducted with the constant moment span of 300 mm and shear span of 250 mm (see Fig. 4). The loading rate was approximately 0.15–0.2 N/s. The load and strains were carefully measured during the loading. The stress exerted on the bottommost part of specimen was determined by assuming that the linear distribution of strain and the neural axis is at the center. The stress can then be calculated from external load according to elastic analysis of the section.

Table 4
Properties of cement, expansive agent and sand.

Cement	SG: 3.15	Fineness: 3270 cm^2/g	–
Expansive agent	SG: 2.90	Fineness: 3180 cm^2/g	–
Sand	SG: 2.63	F.M.: 2.9	Absorption: 1.89%

Table 5
Mechanical properties of reinforcement.

	Area (mm^2)	Young’s modulus (MPa)
D13	126.7	191,000
D16	198.6	197,000
D19	286.5	195,000

2.3. Experimental results

2.3.1. Expansion, chemical prestress, and rebound strain

Table 6 shows final expansion strain and corresponding chemical prestress as well as rebound strain that was measured during the removal of restraint. The chemical prestress can be calculated from following equation:

$$\sigma_{prestress} = \frac{A_s E_s}{A_c} \varepsilon_{\exp} \quad (1)$$

where $\sigma_{prestress}$ is chemical prestress (N/mm^2); $\varepsilon_{\exp}$ is final restrained expansion (before restraint removal) (μ); A_s and A_c are nominal cross-sectional area of rebar and concrete, respectively (mm^2); and E_s is modulus of elasticity of reinforcing bar (N/mm^2).

Under moist curing, higher restraint gives less expansion and the expansion at 28 days is not much different from the expansion at 7 days since the reaction of expansive additive is usually faster than hydration of cement and takes place in very early age. A slight reduction of expansion in the specimen with D16 steel bar (E16-7, E16-28, and E16-3M) might be caused by some moisture loss during moist curing period. The expansion of E16-D1M, E16D3M greatly reduced after exposure to drying condition and the E16D3M had a net reduction in volume (shrinkage) after drying for 3 months. The shrinkage of normal mortar in dried condition was 552 μ and 1136 μ at 1 month and 3 months, respectively. Fig. 5 compares the rebound strain measured during the restraint removal and the chemical prestress. There is a tendency, from the results of most specimens, that the rebound strain is higher in the specimens with higher chemical prestress except for the case of E16-7.

2.3.2. Tensile stress–strain relationship

Fig. 6 and 7 are examples of the tensile stress–strain relationship at 7 days of normal mortar and restrained expansive mortar (with D13 steel bar), respectively. In the case of normal mortar (Fig. 6), the stress–strain relationship was almost linear up to the tensile strength. In this elastic range, the strain at all locations in the constant moment span deformed equally. Although, at 3.3 MPa, early reduction of stiffness could be seen at the gage number 7, the mortar at other sections still continued to deform more.

Table 3
Compressive strengths of mortars.

	7 days	28 days	28 days (dry)	84 days	84 days (dry)
Normal	28.89 MPa	33.16 MPa	36.49 MPa	42.2 MPa	35.8 MPa
Expansive	–	41.75 MPa	49.08 MPa	52.67 MPa	44.61 MPa

(a) Reinforcement and transparent sheath (b) Steel plate and nut

Fig. 2. Setting of apparatus.

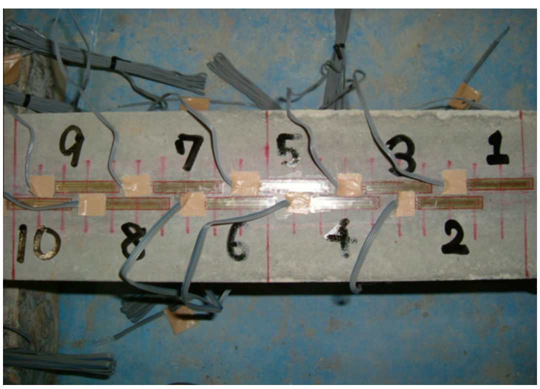


Fig. 3. Arrangement of strain gages.

Table 6
Expansion, chemical prestress, and rebound strain of restrained expansive mortar.

Specimen	Expansion/ shrinkage (με)	Chemical prestress (N/mm²)	Rebound strain (με)
E13-7	959	2.19	75
E16-7	772	2.58	125
E19-7	576	2.78	307
E13-28	1042	2.39	75
E16-28	761	2.61	95
E19-28	620	2.95	106
E16-D1M	424	1.55	34
E16-3M	615	2.21	70
E16-D3M	−442	N/A	N/A

Note #1: the values in this table is an average from three duplicate specimens.
Note #2: chemical prestress is calculated from Eq. (1).

This can be considered as the beginning of localization, sometimes called 'discontinuity point', which represents the point at which concrete can no longer be treated as a continuum. Stress transfer ceases to be continuous at this point [7]. When stress reaches the tensile strength (approximately 4 MPa), crack formation took place at gage number 7. Since there is no reinforcing bar, the crack will propagate very fast and the specimen collapses. The tensile strain capacity is represented, in this study, by the strain corresponding to the maximum stress (peak strain, ε_p). After cracking, the strain at other locations (uncracked position) sharply reduced because stress vanished. After the collapse of the specimen, some strain can still be observed although there is no loading. This strain is called residual strain (ε_{RES}) that represents the plastic deformation caused by the stress history. It was found, however, that the residual strain of normal mortar was less than 25 μ (see Fig. 6).

