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Cement and Concrete Research 33 (2003) 1687–1694

CEMENT AND CONCRETE RESEARCH

Effect of water-to-cementitious materials ratio and silica fume on the autogenous shrinkage of concrete

M.H. Zhang*, C.T. Tam, M.P. Leow

Department of Civil Engineering, National University of Singapore, 1 Engineering Drive 2, Singapore 117576, Singapore

Received 26 July 2001; accepted 16 April 2003

Abstract

This paper presents an experimental study on the autogenous shrinkage of Portland cement concrete (OPC) and concrete incorporating silica fume (SF). The results were compared with that of the total shrinkage (including drying shrinkage and part of the autogenous shrinkage) of the concrete specimens dried in 65% relative humidity after an initial moist curing of 7 days. The water-to-cementitious materials (w/c) ratio of the concrete studied was in the range of 0.26 to 0.35 and the SF content was in the range of 0% to 10% by weight of cement.

The results confirmed that the autogenous shrinkage increased with decreasing w/c ratio, and with increasing SF content. The results showed that the autogenous shrinkage strains of the concrete with low w/c ratio and SF developed rapidly even at early ages. At the w/c ratio of 0.26, the autogenous shrinkage strains of the SF concrete were more than 100 micro strains at 2 days. For all the concretes studied, 60% or more of the autogenous shrinkage strain up to 98 days occurred in the first 2 weeks after concrete casting. The results indicated that most of the total shrinkage of the concrete specimens with very low w/c ratio and SF exposed to 65% relative humidity after an initial moist curing of 7 days did not seem to be due to the drying shrinkage but due to the autogenous shrinkage.

Keywords: Autogenous shrinkage; Concrete; Drying shrinkage; Silica fume

1. Introduction

Concrete used in practice has undergone significant changes for the past two decades, and those with low water-to-cement ratios and incorporating silica fume (SF) have often been used to achieve strength and durability requirements. Although such concrete has improved properties, it appears to have an increased tendency to develop cracks during hardening, and this is sometimes attributed, at least partly, to autogenous shrinkage (or autogenous volume change).

ACI 116R defines autogenous volume change as "change in volume produced by the continued hydration of cement, exclusive of the effects of applied load and change in either thermal condition or moisture content."

The expression "chemical shrinkage" is also found sometimes in the literature for such volume change because chemical shrinkage is the phenomenon in which the absolute volume of hydration products is less than the total volume of unhydrated cement and water before hydration, and the consequence is a decrease in the absolute volume of the hydrated cement paste during its hydration (autogenous shrinkage) [1]. Whereas the chemical shrinkage results in the reduction of the absolute volume of the reactants, the autogenous shrinkage is the reduction of the external volume of cement paste or concrete after initial setting in cases where there is a lack of external water supply.

In general, the autogenous shrinkage in concrete is an order of magnitude smaller than that in cement paste [2] due to restraint by the aggregate. Typical values of the autogenous shrinkage of ordinary concrete are about 40×10^{-6} at the age of 1 month and 100×10^{-6} after 5 years [3], which are relatively low compared with those of drying shrinkage. Because of this, autogenous shrinkage has been ignored for practical purposes for ordinary concrete.

However, for concrete with a low w/c ratio, particularly when it contains SF, autogenous shrinkage may be of significance. According to Aïtcin et al. [4], the autogenous shrinkage will not be high if the w/c ratio is greater than about 0.42, but will develop rapidly if the w/c ratio is lower than 0.42. At a very low w/c ratio of 0.17, an autogenous shrinkage of 700×10^{-6} for concrete was reported [5].

* Corresponding author. Tel.: +65-6874-2273; fax: +65-6779-1635.

0008-8846/03/$ – see front matter © 2003 Published by Elsevier Ltd.
doi:10.1016/S0008-8846(03)00149-2

In the past, the term "drying shrinkage" has been frequently used to include both the drying shrinkage and the autogenous shrinkage. ACI 116R defines drying shrinkage as "shrinkage resulting from the loss of moisture." The shrinkage of a specimen under drying conditions without being subjected to applied load and temperature change includes both the autogenous and drying shrinkage. For normal-strength concrete, this is of minor importance because of its relatively low autogenous shrinkage. For high-strength concrete, however, autogenous shrinkage may not be ignored.

