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Tensile creep due to restraining stresses in high-strength concrete at early ages

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Abstract

This paper reports an experimental study on the early-age tensile creep behavior of high strength concrete (HSC) comprising of silica fume concrete, fly ash concrete and plain concrete under uniaxial restraining stresses. A series of restraint shrinkage tests were carried out adopting semi-adiabatic and isothermal conditions to determine the effects of temperature history on the tensile creep properties for young concretes. Furthermore, the effects of restraining stress history on creep were also discussed under three different degrees of restraint conditions. It was found that the initial thermal dilation deformation delayed the development of tensile creep and weakened the creep potential of early age concretes. It was also observed that the young concrete subjected to a lower restraining tensile stress history had a higher potential of visco-elastic response in tension at early ages.

Keywords: Creep; Shrinkage; High-strength concrete; Fly ash; Silica fume

1. Introduction

It is well known that modern high strength concretes adopting low water/binder ratio are sensitive to crack at early age. The driving forces to cracking during concrete hydration are thermal and autogenous deformations. However, the cracking tendency of concrete is determined by many factors such as shrinkage potential, shrinkage rate, tensile strength, Young's modulus, restraint conditions and tensile creep, etc. [1,2]. Creep behavior in tension is of greater importance when potential for cracking is to be determined. Creep is extremely important in estimating the possibility of cracking due to restrained shrinkage and thermal stresses at early ages [3]. Due to relatively high creep deformation and considerable stress relaxation, early-age restraining stresses in concretes can be greatly reduced. Considerable creep/relaxation occurs in the hardening concrete, once the restraining stress induced under restrained condition. In many cases, the early-age creep can be as high as 30% to 70% of the autogenous shrinkage, and the stress relaxation leads to a reduction of restraining stresses by about 50% in hardening concrete [4,5].

The vast majority of past work on the creep of mature concrete has been concerned with creep behavior in compression, but very few studies on tensile creep for very early age concrete are found in literatures. In the RILEM Conference on thermal cracking at early age in 1994, two articles on early-age tensile creep were presented. One demonstrated the influence of temperature on early-age tensile creep [6], and the other reported the influence of stress/strength ratio on tensile creep at early ages [7]. In view of the early-age creep's influences on cracking of young concretes, more and more attention has been given recently to evaluate and model the tensile creep and stress relaxation of concrete at early ages. Some testing methods including uniaxial tensile creep tests, creep and stress relaxation tests, and tensile creep ring testing apparatus, and several empirical models have been developed for early-age tensile creep evaluations [8–12]. The uniaxial restrained test is very valuable and has been used in a number of studies to determine the creep characteristics of concrete under restrained shrinkage at early ages [3,12–17]. The early-age tensile creep behaviors under restraining stresses induced by dry shrinkage at different drying conditions or autogenous shrinkage at sealed

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conditions with a constant temperature have been reported [17–19].

Creep is affected by a large number of material variables including cement type, pozzolans, w/b ratio, aggregate type and content, age, temperature and humidity, etc. [8]. For a given concrete in practical structures, temperature and stress histories were the most important factors on early-age creep behavior. In this present work, the early-age tensile creep characteristics due to restraining tensile stress of high strength concrete were investigated under isothermal and semi-adiabatic conditions, and the effects of combination of autogenous shrinkage and thermal dilation on creep behavior were taken into account. Furthermore, in these uniaxial restrained shrinkage tests, the restraining stress is determined by not only the total shrinkage deformation but also the restraint status, so the influences of the degree of restraint on the measured creep of young concretes were also discussed. For many practical problems related to early-age concrete, especially in high strength concretes cured in sealed conditions, there is no significant moisture exchange with the environment. In this way, drying creep is of less importance [5], so only basic creep is considered in this study.

2. Experiment

2.1. Materials and mixture proportions

The physical and chemical properties of ordinary Portland cement, fly ash (FA) and silica fume (SF) used in this study are presented in Table 1, and the strength characteristics of cement are given in Table 2. A natural river sand and crushed limestone (maximum size of 20 mm) were used as fine and coarse aggregates, and a superplasticizer (SP) of sulfonated naphthalene formaldehyde type was used in this study.