Fig. 7 is the tensile stress–strain relationship of the restrained expansive mortar with D13 steel bar. Remarkable non-linearity and peak strain (ε_p) could be observed clearly from the results. The peak strain was around 160 μ in the case of normal mortar but that of the restrained expansive mortar was around 280 μ. The comparison clearly show that the restrained expansive mortar allows larger deformation before damage localization when compared with normal mortar. In addition, unlike the case of normal mortar, the residual strain (ε_{RES}) of restrained expansive mortar is considerably large (more than 100 μ). This remarkable non-linearity and residual strain indicate that considerable plastic deformation was involved in the tensile deformation of restrained expansive mortar.

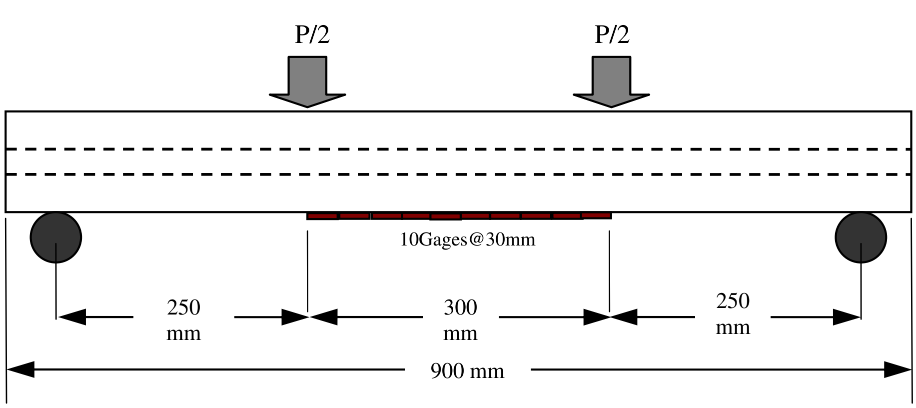


Fig. 4. Loading conditions.

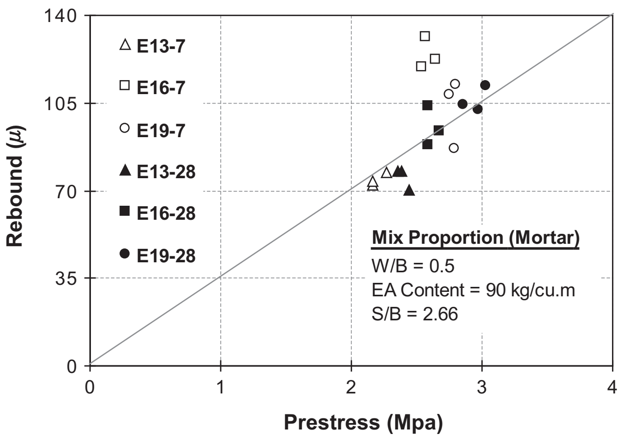


Fig. 5. Relationship between prestress and rebound strain.

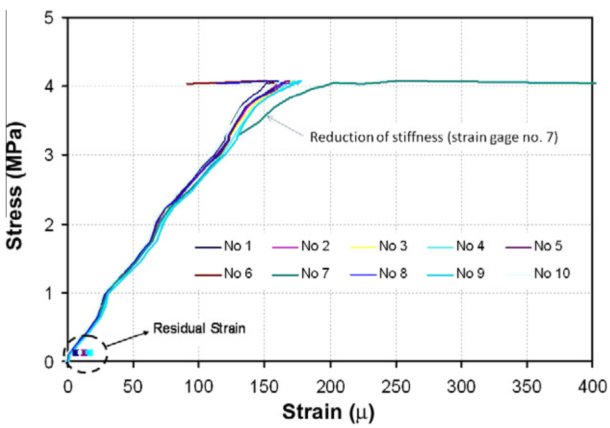


Fig. 6. Stress–strain relationship of N-7.

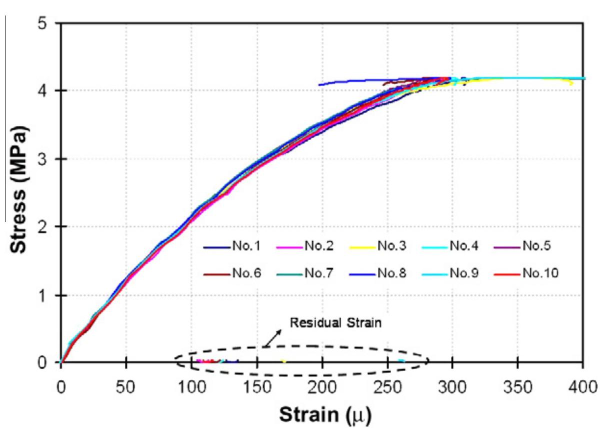


Fig. 7. Tensile stress–strain relationship of E13-7.

2.3.3. Tensile strength and peak strain (ε_p)

In order to compare the tensile strain capacity, the peak strain (ε_p) was determined as an average of strain readings from all strain gages at the maximum stress. The estimated tensile strength and peak strain of normal mortar and free expansive mortar at 7 days and 28 days are given in Table 7. The tensile strength of normal mortar was more than that of free expansive mortar while the peak strain is lower. The tensile properties of both normal mortar and free expansive mortar hardly changed when ages of mortars changed from 7 days to 28 days. Fig. 8 shows the relationship between peak strain and expansion before restraint removal as well as the relationship between peak strain and chemical prestress. The results show that the different expansion barely affects the peak strain of mortars, while it seems that chemical prestress has some correlation with the peak strain at 7 days.

The peak strain of restrained expansive mortar was much larger than that of normal mortar at 7 days. However, the difference became smaller at 28 days. The results also indicates that there is no substantial difference between the peak strain of free expansive mortar and that of restrained expansive mortar at 28 days.