The objectives of this study were to determine the autogenous shrinkage of Portland cement concrete (OPC) and concrete incorporating SF by using strain transducers embedded in sealed specimens, and to compare the results with that of the total shrinkage (including drying shrinkage and part of the autogenous shrinkage) of the concrete specimens dried in 65% relative humidity after an initial moist curing of 7 days. The effect of w/c ratio in the range of 0.26 to 0.35 and the effect of SF in the range of 0% to 10% by weight of cement were investigated. The experimental work provided information for concrete exposed to temperatures of about 30 °C, whereas most of the published literature dealt with concrete exposed to temperatures of about 20 °C.

2. Experimental

2.1. Materials used

2.1.1. Cement

ASTM Type I normal Portland cement was used for making concrete. Its physical properties and chemical composition are given in Table 1, and the information was provided by the cement supplier.

Table 1
Physical properties and chemical composition of cement and SF

	Cement	Silica fume
Physical properties		
Specific surface (m^2/g)	0.35[a]	23[b]
Specific gravity	3.15	2.0
Amount retained on 45-μm sieve (%)	–	1.8
Chemical composition (%)		
CaO	64.0	0.9
SiO_2	21.1	93.6
Al_2O_3	4.9	0.5
Fe_2O_3	3.0	1.5
SO_3	2.1	0.3
MgO	1.6	0.6
K_2O	0.78	0.54
Na_2O	0.18	0.04
LOI	2.1	2.0
Free CaO	0.95	–

[a] Blain fineness.
[b] Determined by nitrogen absorption method.

2.1.2. Silica fume

The SF used was a dry, uncompacted powder from the production of silicon metal with SiO_2 content of 93.6%. The amount retained on a 45-μm sieve was 1.8%. Detailed physical properties and chemical composition are also given in Table 1.

2.1.3. Aggregate

The coarse aggregate used was crushed granite with a maximum nominal size of 20 mm, and the fine aggregate used was natural sand. The specific gravity for both the coarse and fine aggregates was 2.65.

2.1.4. Superplasticizer

A superplasticizer of sulfonated, naphthalene formaldehyde condensate type was used in all the concrete mixtures. The superplasticizer is a dark brown solution with solid content of ~40% and specific gravity of 1.21.

2.2. Concrete mixtures and specimen preparation

2.2.1. Mixture proportions

Mixture proportions of the concrete studied are given in Table 2. The w/c ratio of the concrete ranged from 0.26 to 0.35, and the SF content ranged from 0% to 10% by mass of the total cementitious materials as cement replacement.

2.2.2. Preparation and curing of concrete specimens

The concrete was mixed in a laboratory pan mixer. The fine and coarse aggregates were mixed first, followed by the addition of cement and SF. After the materials were uniformly dispersed, water and the superplasticizer were added and mixed together until a consistent mixture was obtained. The slump of the fresh concrete was determined immediately after the mixing according to ASTM C 143-78, and was controlled in the range of 50 to 100 mm.

For each concrete mixture, three 100 × 100 × 100-mm cubes were cast for determining the compressive strength, two prisms of 400 × 100 × 100 mm were cast for determining the total shrinkage, and one prism of 300 × 100 × 100 mm was cast for determining the autogenous shrinkage except for the concrete Mix N30 for which two prisms were made to determine the autogenous shrinkage.

After casting, all the cubes and prisms for the total shrinkage measurement were left in the casting room (~30 °C), covered with plastic sheet for approximately 24 h, then demolded and cured in a moist-curing room at ~30 °C and >95% relative humidity until required for testing. The compressive strength of the concrete was determined after 28 days of moist curing. The total shrinkage of the prisms dried at ~30 °C and ~65% relative humidity was monitored after an initial moist curing of 7 days.

For each prism of the autogenous shrinkage measurement, a strain transducer and a thermocouple were embedded horizontally in the centre of the prism (Fig. 1). The

Table 2
Mix proportions, slump, and 28-day compressive strength of the concrete

Mix ID	w/c	SF (%)	Mix proportions (kg/m^3)					Dosage of SP (l/m^3)	Slump (mm)	28-Day strength (MPa)
			Cement	Silica fume	Water[a]	Sand	Coarse aggregate			
N26	0.26	0	496	0	135	695	1141	7.5	50	86.6
S26-5		5	471	25	134	684	1121	7.0	65	91.2
S26-10		10	446	50	134	684	1110	7.5	70	96.6
N30	0.30	0	497	0	153	696	1093	6.0	90	70.1
S30-5		5	472	25	153	686	1074	5.8	50	83.7
S30-10		10	447	50	153	686	1064	6.1	50	91.1
N35	0.35	0	498	0	176	698	1047	3.4	60	63.7
S35-5		5	473	25	178	676	1015	5.3	100	70.3
S35-10		10	447	50	177	675	1003	5.6	70	75.2

[a] Including water in superplasticizer (SP).