The experiments were performed with three 0.35 w/b mixtures, including plain concrete OPC, double-blended concrete SF (6% replacement of OPC by SF) and FA (30% replacement OPC by FA). The mixture proportions of concretes are presented in Table 3. The compressive strength at 28-day age for OPC, SF and FA are 72, 76 and 56 MPa, respectively.

Table 1
Physical and chemical properties of cement, fly ash and silica fume

Item		Cement	Fly ash	Silica fume
Chemical composition (%)	SiO_2	22.71	60.20	89.22
	Al_2O_3	4.57	20.46	
	Fe_2O_3	2.85	8.6	
	CaO	66.10	3.46	
	MgO	1.90	4.50	
	SO_3	0.37	1.28	
	K_2O	0.68	0.76	
	Na_2O	0.15	0.52	
	LOI	0.50	1.8	
Specific surface Blaine (m^2/kg)			328	20000
Specific gravity		3.15	2.28	2.23

Table 2
Strength characteristics of cement

Setting time (min)		Flexural strength (MPa)		Compressive strength (MPa)	
Initial	Final	3 days	28 days	3 days	28 days
166	211	5.2	9.2	26.2	52.8

2.2. Method

A uniaxial restrained shrinkage testing rig with a closed loop computer controlled system (based on the system suggested by Kovler [16,20,21], see Fig. 1) was developed at the Institute of Building Materials of Tsinghua University to investigate early-age tensile creep properties of high-strength concrete. This testing rig includes two identical specimens: One for free shrinkage, the other for restrained shrinkage with different restraint degrees. In this study, the degree of restraint (δ) in value is defined as:

$$\delta = [(\varepsilon_{fr} - \varepsilon_r)/\varepsilon_{fr}]*100\% \quad (1)$$

where ε_{fr} is the total free deformation, i.e. the sum of thermal dilation and autogenous shrinkage, which was directly measured in the free deformation rig; ε_r is the strain development in the restrained test, which is obtained and monitored by the closed loop computer-controlled system. When the degree of restraint δ is chosen, a compensation cycle (as shown schematically in Fig. 2 [16,20]) is repeated at increments of 2 μm (2 microstrain for a 1000-mm long specimen adopted in this study) to control the strain ε_r according to Eq. (2):

$$\varepsilon_r(t) = \varepsilon_{fr}(t) \times (1 - \delta). \quad (2)$$

Each cycle consists of an elastic response including an elastic strain ($\Delta\varepsilon_{el}$) due to an increase in load (to pulling the gripped end back to the predetermined position). The induced load is recorded and the cumulative elastic strain (ε_{el}) is calculated as the sum of the elastic strain increments in each loading cycle. The deformation consists of two components: one is the result of additional deformation strain ($\Delta\varepsilon_{sh}$), and the other is a consequence of some creep strain ($\Delta\varepsilon_{cr}$) under restraining load [21]. For the increment of each cycle:

$$\Delta\varepsilon_r(t) = \Delta\varepsilon_{el}(t) + \Delta\varepsilon_{sh}(t) + \Delta\varepsilon_{cr}(t) = \Delta\varepsilon_{fr}(t) \times (1 - \delta) \quad (3)$$

Table 3
Concrete mixture proportions

Concrete composition (kg/m^3)	Concrete mixtures		
	SF	OPC	FA
Cement	470	500	350
Silica fume	30	–	–
Fly ash	–	–	150
Coarse aggregate	1030	1030	1030
Fine aggregate	690	690	690
w/b	0.35	0.35	0.35
Superplasticizer	3.0	3.25	2.75

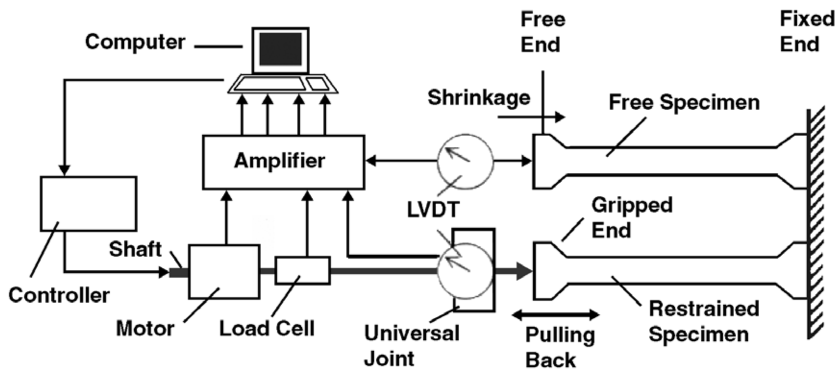

Fig. 1. Schematic description of the restrained shrinkage testing rig [16].