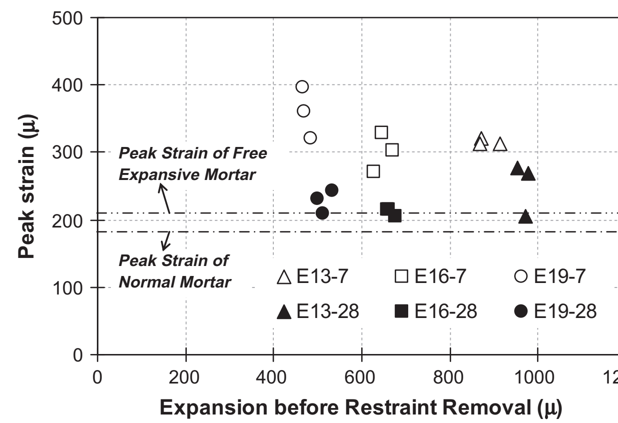
2.3.4. Strain distribution and average residual strain

Figs. 9–11 show strain distribution at various relative stress levels (as percentage of strength) of N-7, FE-7, and E16-7. Initially, strains at all points were almost same because the damage had still

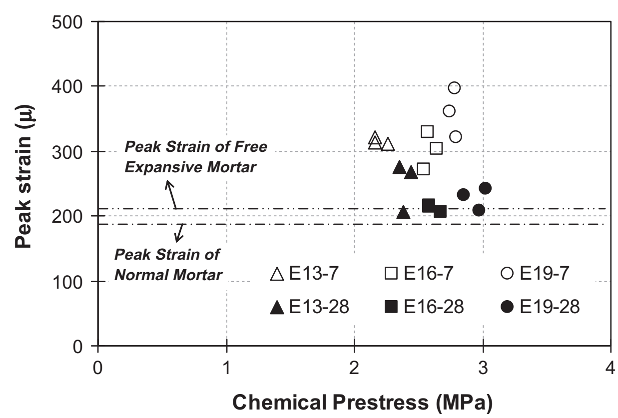
Table 7
Tensile strength and peak strain of normal and free expansive mortars.

Mortar	Tensile strength (N/mm^2)		Peak strain (μ)	
	7 days	28 days	7 days	28 days
Normal mortar	4.25	4.15	176	183
Expansive mortar	3.56	3.97	217	214

Note: values in this table is an average from three duplicate specimens.



(a) Peak strain of restrained expansive mortar with different expansion



(b) Peak strain of restrained expansive mortar with different chemical prestress.

Fig. 8. Peak strain of restrained expansive mortar with different restraining level and ages.

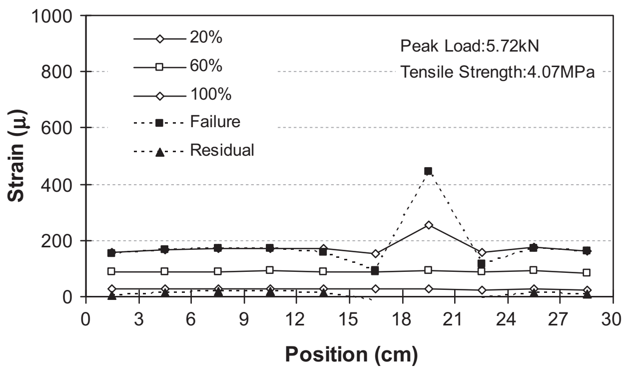


Fig. 9. Strain distribution of normal mortar (N-7) under different load levels at 7 days.

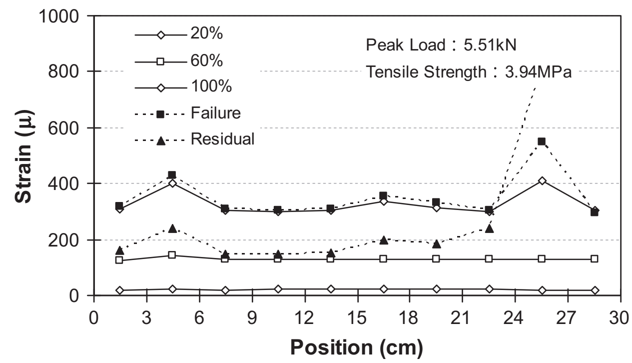


Fig. 11. Strain distribution of restrained expansive mortar (E16-7) under different load levels at 7 days.

not localized at any position; however, the difference in strain became observable when stress level was greater than 90% of its tensile strength. From the results, it was found that localizations may take place at only one (like in Fig. 9 and 10) or more locations (like in Fig. 11). Some locations show more deformation (or lower stiffness) than the others during this state. This larger deformation indicates that fracture progressed in those locations; however, mortar is still capable to resist the stress as a continuum. The number of localization points may indicate an ability of the material to resist the localization and to distribute the damage. However, when the stress reached 95–97% of tensile strength, the localization concentrates at a single location and cracking takes place at that location.

After crack localization there was still some remaining residual strain (ε_{RES}) (see Figs. 6 and 7). This residual strain indicates the plastic nature of each material. The residual strain takes place in all locations that were subjected to tension and the distribution of this residual strain is also shown in Figs. 9–11. In the case of normal mortar, this residual strain (ε_{RES}) is very small and therefore generally neglected (see Figs. 6 and 9). Free expansive mortar has, however, more residual strain of around 50 μ (see Fig. 10). This residual strain became substantial in the case that expansive mortar was under restraint. The residual strain (ε_{RES}) of more than 100 μ could be achieved in the case of restrained expansive mortar (see Figs. 7 and 11). It was found that, in the case of 7 days, the residual strain (ε_{RES}) of restrained expansive mortar is approximately equal to the strain corresponding to 60% of the mortar tensile strength.