transducer and thermocouple were tied onto a chair with wire at their two ends to prevent movement during casting. The interior surfaces of the wood moulds were lined with a layer of smooth polymer material to reduce the friction between the prisms and the moulds. Immediately after the concrete casting, each prism with the wood mould was sealed individually in a plastic bag and kept at ~30 °C for the entire period of the experiment except for the first 24 h, during which it was kept in a water bath with a temperature of ~28 °C to reduce the temperature rise of concrete at early ages. The temperature of each concrete prism used for determining the autogenous shrinkage was recorded by the thermal couple embedded. The results indicated that from an initial temperature of ~30 °C, the maximum temperature reached was 41 °C approximately 7–9 h after the casting, and it dropped to approximately 30 °C after about 1 day.

2.3. Determination of concrete properties

2.3.1. Slump of fresh concrete and compressive strength of hardened concrete

The slump of the fresh concrete was determined immediately after the mixing, and the compressive strength of the hardened concrete was determined at 28 days. The results are given in Table 2. The slump of the concrete ranged from 50 to 100 mm. The compressive strength of the concrete ranged from 63.7 to 86.6 MPa for the control OPC, and from 70.1 to 96.6 MPa for the SF concrete. The compressive strengths reported were the average determined from three cubes.

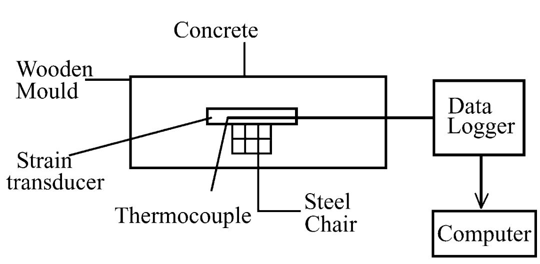

Fig. 1. Schematic illustration for the measurement of the autogenous shrinkage with embedded strain transducer.

2.3.2. Autogenous shrinkage

The strain transducer and thermocouple embedded in each concrete prism were connected to a computer-controlled data logger (Fig. 1) right after the casting of the concrete specimen, and the shrinkage strain and temperature variation of the concrete specimen with time were recorded.

The embedded strain transducers used in the experiment (Tokyo Sokki Kenkyujo, KM series) can measure the strain of concrete that undergoes a transition from compliant to hardened state. Their low modulus (400 kgf/cm^2) and waterproof construction are suited for internal strain measurement during the very earliest stages of curing. In addition, they are impervious to moisture absorption; thus, they can produce stability for long-term strain measurement as well.

The measured values or data obtained directly from the computer (which is connected to the data logger) included the shrinkage values before calibration and the temperature variation with time. The start of the shrinkage observed, which was usually within hours, was used as a reference value. Subsequent values obtained were subtracted from the reference values and multiplied by the calibration coefficient of the transducer to obtain the autogenous shrinkage.

The calibration coefficient for each strain transducer was obtained from the manufacturer's test data sheet. The strain transducer is calibrated by connecting the input/output cable to the strain meter having the constant voltage bridge excitation. By setting the gauge factor of strain meter to 2.00, rated output, calibration coefficient and zero balance are obtained. Each strain transducer has a different calibration coefficient, which is to be multiplied by the difference between the measured value and the reference value to obtain the autogenous shrinkage, as described earlier in the previous paragraph.

The starting point of the autogenous shrinkage may be delayed by the temperature increase at early ages due to thermal expansion, and this also contributed to different starting points of the concrete. To estimate the autogenous shrinkage strain without temperature effect, a reference concrete temperature ranging from 29.0 to 30.5 °C was selected for each concrete mix and an average thermal expansion coefficient of 10×10^{-6}/°C [6] was used to apply temperature correction to the strain values. There is not much information available on the thermal expansion coefficient of concrete. The coefficient used in the study is the value commonly mentioned in textbooks. The correction was calculated assuming that the temperature profile varies linearly between the surface and the center of the test prism, and half of the temperature rise was accounted to take the temperature difference between the surface and core into consideration.

2.3.3. Total shrinkage

After the initial moist curing for 7 days, the prisms were placed in the temperature- and humidity-controlled room (~ 30 °C and 65% relative humidity). Two pins 200 mm apart were glued to both sides of the side-casting surfaces with epoxy after about 1.5 h drying. The length between the pins was measured by a Demec gauge every week, and compared with the initial length that was determined after 7 days moist curing to calculate the total shrinkage of the concrete. Thus, the total shrinkage included the drying shrinkage and part of the autogenous shrinkage.