Considering $\Delta\varepsilon_{sh}$ is essentially the increment of free deformation $\Delta\varepsilon_{fr}$ during the cycle, Eq. (3) can be also expressed as:

$$\varepsilon_{cr}(t) = -\varepsilon_{el}(t) - \varepsilon_{fr}(t) \times \delta. \quad (4)$$

Thus, the creep strain (ε_{cr}) can be calculated from Eq. (3) at any time.

2.3. Test procedure

In this experimental study, a series of tests were conducted with this rig under semi-adiabatic condition (like a realistic temperature history in practice) and isothermal condition (at a constant temperature of 20 °C). In the restrained shrinkage tests, the specimens were restrained with 100%, 75% and 50% restraint degree, respectively. In parallel with the restraint test, the free shrinkage tests were carried out with the same temperature history.

The tests were carried out for 3 or 4 days in a room at 20 ± 1 °C with sealed specimens, and each specimen is 1000 mm long and 100 × 100 mm in cross section. Concretes were mixed with a temperature of 20 ± 1 °C and directly cast into the molds of the restrained shrinkage and free shrinkage testing rig. Concrete specimens were sealed and restraint was given to the restrained one immediately after casting.

3. Results and discussions

3.1. Creep behavior under semi-adiabatic condition

To investigate the early-age tensile creep behavior for concrete with a temperature history close to that in the practical structures, semi-adiabatic condition was adopted in these full restrained shrinkage tests.

3.1.1. Temperature history and free deformation

The temperature–time curves are shown in Fig. 3. The temperature histories of three concrete mixtures are similar in the same insulation conditions. The specimen temperature increased from 20 °C to above 45 °C at a rapid rate within the first day, and then cooled down to room temperature gradually.

The measured free deformation (as shown in Fig. 4) was the sum of thermal dilation and autogenous deformation. The total deformation is driven by a combination of thermal and self-desiccated effects. During the temperature rising phase (in the first 20 h), the autogenous shrinkage developed rapidly; if the thermal effect dominated this period, then the deformation showed an expansion tendency (for example, the case of the concrete mixtures OPC and FA), nonetheless, if self-desiccated effect dominated the period, shrinkage occurred. The two effects seemed to be equal approximately in mixture SF, so the deformation of SF in the first day was slight. The maximum

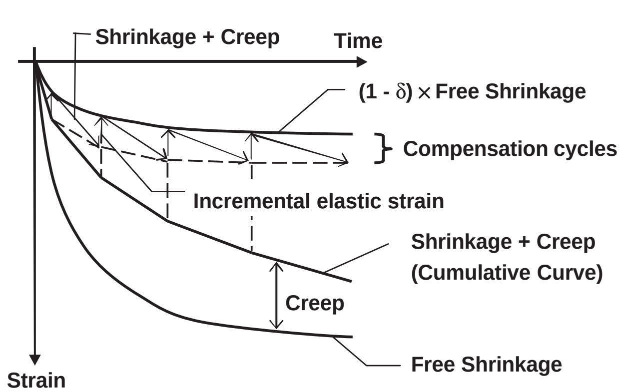

Fig. 2. Creep strain calculated from the data of restrained shrinkage tests [16].

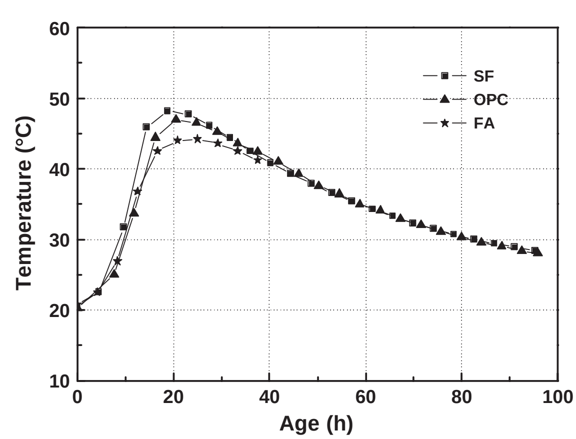

Fig. 3. Temperature development under semi-adiabatic condition.