In fact, the residual strains (ε_{RES}) at all locations were not precisely the same since the damage introduced to each location was not equal even though the maximum experienced stress was

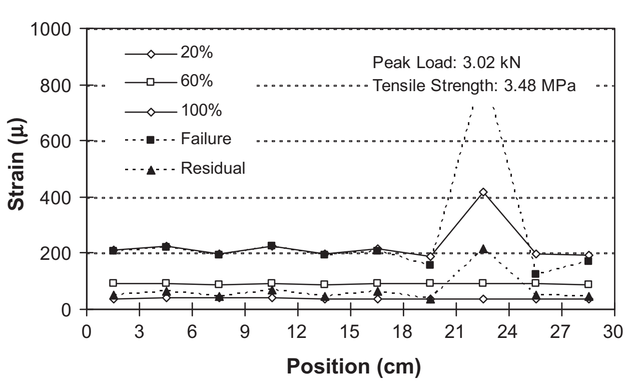


Fig. 10. Strain distribution of free expansive mortar (FE-7) under different load levels at 7 days.

Table 8
Average residual strain of mortar prisms at 7 days and 28 days.

	Normal mortar	Free expansive mortar	Restrained expansive mortar		
			D13	D16	D19
7 days	30.99	74.18	135.68	147.94	153.88
28 days	24.11	43.12	62.3	64.4	54.4

same. The residual strain was then evaluated based on average basis. The average residual strain of each specimen is given in Table 8. Fig. 12 compares the residual strain of the normal mortar, free expansive mortar, and restrained expansive mortar (E16). The average residual strain at 28 days was less than that of the value at 7 days for all mortars. It can also be observed that while presence of restraint is crucial in developing larger residual strain in expansive mortar, the difference in restraining level has no significant effect on the residual strain (see Fig. 13).

2.3.5. Effect of drying condition on tensile behaviors of restrained expansive mortar

The tensile strength, peak strain, and average residual strain of specimens subjected to drying conditions are given in Table 9. The peak strain (ε_p) of normal mortar cured under wet condition remains almost constant even though the age increased from 7 days to 3 months. However, the peak strain (ε_p) of dried normal mortar increased when the age increased from 1 month to 3 months.

In case of restrained expansive mortar, the peak strain (ε_p) at 7 days is obviously larger than that of normal mortar. However,

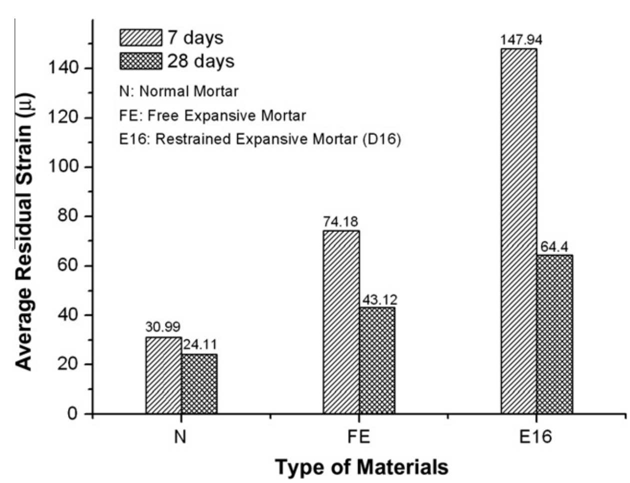


Fig. 12. Comparison of the average residual strain of the different mortars.

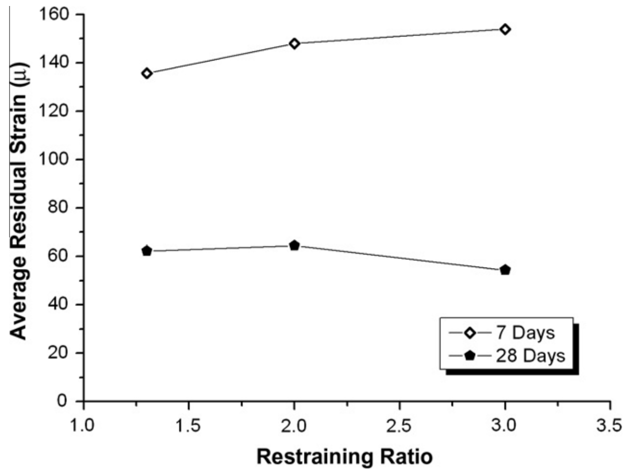


Fig. 13. Average residual strain of restrained expansive mortar with different restraining levels.

it was found that this peak strain (ε_p) reduced at 1 month. The reduction at 1 month is slightly more in the case of dried restrained expansive mortar. From 1 month to 3 months, the recovery of peak strain can be seen in the case of dry curing while the peak strain (ε_p) was almost constant in the case of wet curing.

As for the effect of drying on the average residual strain of restrained expansive mortar, it can be concluded from Table 9 that, in addition to the effect of age, the average residual strain of restrained expansive concrete was also substantially reduced regardless of curing condition.

2.3.6. Discussion on tensile behaviors of expansive mortar with un-bonded restraint

By testing expansive mortar with un-bonded restraint, the tensile properties of restrained expansive mortar were fully separated from the prestress effect. Not only cracking tensile strength but also cracking strain capacity and plastic deformation of restrained expansive mortar were evaluated from peak strain and residual strain after failure of specimens, respectively. The larger cracking strain capacity and substantial plastic deformation can significantly improve cracking resistance and thus reduce cracking risk of RC member.

Since only tensile deformation under flexural loading in comparatively short duration was measured in this study, the results cannot give information about time-dependent deformation. However, a previous research on the properties of early-age expansive mortar under direct tension shows that the early-age expansive mortar has both considerable plastic deformation and tensile creep [15]. This information emphasizes the potential of expansive concrete application in cracking prevention. It was also suggested that the unique tensile behaviors of restrained expansive mortar is a result of unevenness of strains in microstructure [15]. These unique tensile properties play an important role in preventing cracking in the early age (from setting to 7 days) at which tensile stress may be induced by various factors; for instance, early age shrinkage or thermal stress [16,17].