2.3.4. Weight change

Concrete prisms used for determining the total shrinkage was weighed once a week to determine the weight change over time.

3. Results and discussion

3.1. Autogenous shrinkage

Autogenous shrinkage up to 98 days was presented in Table 3, and the effect of the w/c ratio and SF content on the autogenous shrinkage development was shown in Figs. 2 and 3, respectively.

It appears that both the w/c ratio and the incorporation of SF had significant effect on the autogenous shrinkage strain of the concrete. The autogenous shrinkage increased with decreasing w/c ratio and with increasing SF content. This is in agreement with those reported by Tazawa and Miyazawa [5], Brooks et al. [7], Mak et al. [8] and Persson [9].

For the control OPC, a reduction of w/c ratio from 0.35 to 0.30 resulted in a significant increase in the autogenous shrinkage from 40 to 180 micro strains at 98 days, whereas a further reduction of w/c ratio to 0.26 only increased the autogenous shrinkage slightly to197 micro strains.

For the concrete with SF, the autogenous shrinkage after 98 days was relatively high even at a w/c ratio of 0.35 (>200 micro strains), but decreasing w/c ratio to 0.26 only increased the autogenous shrinkage by ~ 50 micro strains for the concrete with 5% SF, and by ~ 30 micro strains for the concrete with 10% SF.

Sixty percent or more of the autogenous shrinkage strain up to 98 days occurred in the first 2 weeks after concrete casting (Table 3).

3.2. Early-age autogenous shrinkage

3.2.1. Starting point for the autogenous shrinkage

For all the specimens with the embedded strain transducer, shrinkage was noted a few hours after casting. The start of the shrinkage observed was used as the reference or initiation point of the autogenous shrinkage. As an example, Fig. 4 shows the early-age autogenous shrinkage and the temperature variation of the control concrete mixtures with the w/c ratio of 0.30 during the first 48 h after casting. The autogenous shrinkage of the specimens was observed to start within 4–8 h after casting.

It was mentioned by Aitcin [1] that the autogenous shrinkage starts at the initial setting time of concrete. However, the accurate prediction of the initial setting of concrete is difficult. In this experiment, the estimation of the initiation of the autogenous shrinkage was based on the start of shrinkage observed. This usually corresponded to rapid rise in temperature of the concrete (Fig. 4a), which was most likely to be the period between the initial and the final setting of the concrete. The peak temperature of the concrete is most likely to correspond to the final setting of the concrete [6,10].

3.2.2. Effect of the temperature rise of concrete on the autogenous shrinkage

One of the factors affecting the starting point of the autogenous shrinkage in addition to the composition and w/c ratio of the concrete is the temperature rise in the concrete at early ages due to the heat of cement hydration. The temperature rise may result in an increase in the volume of the concrete. When the volume increase due to thermal expansion equals to the autogenous shrinkage, the shrinkage

Table 3
Autogenous shrinkage of concrete

w/c	Autogenous shrinkage (micro strain)/% of 98-day shrinkage											
	SF 0%				SF 5%				SF 10%			
	2 days	7 days	14 days	98 days	2 days	7 days	14 days	98 days	2 days	7 days	14 days	98 days
0.26	49/25	100/51	129/65	197	101/38	170/64	194/73	266	101/36	174/62	221/78	282
0.30	36/20	87/48	115/64	180	77/35	149/68	174/80	218	74/27	161/59	213/78	274
0.35	25/63	34/85	40/100	40	49/22	101/47	128/60	215	41/16	115/46	160/64	251