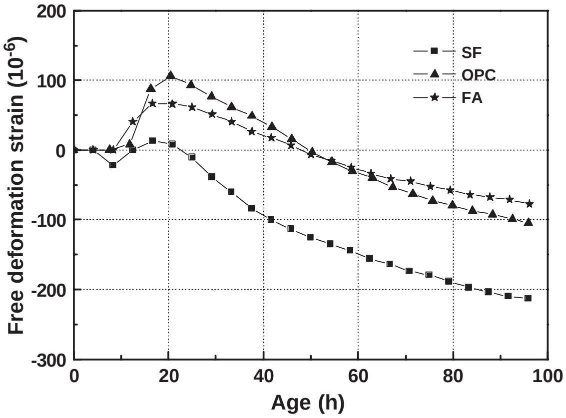

Fig. 4. Free deformation strain under semi-adiabatic condition.

expansion strains reached 105 and 70 microstrain in mixtures OPC and FA, respectively.

When the specimen temperature dropped, shrinkage occurred at a rapid rate until specimen temperature close to home temperature and the rate decreased afterward. The shrinkage strain reached 213, 104 and 78 microstrain at the age of 96 h for the mixtures SF, OPC and FA, respectively.

3.1.2. Restraining stress histories

The development of restraining stresses with time is presented in Fig. 5. The restraining stress can be either compressive or tensile, depending on whether the early deformation is expansion or contraction. In the restrained tests of sealed low w/b ratio concrete, this early expansion shows up as slight compression which precedes the tensile stress development. For example, the initial expansion strain induced compressive stresses about 0.5 MPa in OPC specimen at the age of 16 h. The tensile stresses developed rapidly after the first day, due to the high rate of shrinkage, and it was found that the tensile restraining stress generated in SF specimen was greater than those in other two mixtures for higher shrinkage.

3.1.3. Creep behaviors

In this experimental study, the visco-elastic response of early age concrete under restraining stress was expressed in terms of basic creep and specific creep in tension; moreover, the creep–shrinkage ratio [4] (the ratio of the tensile creep strain to total free shrinkage strain) which reflects reduction of the development of tensile strain in the restrained concrete specimen, was also adopted to account for the creep behaviors.

The restrained specimen was initially subjected to compressive creep (typically within the first 20 h) followed by tensile creep. During initial hydration stage, concrete transforms from a fluid fresh material into load-bearing solid material, and it experiences high creep rate [22]. The compressive creep strain for SF, OPC and FA concretes during the temperature rising period is shown in Fig. 6. Comparing Fig. 4 with Fig. 6, it was found that about 70% of free expansion deformation was compensated by compressive creep within the first day. After this period, the compressive creep was replaced by tensile creep due to high tensile stress development in specimens. In this study, only tensile creep behavior after the liquid–solid transition time (in restrained shrinkage tests of sealed low w/b ratio concretes, the time zero definition, it has been suggested to be defined as the time at the peak compressive stress, since it is at this instant that tension is being applied [22]) was discussed primarily.

In restrained shrinkage tests, the tensile creep is determined by the magnitude of shrinkage and the shrinking rate. Generally, the greater total shrinkage strain and higher rate of shrinkage may result in the greater creep strain and higher creep rate. The developments of tensile creep strain and creep–shrinkage ratio with time are presented in Figs. 7 and 8, respectively. The results showed that the tensile creep strains increased rapidly and almost linearly with time in the first 4 days. The tensile creep strain for SF, OPC and FA mixtures reached 148, 95 and 44 microstrain, corresponding to 67%, 45% and 30% of the free shrinkage strains at the age of 96 h, respectively. Fig. 8 indicated a significant increase in the creep–shrinkage ratio due to 6% replacement of Portland cement by silica fume, while the value of the creep–shrinkage ratio for FA mixture was only about 0.25. The creep–shrinkage ratio increased continuously before the temperature cooling down to room temperature. The higher creep–shrinkage ratio implied the higher degree of stress relaxation in the restrained concrete specimen, and it was clear that silica fume increased creep strain for causing much larger autogenous shrinkage and