Although the results show that age of the restrained expansive mortar has a large influence on its improved tensile properties and the tensile properties become similar to those of normal mortar at 28 days, it must be noted that the restraining condition in these specimens are different from the expansive mortar with bonded reinforcement. In restrained expansive mortar the bonding between rebar and reinforcement plays a significant role in inducing the confinement to the mortar and the unique tensile behavior can still be expected in the long term. In the following sections, the performances of chemically prestressed mortar (CPM) and chemically prestressed concrete (CPC) were experimentally investigated.

3. Chemically prestressed mortar with concentric reinforcement

3.1. Specimens and materials

Reinforced mortar (RM) and chemically prestressed mortar (CPM) specimens with a centrally located reinforcing bar were tested under flexure. The reinforcement was located at the center to restrain expansion of specimens efficiently as well as minimize the bending moment carried by reinforcement. Height of the specimens was varied as an attempt to change the curvature of cross-section for the same strain at the tension fiber. There were three different heights of specimen: 50 mm, 100 mm and 150 mm. There were totally 12 specimens in this series. Table 10 summarizes details of each specimen and profiles of the specimens are given in Fig. 14. Mix proportions of mortars as well as properties of materials are same with test on mortar with un-bonded restraint (see Tables 2–5).

3.2. Procedure

Measurement of expansive strain started as soon as casting was finished. All specimens in this series were subsequently kept in

Table 10
List of specimens.

Name	Reinforcement ratio (%)	Type of mortar	Height	Curing method	Ages of loading
N13-50-1	2.8	Normal	50 mm	Moist curing	28 days
N13-50-2					
N16-100-1	2.0		100 mm		
N16-100-2					
N19-150-1			150 mm		
N19-150-2					
E13-50-1	2.8	Expansive	50 mm		
E13-50-2					
E16-100-1	2.0		100 mm		
E16-100-2					
E19-150-1			150 mm		
E19-150-2					

Table 9
Effect of drying condition on tensile strength, peak strain, and residual strain.

	Normal mortar			Restrained expansive mortar (D16)		
	Tensile strength (N/mm^2)	Peak strain (μ)	Average residual strain (μ)	Tensile strength (N/mm^2)	Peak strain (μ)	Average residual strain (μ)
7 Days (wet)	4.25	176.15	30.99	4.02	301.28	147.94
28 Days (wet)	4.15	183.29	24.10	3.66	212.02	64.40
3 Months (wet)	4.33	168.36	16.57	4.58	190.05	23.47
28 Days (dry)	3.79	191.05	32.96	4.12	193.52	28.20
3 Months (dry)	6.95	290.27	28.58	5.50	232.99	21.19

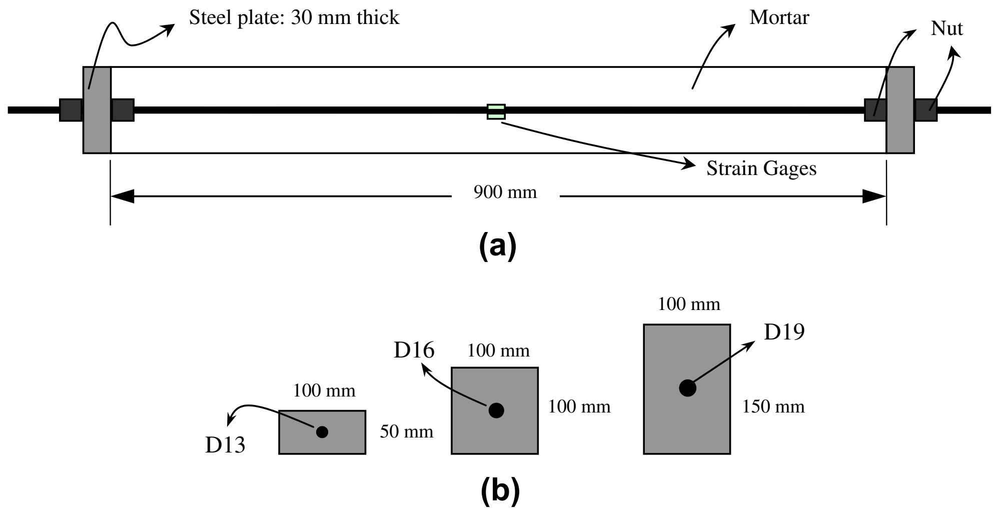


Fig. 14. Profiles of the specimens.

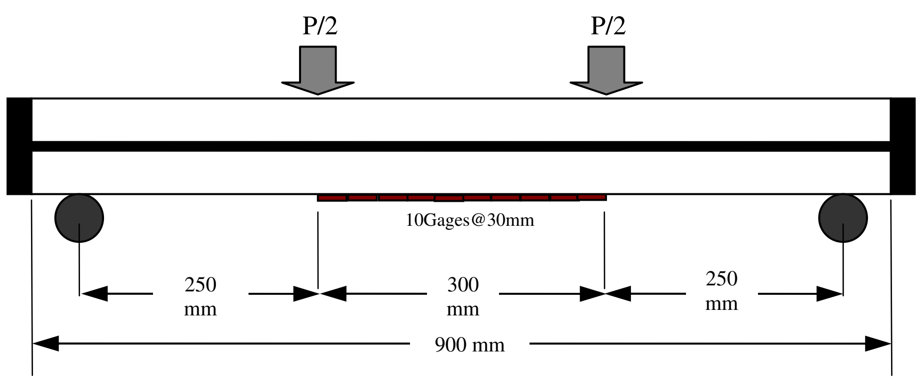


Fig. 15. Loading conditions.

moist condition until a few hours before loading at 28 days. The loading was done without removing the steel plate. The experimental procedure, condition of loading, and measurements were similar to the experiment on mortar with un-bonded restraint (see Fig. 15). The cracking was observed visually during the loading. The loading continues until the strain value at the position of cracks reaches 2000 μ, which is adopted as an indicator though it is rather symbolic. Subsequently, the load was gradually released. The residual strain distribution is then measured after the unloading is completed.