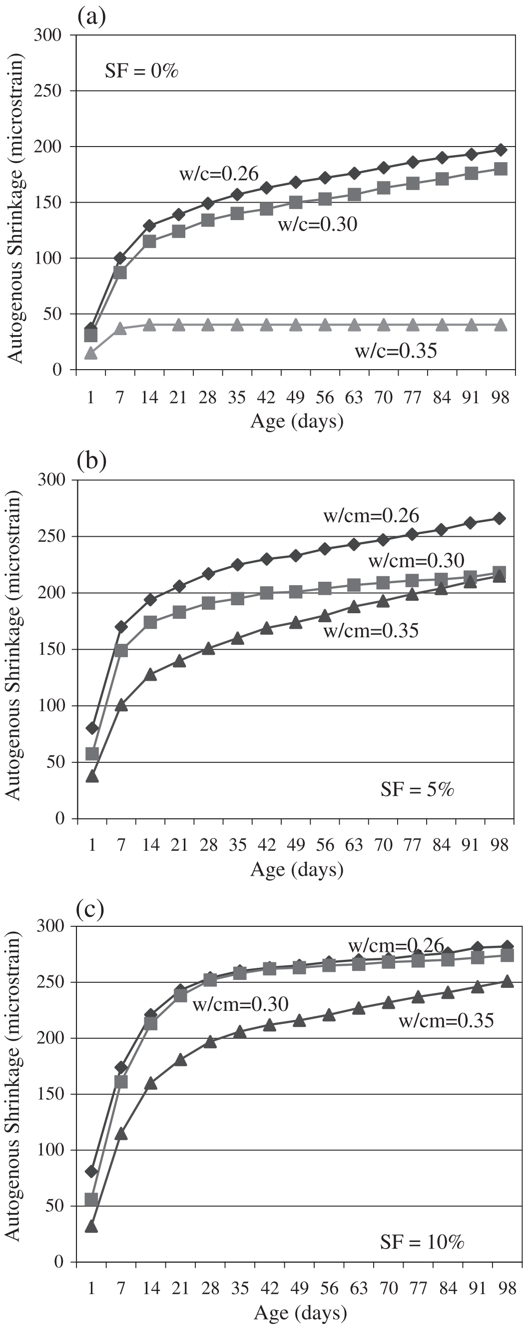

Fig. 2. Effect of w/c ratio on the autogenous shrinkage of concrete.

will not be observed. Aitcin [1] observed that during the early hours of hardening, concrete with a very low water/binder ratio swells as long as the thermal expansion is larger than the autogenous shrinkage, but the autogenous shrinkage overtakes the thermal expansion quite rapidly, so that low-w/c ratio concrete shrinks after the initial swelling phase.

In this study, the temperature rise in all the nine concrete mixtures was observed to be between 7 and 10 °C. Maximum early-age autogenous shrinkage after the temperature correction was observed to occur near the time the concrete reached peak temperature, and was relatively high. However, after about 48 h, the effect of the temperature rise was insignificant. It should be noted that the autogenous shrinkage with the temperature adjustment was only approximate because only the average thermal expansion coefficient and average temperature of the prism were used for the calculation.

Tazawa and Miyazawa [11] mentioned that in order to estimate the autogenous shrinkage precisely, it is important to establish a test method to determine the coefficient of thermal expansion for concrete at early ages.

Nevertheless, the deformation caused by the thermal effect is reversible and thus less critical. In reality, it is the

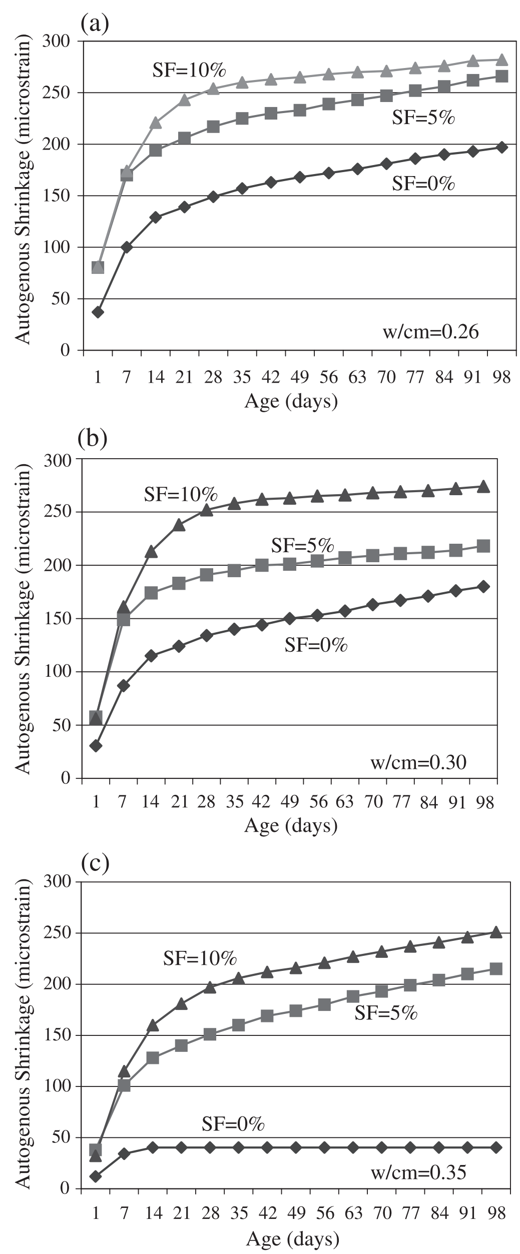

Fig. 3. Effect of SF content on the autogenous shrinkage of concrete.