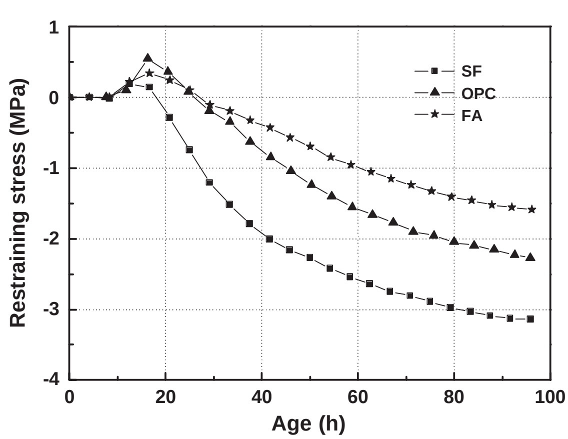

Fig. 5. Restraining stress development under semi-adiabatic condition.

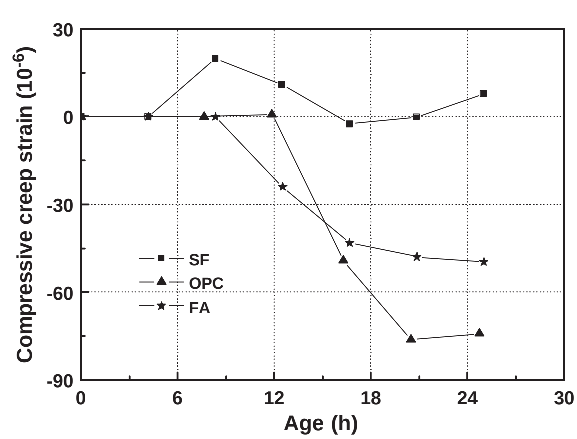

Fig. 6. Compressive creep strain under semi-adiabatic condition.

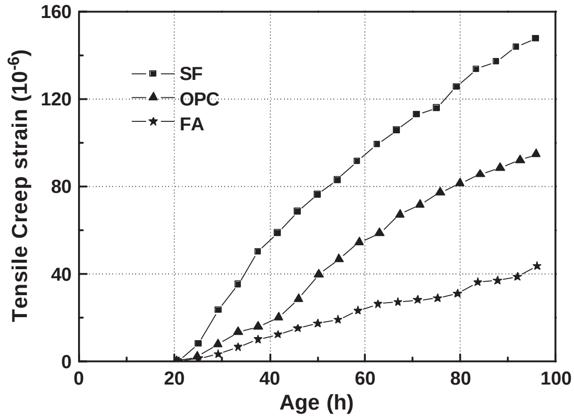

Fig. 7. Tensile creep strain under semi-adiabatic condition.

higher shrinkage rate, while fly ash decreased creep strain due to reducing the shrinkage strain and the rate of shrinkage at early ages.

Specific creep is conventionally defined as the creep strain per unit stress (microstrain/MPa) in a constant load creep test. Since the restraining tensile stress develops with time in the restrained shrinkage test, in this study, the specific creep is defined as the ratio of cumulative creep strain to tensile stress at any point in time, and it reflects the history dependence of tensile creep properties.

The results in Fig. 9 reveal that the specific creep in tension increased continuously due to the high restraining stress development, especially, during the first 2 days. SF mixtures recorded the greatest specific tensile creep among the three concrete mixtures, and the value of specific tensile creep in SF specimen was approximately 1.4 and 2.1 times of those in OPC and FA specimens, respectively. This tendency indicated that the early-age visco-elastic response in silica fume concrete was higher than those in plain concrete and fly ash concrete with a similar w/b ratio under restrained shrinkage conditions.