The stress at the tension fiber was determined by assuming that plane sections remain plane until cracking. The tensile relationship between stress and strain of each specimen was thus obtained. Since the reinforcing bar plays a role in transferring stress along the specimen, the localization might take place at more than one location. Due to this reason, the initial point of localization stress was evaluated based on a statistical method. The criterion was that localization takes place when the increment of strain at any point is more than the 90th percentile calculated from average increment and standard deviation of that loading step. While the average strain is used to represent the properties before the localization, the cracking strain is obtained from only a single location (from one specific strain gage), that is, at the location of cracks. The difference between localization strain and cracking strain is thus recognized as the indicator of plastic deformation before cracking, though the cracking strain recorded is a rather symbolic value.

3.3. Experimental results

3.3.1. Plastic deformation before cracking of chemically prestressed mortar

Fig. 16 shows the tensile stress–strain relationship of RM. All specimens with different heights (and thus different curvatures)

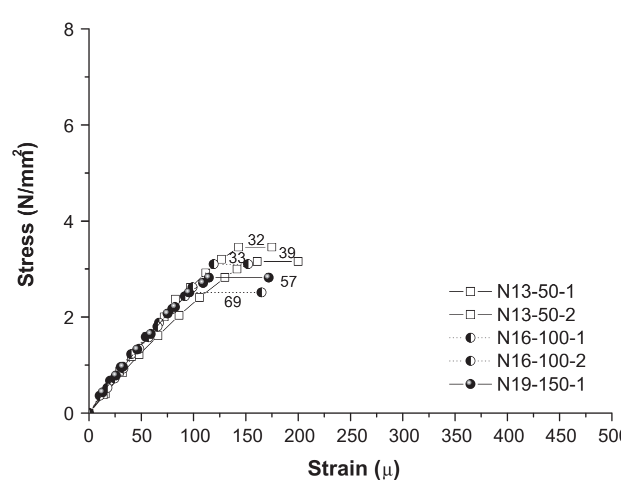


Fig. 16. Tensile stress–strain relationship of reinforced mortar.

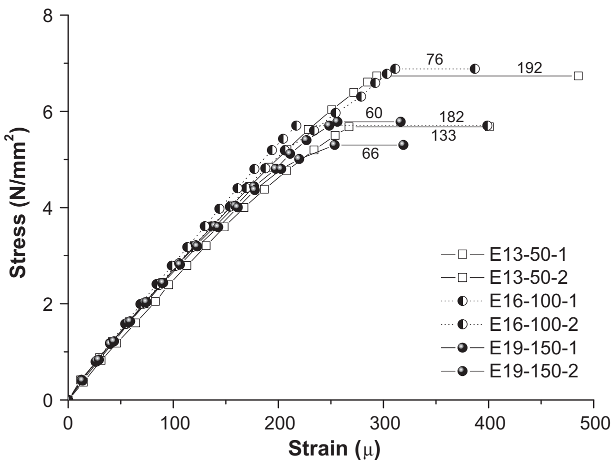


Fig. 17. Tensile stress–strain relationship of chemically prestressed mortar.

show very similar performance. The plastic deformation before cracking is in the range of 30–70 μ. A tensile stress–strain relationship of the CPM is given in Fig. 17. A special attention should be paid to a larger plastic deformation before cracking which is observable from specimens with relatively high curvature. This plastic deformation before cracking becomes larger when the curvature is increased (height is reduced). These results show that CPM is more sensitive to curvature than RM.

3.3.2. Anti-localization properties and effect of curvature on residual strain

Figs. 18–20 show comparisons between the residual strain distribution of RM and CPM. There are two data of RM and CPM in each graph (a total of four specimens), except in Fig. 20 which has only one reinforced mortar data. It is clear that the damage of RM is localized fully at the cracking location as can be observed from the very high residual strain value at the location of cracks. Interestingly, the residual strain at cracks of CPM is much smaller than that of RM in all cases. This smaller damage at the crack location is compensated by a larger residual strain observable along the constant moment span. This feature is an ability of CPM to prevent the localization of the damage at any location.

The average residual strain (excluding the strain at cracking position) is shown in Fig. 21. The average residual strain of CPM is much higher than RM in general. Additionally, the effect of curvature is remarkable for both RM and CPM. Higher curvature allows the material to undergo more plastic deformation before failure.

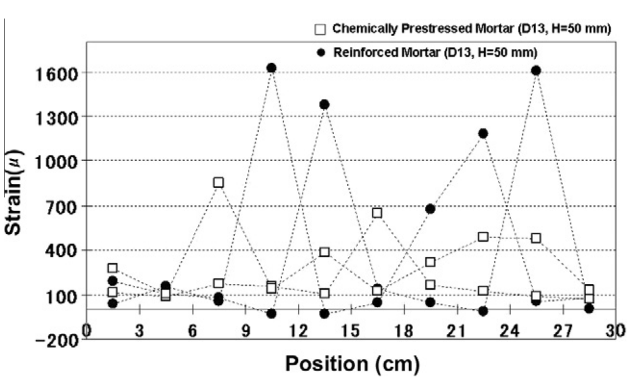


Fig. 18. Residual strain distribution of specimen with height of 50 mm and D13 reinforcing bar.