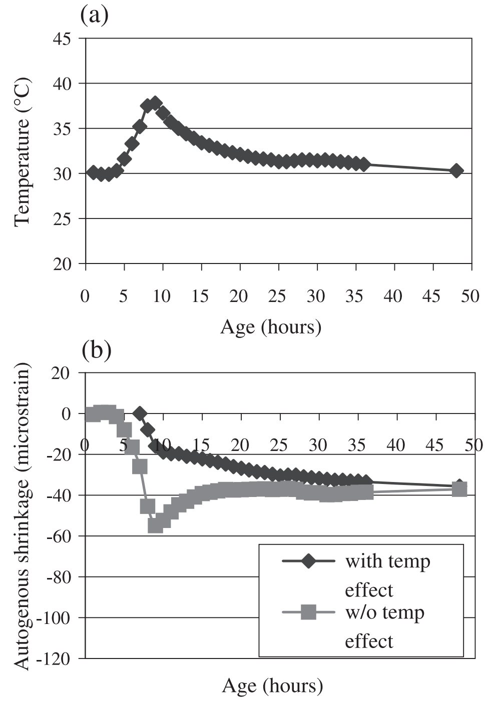

Fig. 4. (a) Temperature change and (b) early age. Autogenous shrinkage of the control concrete with w/c ratio of 0.30. (Reference temperature = 30 °C).

autogenous shrinkage strain including thermal strain that is of interest. Research by Mak et al. [8] showed that a moderate temperature rise of 15 °C has a significant impact in reducing the early-age autogenous shrinkage in some concretes by 25% to 50%. They also pointed out that if the autogenous deformations were measured under standard temperature conditions only, the actual deformations might not be estimated accurately.

3.2.3. Early-age autogenous shrinkage

Early-age autogenous shrinkage strains of the concrete (during the first 48 h after casting) are given in Table 3. The results indicated that the concrete with low w/c ratio and with SF induce autogenous shrinkage rapidly even at early ages. Particularly at w/c ratio of 0.26, the autogenous shrinkage strains of the SF concrete at the age of 2 days were more than 100 micro strain. Thus, the early-age autogenous shrinkage should not be overlooked, as the concrete is most susceptible to cracking at early ages due to its low tensile strength and tensile strain capacity.

It should be noted that the early-age autogenous shrinkage obtained in this experiment may be somewhat different from the actual autogenous shrinkage in real structures due to size effects. As mentioned by Tazawa and Miyazawa [5], size may have some effects on the autogenous shrinkage. Mak et al. [8] pointed out that the autogenous shrinkage is an intrinsic material property that affects elements of any size to the same degree unless mitigated by temperature effects. The temperature effects are in turn controlled by the size of the element.

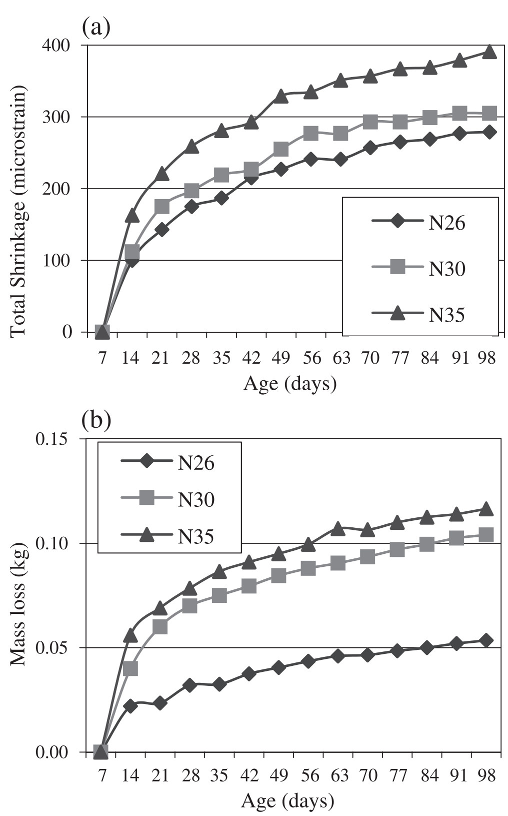

Fig. 5. (a) Total shrinkage and (b) mass loss of the control concrete.