This trend of enhanced early age creep in silica fume concrete observed here differs from the conventional understanding that a mature silica fume concrete would have lower creep for its lower porosity and higher stiffness. A similar trend for tensile creep at early age not only in restrained shrinkage

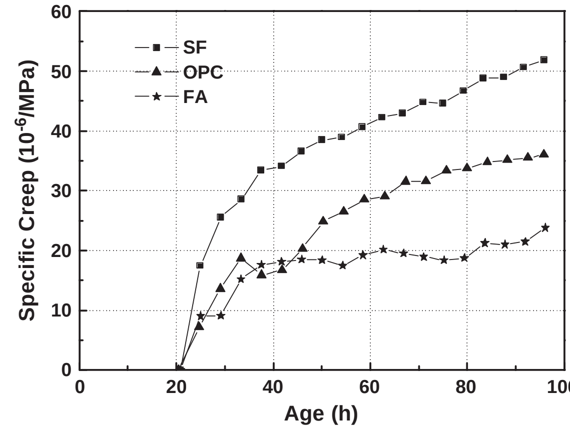

Fig. 9. Specific creep under isothermal condition.

test but also in conventional creep test of constant loading was reported by Kovler et al. [16], but no satisfactory explanation for the type of enhancing mechanism involved has been provided.

This trend may be related with the time at which the initiation of restraint is begun. It was well known that the creep behavior was significantly influenced by the loading time, especially in high strength concrete. Very early-age loading may result in significantly higher creep due to the formation of cement hydration products [23]. Furthermore, there is a very strong correlation between the basic creep at very early age and the self-desiccation shrinkage during hydration. The curvature radius of menisci in the capillaries may increase under tension, and that would result in capillary stress weakening. As a result of the changes in capillary tension, an extra strain component regarded as a part of tensile creep is developed [24]. The extra strain component may be higher for earlier self-desiccation and higher restraining stress in silica fume concrete.

3.2. Effect of temperature history creep behavior

The creep behavior of restrained concrete is determined by the temperature history and restraining stress history. With a realistic temperature history, the thermal dilation strain during the initial temperature rising phase may reduce the restraining

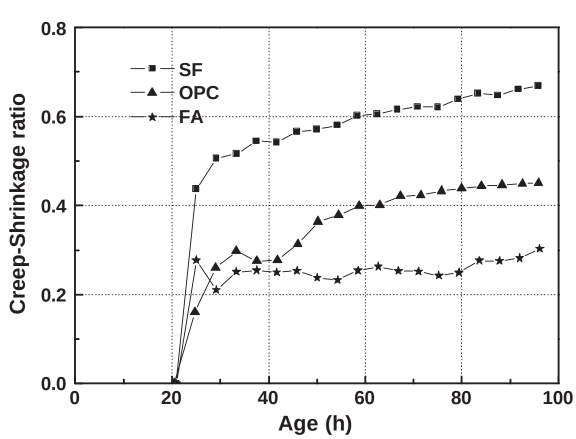

Fig. 8. Creep–shrinkage ratio under semi-adiabatic condition.

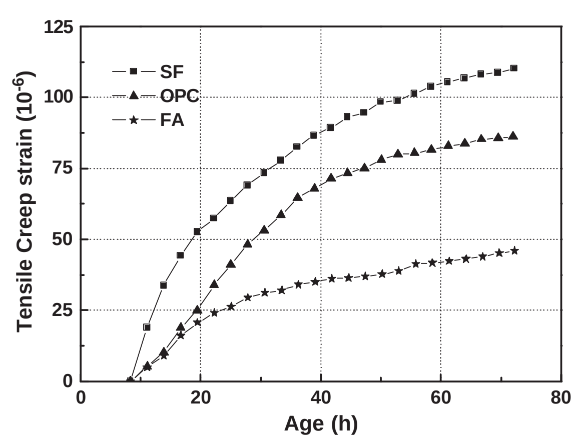

Fig. 10. Tensile creep strain under isothermal condition.

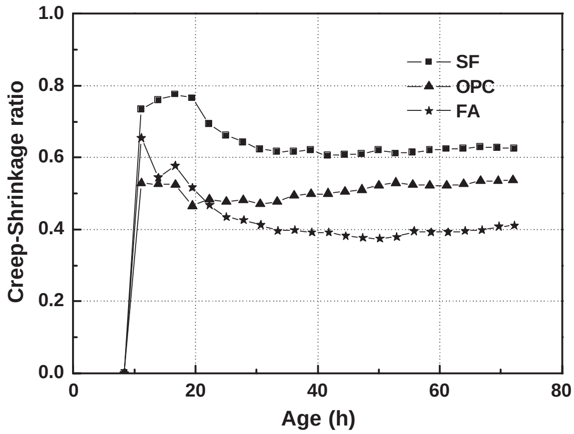

Fig. 11. Creep–shrinkage ratio under isothermal condition.