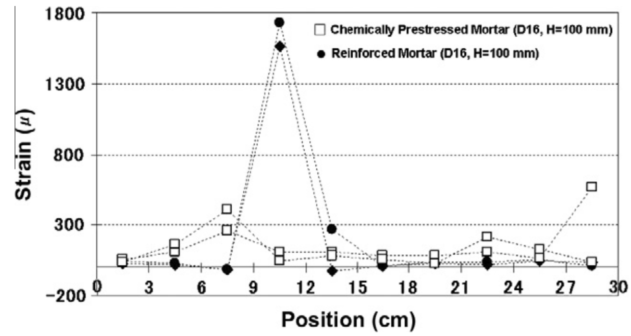


Fig. 19. Residual strain distribution of specimen with height of 100 mm and D16 reinforcing bar.

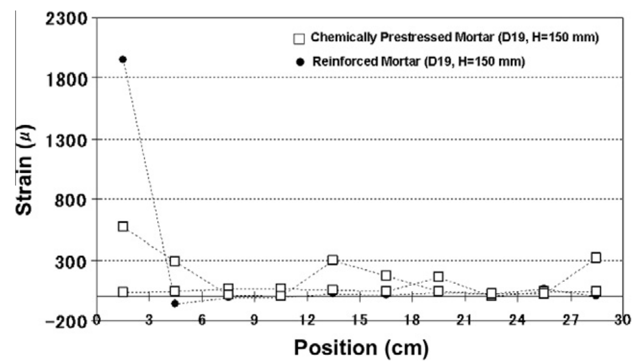


Fig. 20. Residual strain distribution of specimen with height of 150 mm and D19 reinforcing bar.

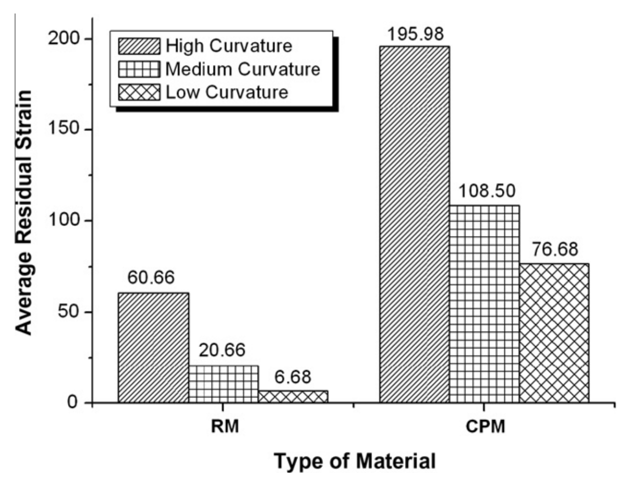


Fig. 21. Effect of curvature on the average residual strain.

3.3.3. Discussion on tensile behaviors of chemically prestressed mortar

From the experiment, tensile behaviors including tensile strength, cracking strain capacity, as well as plastic deformation of CPM and RM can be evaluated. From the stress–strain relationship, it is clear that the localization of CPM occurs at higher stress; this is simply the effect from prestress (which can not be precisely excluded in this test) and better tensile properties induced by restraint (as described in the previous section).

In addition to the behavior before localization, the information about plastic deformation can also be obtained. Both the plastic deformation before cracking and the residual strain after failure could be successfully evaluated. It was found that CPM exhibits higher plastic deformation before cracking than that of RM and it seems that this plastic deformation of CPM before cracking depends on be the curvature at which the materials are loaded. It was also found that the residual deformation of CPM after unloading was more than 3–10 times of the RC loaded under the same curvature. This plastic deformation can be related to the residual deformation of expansive mortar with un-bonded restraint described in the previous section. It seems that bonding between rebar and mortar substantially influences the residual deformation of restrained expansive mortar. The residual strain of CPM with D16 was 108.5 μ (Fig. 21) while the residual strain of expansive mortar with un-bonded D16 restraint was only 64.4 μ (Fig. 12).

4. Chemically prestressed concrete with concentric reinforcement

4.1. Experimental program and materials

This section investigates plastic deformation before cracking of reinforced concrete (RC) and chemically prestressed concrete (CPC), as well as their distributions of residual strain. The experimental procedure, loading condition, and properties of material were exactly same with the experiment in the previous section. Mix proportions of concretes are given in Table 11.

4.2. Experimental results

4.2.1. Plastic deformation before cracking of chemically prestressed concrete

Figs. 22 and 23 show the tensile stress–strain relationship of RC and CPC, respectively. In the case of RC, the presence of coarse aggregate somehow increases the plastic deformation before cracking. However, no clear difference is observable between the properties of CPC (Fig. 23) and the properties of CPM (Fig. 17) with the same height. However, this plastic deformation of CPC is still remarkably higher than that of RC.

Table 11
Mix proportion of concretes.

	W/(C + E)	Unit content (kg/m^3)				
		W	C	E	S	G
Normal	0.5	165	330	0	860	956
Expansive	0.5	164	268	60	860	956

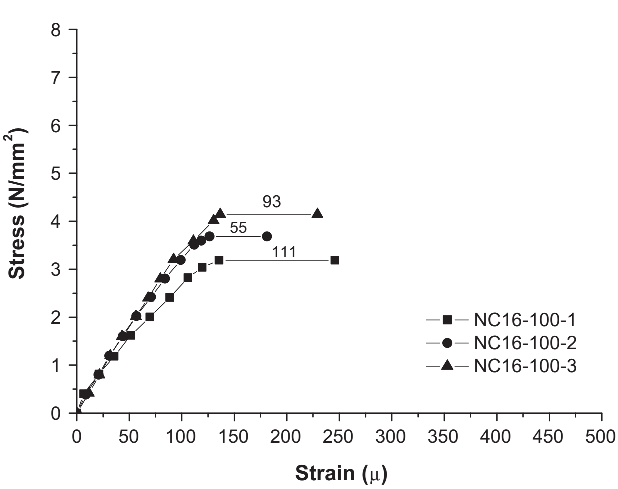


Fig. 22. Tensile stress–strain relationship of reinforced concrete.