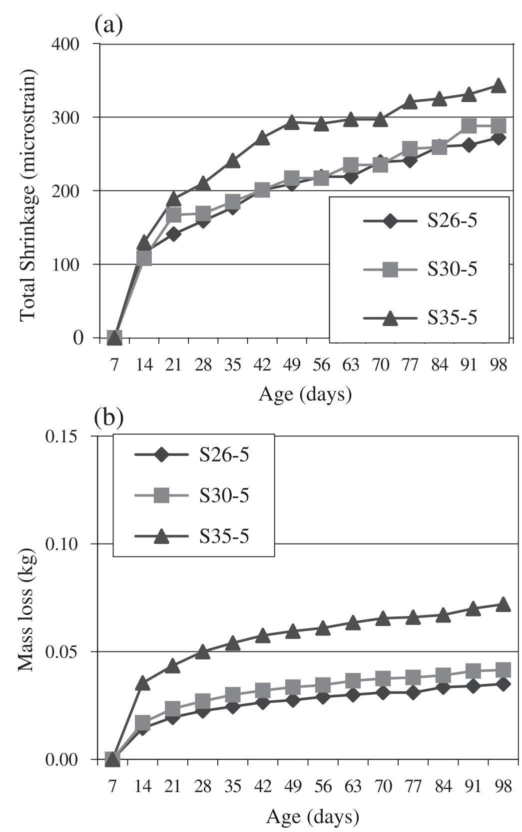

Fig. 6. (a) Total shrinkage and (b) mass loss of the concrete with 5% SF.

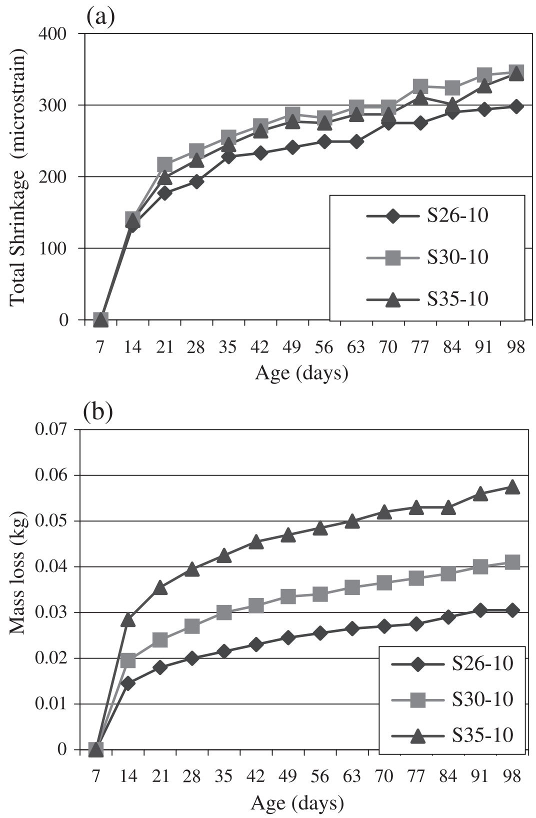

Fig. 7. (a) Total shrinkage and (b) mass loss of the concrete with 10% SF.

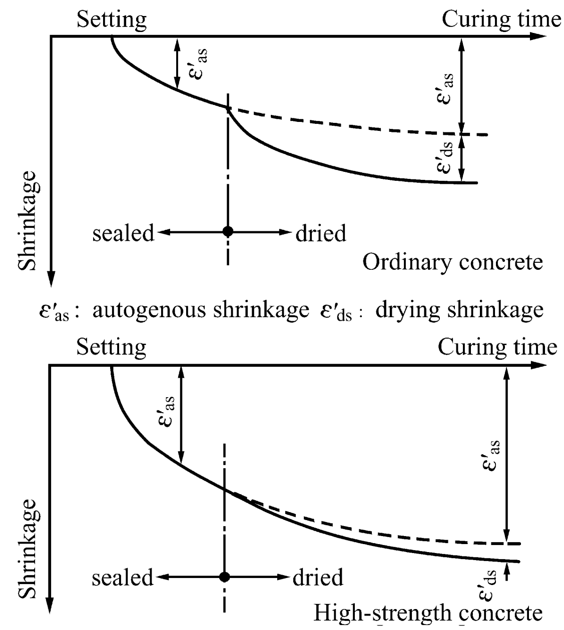

Fig. 8. Schematic illustration of the shrinkage of concrete (Japan Concrete Institute, 1996).

3.3. Autogenous shrinkage vs. drying shrinkage

Because it is difficult to determine the drying shrinkage excluding the effect of the autogenous shrinkage, the total shrinkage of the concrete specimens in 65% relative humidity was determined after the specimens had been cured for 7 days in moist condition. The total shrinkage thus included both the drying shrinkage (DS) and part of the autogenous shrinkage (AS′).

3.3.1. Total shrinkage and mass loss

The total shrinkage and weight loss of the specimens vs. age are shown in Figs. 5–7.