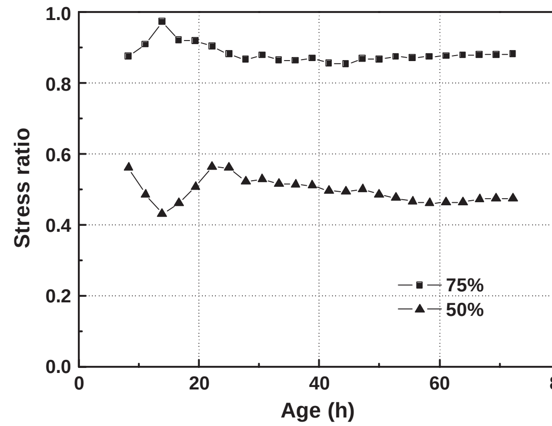

Fig. 13. The ratios of stress under different degree of restraint conditions.

tensile stress; while the thermal shrinkage strain during the followed temperature dropping phase will enhance the tensile stress in restrained shrinkage tests. Furthermore, temperature has a twofold effect on creep. Generally, increases in temperature give increased creep and higher maturity, while this increased strength and elastic modulus reduce creep strain at the same time [12].

Comparisons were made between creep behaviors at a constant temperature of 20 °C and those at a realistic temperature history (in the semi-adiabatic tests mentioned above). It can be seen from Fig. 10 that the tensile creep strain in isothermal specimens developed rapidly due to the high rate of autogenous shrinkage in the first 2 days. It was well known that the creep behavior of concrete was significantly influenced by the loading time, especially, at the very early ages. By comparing the results shown in Fig. 7 with Fig. 10, it was clear that the initial thermal dilation deformation in semi-adiabatic specimens delayed the time for the occurrence of restraining tensile stress and that the tensile creep strains at age of 2 days reduced about 23, 40 and 21 microstrain for SF, OPC and FA mixtures, respectively. On the other hand, the rates of creep in the semi-adiabatic specimens were slightly higher than those in the isothermal specimens, during the age of 2 to 4 days, because the thermal shrinkage strains enhanced the tensile stress at that stage.

The creep–shrinkage ratio and specific tensile creep for isothermal specimens were presented in Figs. 11 and 12, respectively. The results showed an obvious difference in creep–shrinkage ratio for concretes at the two different temperature histories. The creep–shrinkage ratio for isothermal specimens was greater in the first day and then decreased afterward to approach a stable value. A similar trend was found in the development of specific tensile creep in isothermal specimens, as the result of the higher visco-elastic response in the first day.

3.3. Effect of the restraint degree on creep behavior

The restraining stress history depends on not only the development of shrinkage in specimens but also the degree of restraint adopted in restrained tests. Generally, the degree of restraint is less than 100% and may change with time in realistic structure members. To account for the effect of the restraint degree on the creep characteristics, the creep behavior for SF mixture was also investigated adopting 75% and 50% restraint degree, besides full restraint.

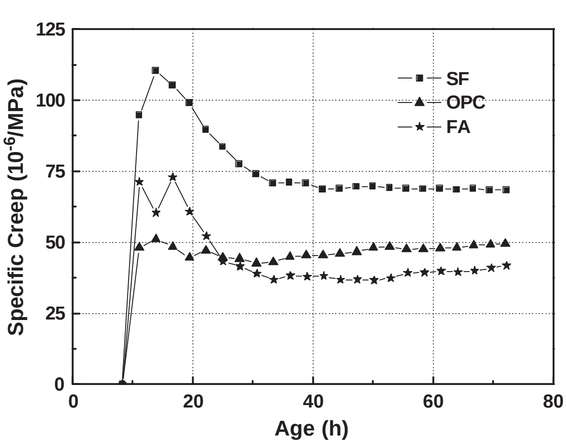

Fig. 12. Specific creep under isothermal condition.