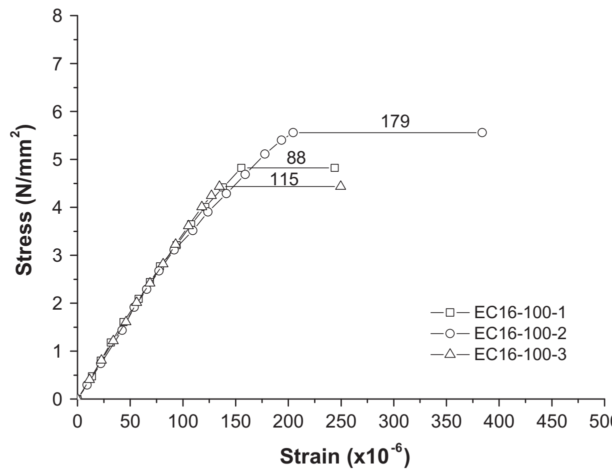


Fig. 23. Tensile stress–strain relationship of chemically prestressed concrete.

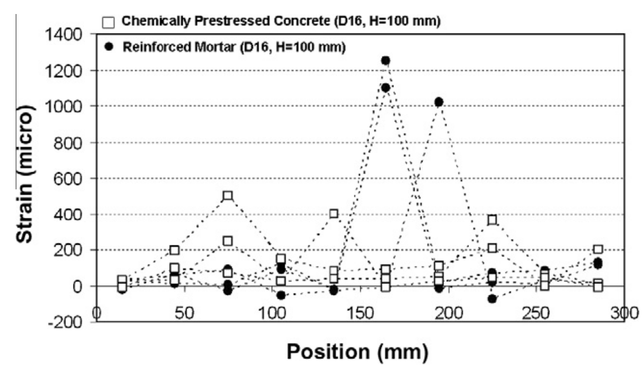


Fig. 24. Tensile stress–strain relationship of chemically prestressed concrete.

4.2.2. Residual strain distribution of RC and CPC

The similar behavior against localization found in the case of CPM could also be observed in CPC as shown in Fig. 24. In contrast to the localized damage of RC at the crack location, CPC shows an ability to distribute the damage along the constant moment span.

5. General discussion

Fig. 25 shows the comparison of average residual strain between the restrained expansive mortar with un-bonded restraint,

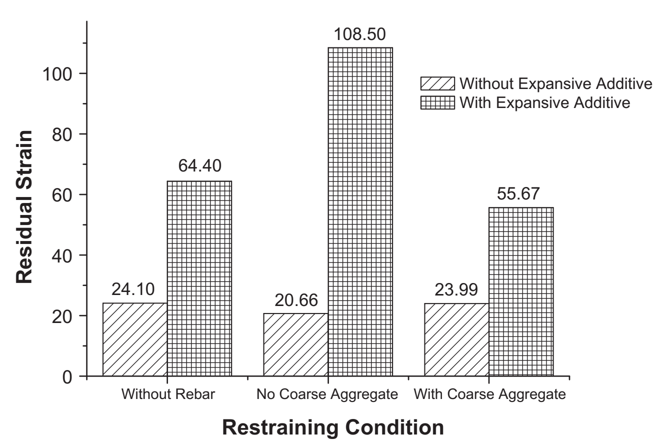


Fig. 25. Effect of reinforcing bar and coarse aggregate on the average residual strain (D16 restraint at the age of 28 days).

the chemically prestressed mortar, and the chemically prestressed concrete. In the case of normal mortar or concrete, it seems that there is apparently no effect from the presence of reinforcing bar or coarse aggregate on the average residual strain. Without bonding, the residual strain of restrained expansive concrete was approximately three times of that of normal mortar while the effect increased to five times when there was a bonding between rebar and concrete (Fig. 25). However, this improvement is limited if coarse aggregates are in the mix. The main reason could be that the interface between coarse aggregates and cement paste may act as a formation location of micro-cracking and prevent the restrained expansive mortar from performing its full tensile behaviors. However, it should be also noted that the number of cracks induced to the chemically prestressed concrete is increased and strains observed at the position of cracks are maintained at lower levels compared to those in reinforced concrete (Fig. 24). This is also supposed as the feature of deformability, which the chemically prestressed concrete shows.

Although the improvement of cracking strain and plastic deformation is less in the case of restrained expansive concrete when compared with expansive mortar, the cracking strain and plastic deformation can be doubled. Due to this property, the cracking strain should be accurately taken into account when considering cracking of CPC. It was reported that mix proportion, type of binders, moisture, and temperature influence the mechanical properties of concrete; especially cracking strain capacity [18–20]. Therefore, in order to employ expansive concrete in crack prevention, there should be more quantitative study on the tensile properties of restrained expansive concrete.

6. Summary

- Tensile properties of expansive mortar can be highly influenced by restraint. Not only higher cracking strain capacity, but also non-linearity and substantial plastic deformation can be achieved.
- Without bonding between rebar and mortar, the differences between cracking strain capacity and plastic deformation of restrained expansive mortar and normal mortar become smaller as the mortar ages.
- Bonding between rebar and concrete allow the restrained expansive mortar to undergo much larger plastic deformation before cracking as well as residual deformation after failure.
- Curvature due to flexure affects the residual deformation of both normal mortar and CPM.
- Although the presence of coarse aggregate limits the improvement of tensile properties of restrained expansive concrete, there was still a remarkable increase of residual deformation.

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