The total shrinkage of the control OPC decreased with decreasing w/c ratio (Fig. 5). This was probably due to the greater water loss from concrete to environment, which induces higher drying shrinkage when the w/c ratio increased. This was confirmed by the increased mass loss of the concrete observed with increasing w/c ratio.

For concrete with 5% SF, the total shrinkage was reduced with decreasing w/c ratio from 0.35 to 0.30. However, a further decreasing of w/c ratio to 0.26 did not result in further reduction in the total shrinkage although the concrete with w/c ratio of 0.26 showed less mass loss over the period (Fig. 6). This might be due to the high autogenous shrinkage of the concrete with w/c ratio of 0.26.

The total shrinkage of the concrete with 10% SF was similar regardless of the w/c ratio (Fig. 7). However, the mass loss decreased with decreasing w/c ratio, which indicated decreased drying shrinkage. This suggests increased autogenous shrinkage with decreasing w/c ratio.

It should be noted that it is not possible to obtain the drying shrinkage by subtracting the autogenous shrinkage directly from the total shrinkage measured in this experiment due to the different curing conditions for the autogenous and total shrinkage specimens. However, the difference can be used as an indication of the relative proportions of the drying shrinkage vs. the autogenous shrinkage.

Table 4
Shrinkage of dried and sealed concrete specimens at 98 days

w/c	SF 0%			SF 5%			SF 10%		
	AS	DS + AS′	AS/(DS + AS′) (%)	AS	DS + AS′	AS/(DS + AS′) (%)	AS	DS + AS′	AS/(DS + AS′) (%)
0.26	197	279	71	266	272	98	282	298	95
0.30	180	305	59	218	288	76	274	346	79
0.35	40	391	10	215	343	63	251	344	73

AS = autogenous shrinkage determined using sealed specimens, in micro strain.
DS = drying shrinkage determined on specimens cured for 7 days in moist condition followed by drying in laboratory air, in micro strain.
AS′ = autogenous shrinkage occurred in the specimens cured for 7 days in moist condition followed by drying in laboratory air, in micro stain.

3.3.2. Autogenous shrinkage vs. drying shrinkage

The results of the total shrinkage of the dried specimens at 98 days in comparison with the autogenous shrinkage of the sealed specimens are given in Table 4.

At the higher w/c ratio of 0.35, the total shrinkage (DS + AS′) of concrete, particularly the concrete without SF, was higher than the autogenous shrinkage of the sealed concrete specimens. On the other hand, at the low w/c ratio of 0.26, the total shrinkage of the concrete with SF was almost the same as the autogenous shrinkage of the sealed specimens. This suggests that most of the total shrinkage of the dried concrete specimens with very low w/c ratio and SF was not due to the drying shrinkage but due to the autogenous shrinkage. This was in line with the results reported in Ref. [12] and illustrated in Fig. 8.

4. Summary and conclusions

Based on the limited experimental work for concrete with w/c ratio in the range of 0.26 to 0.35 and with SF content in the range of 0% to 10% by mass of the total cementitious materials as cement replacement, the following conclusions appear warranted.

1. The autogenous shrinkage increased with decreasing w/c ratio, and with increasing SF content. For the control Portland cement concrete, a reduction of w/c ratio from 0.35 to 0.30 resulted in a significant increase in the autogenous shrinkage from 40 to 180 micro strains at 98 days, whereas a further reduction of w/c ratio to 0.26 only increased the autogenous shrinkage slightly to197 micro strains. For the concrete with SF, the autogenous shrinkage after 98 days was relatively high even at a w/c ratio of 0.35 (>200 micro strains), further decreasing w/c ratio to 0.26 only increased the autogenous shrinkage by ~50 micro strains for the concrete with 5% SF, and by ~30 micro strains for the concrete with 10% SF.

2. The autogenous shrinkage strains of the concrete with low w/c ratio and SF developed rapidly even at early ages. At the w/c ratio of 0.26, the autogenous shrinkage strains of the SF concrete were more than 100 micro strains at 2 days. For all the concretes studied, 60% or more of the autogenous shrinkage strain up to 98 days occurred in the first 2 weeks after concrete casting.

3. Most of the total shrinkage of the concrete specimens with very low w/c ratio and SF exposed to 65% relative humidity after an initial moist curing of 7 days did not seem to be due to the drying shrinkage but due to the autogenous shrinkage.

Acknowledgements

Grateful acknowledgement is made to P.K. Choo and B.O. Ang of Structural Laboratory, Department of Civil Engineering, National University of Singapore, for their assistance of laboratory work.

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