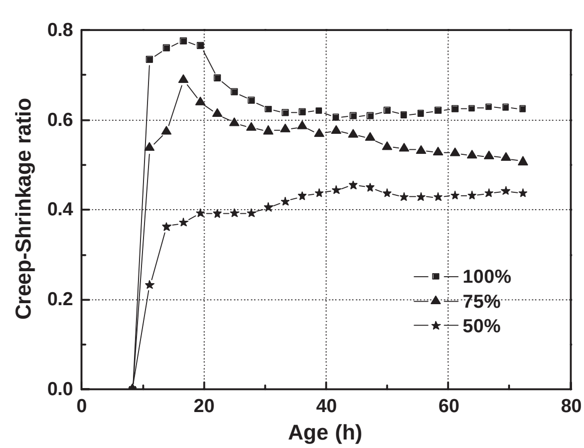

Fig. 14. Creep–shrinkage ratio under different degree of restraint conditions.

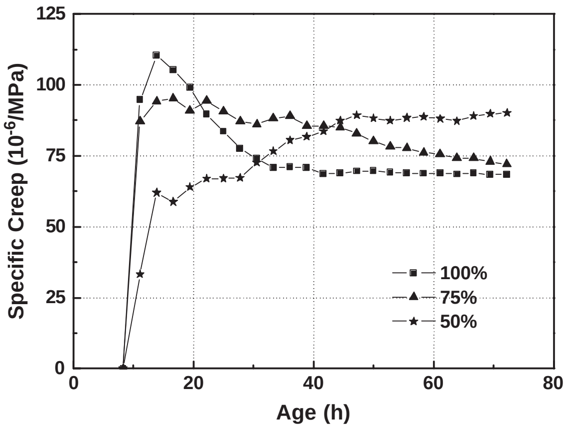

Fig. 15. Specific creep under different degree of restraint conditions.

The results indicated that the restraint degree had a great effect on the development of restraining stress. As presented in Fig. 13, the average restraining tensile stresses under 75% and 50% restraint conditions were about 88% and 47% of that under full restraint condition, respectively. Obviously, the restraining tensile stress decreased with the reduction of restraint degree, but it can be seen that the stress ratio (the ratio of the restraining stress under a certain restraint degree condition to the restraining stress under full restraint condition) was not always equal to the degree of restraint in value. This implied that stress relaxations induced by creep were different under different degree of restraint conditions.

Fig. 14 showed that the lower creep–shrinkage ratio occurred under the lower degree of restraint condition. This is because the measured creep strains increased slowly with the lower rate of stress development in the lower degree of restraint tests. The visco-elastic response of young concrete was variable with different restraining stress histories. It can be seen from Fig. 15 that the higher stress history was associated with the higher visco-elastic response in the first day, and this trend may be interpreted to a contribution of more microcracks developed in young concrete due to higher restraining tensile stress [22]. Nevertheless, it also was found that the concrete specimen undergoing the lowest stress history showed the highest value of specific creep after 2 days, even though the lowest specific creep was observed in it during the first day. That is to say, the higher visco-elastic response potential existed in young concrete with the lower restraining stress history.

The significant stress relaxation predicted in concrete at early ages due to high tensile creep is beneficial to the reduction of cracking risks for early age concrete. Therefore, in analyzing cracking risks of concrete at early ages, the tensile creep and relaxation properties should be considered under the temperature and restrained conditions for realistic structures, as the creep behavior of concrete at early ages is significantly influenced by the temperature and restraining stress histories. Mineral additives such as fly ash and silica fume in Portland cement have a great influence on the creep and relaxation properties at early ages. A better understanding of these effects may be of interest in developing ways to mitigate the high early stresses in restrained conditions.

4. Conclusions

Under the condition of this research, the following can be concluded:

(1) The silica fume concrete obtained a greater creep and specific creep in tension than the plain concrete with the same w/b ratio under restrained conditions, and the result for creep in the fly ash concrete is just the opposite.
(2) The initial thermal dilation delayed the development of tensile creep and weakened the creep potential in tension for early age concretes, even though the following thermal shrinkage enhanced slightly the tensile creep strain under a realistic temperature history.
(3) The stress history had a significant influence on the creep behaviors at early ages. The hardening concrete subjected to a lower restraining tensile stress history had a higher potential of visco-elastic response in tension, despite of a lower response in the first day.

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