Autogenous Shrinkage of Concrete Prepared with the Binders Containing Different Kinds of Mineral Admixture

P.Y. Yan, Z.C. Chen, J.C. Wang, F. Zheng
Tsinghua University, Beijing, China

Abstract:

Autogenous shrinkage of concrete prepared with the binders containing different kinds of mineral admixture was investigated using a computer-controlling measuring system. The effect of kind and replacement percentage of mineral admixture and water-binder ratio was determined. Addition of fly ash and ground granular blast-furnace slag decreases the autogenous shrinkage, but addition of silica fume increases it. Autogenous shrinkage develops rapidly in the first day. After then its developing rate decreases. Autogenous shrinkage in the first day decreases gradually with the increase of replacemental percentage of mineral admixture and the water-binder ratio. An experiential model was developed to simulate the autogenous shrinkage of concrete prepared with complex binders.

1. Introduction

High performance concrete(HPC) with low water-to-binder ratio, high binder content in which part of Portland cement is substituted by mineral admixture is used widely in recent decades. HPC shows a number of excellent desirable properties, such as good workability, high strength and high long-term durability compared with conventional concrete. However, it is also susceptible to increasing cracking risk due to autogenous shrinkage in early age[1,2]. The autogenous shrinkage arises from self-desiccation in dense concrete due to water consumption during the hydration of cementitious materials. This early-age shrinkage may cause micro-cracks in the concrete and even macro cracks in concrete structures.

Much study has been conducted on autogenous shrinkage in cement paste, mortar and concrete(with and without admixture). These studies demonstrate that autogenous shrinkage of concrete increases with decreasing w/b. Most autogenous shrinkage occurs in the first few days of hydration. Engineers are more interested in the stress induced by autogenous shrinkage under restraining conditions and the tendency of cracking, especially at early ages. Paillere et al.[3] reported that a concrete with low w/b failed within a few days when its autogenous shrinkage was restrained. Pigeon et al.[4] observed that autogenous shrinkage can generate a tensile stress and creep at early ages and must be taken into account when analyzing the risk of early-age cracking.

Mineral admixture has been widely used for a long time as a supplementary cementitious material to improve workability and to enhance long-term strength and durability of concrete. Complex binder containing as high as 60% of fly ash was used to prepare high performance concrete[5]. It has been found that various pozzolanic materials, such as silica fume, fly ash and granular blast-furnace slag, also affect autogenous shrinkage behavior of concrete in different manner[2].

Autogenous shrinkage, potentially a major factor causing early-age cracking, must be avoided or minimized from practical point of view. Therefore, it is necessary to study not only how to predict but also to reduce autogenous shrinkage. Only limited information is currently available on autogenous shrinkage of HPC with mineral admixtures. The effects of w/b, kind and replacement percentage of mineral admixture on autogenous shrinkage of concrete were investigated and then a predictive model was developed based on the results.

2. Materials and Experimental Methods

2.1 Materials and mix proportions

Ordinary Portland cement (PO 42.5), fly ash produced in coal-fired electric power stations, ground granulated blast-furnace slag (GGBS) and silica fume were used. Their chemical compositions are shown in Table 1. A polycarboxylate-based superplasticizer was used as the chemical admixture. Washed river sand and crushed limestone were used as fine and coarse aggregate, respectively. The maximum nominal size of coarse aggregate is 20mm. The fineness modulus of sand is 3.1.

The mix proportions of the tested concrete are shown in Table 2. The concrete mix proportions were designed to exhibit high workability or self-compaction capability. The slump of these mixes was controlled at the range of 15 to 23 cm. Their 28d compressive strength is also shown in Table 2.

Table 1 Chemical composition of raw materials,%

	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	Na_2O	MnO_2	SO_3	LOI
cement	22.80	4.55	65.34	2.82	2.74		0.55		2.92	0.50
Fly ash	57.6	21.9	3.87	7.7	1.68	2.51	1.54	0.08	0.018	4.51
GGBS	32.37	14.87	36.85		10.11			0.55	3.00	4.42
Silica fume	93.5	0.43								

The weight ratios of cement replaced by fly ash are 0%, 20%, 30%, 40% and 60%. The ratios are 0%, 20% and 40% for GGBS while 0%, 10% and 20% for silica fume. The water-to-binder ratio adopted in this study were 0.25, 0.30, 0.35, 0.4 and 0.53 for concrete without mineral admixture and 0.25 for the rest of concretes containing various mineral admixture.

Table 2 Mix proportions (kg/m^3) and 28d strength (MPa) of concrete

No.	Cem.	Fly ash	slag	Silica fume	Fine agg.	Coarse agg.	water	Super-plasticizer	w/b	compressive strength
C1	368				694	1132	195		0.53	35.6
C2	430				720	1080	172	1.2	0.40	49.5
C3	480				707	1060	158	2.4	0.35	65.0
C4	550				686	1030	165	4.4	0.30	78.5
C5	550				723	1085	140	5.5	0.25	84.5
FA20	440	110			698	1046	140	4.0	0.25	98.2
FA30	385	165			690	1035	140	3.5	0.25	90.0
FA40	330	220			682	1023	140	3.3	0.25	72.5
FA60	220	330			667	1000	140	3.0	0.25	65.5
SL20	440		110		710	1065	140	5.5	0.25	108.0
SL40	330		220		707	1061	140	5.5	0.25	83.5
SF10	495			55	705	1058	140	5.5	0.25	90.8
SF20	440			110	698	1046	140	6.0	0.25	82.0

2.2 Experimental methods

Measurements of autogenous volume change of concrete specimens conducted by a specially designed computer-controlling measuring system(Fig.1). Linear variable differential transformers system (LVDTs) was contacted on each stud installed onto the both ends of prism specimen and connected with data logger (which is connected to the computer). The instrument can record free length change and the temperature variation with time for concrete specimens.

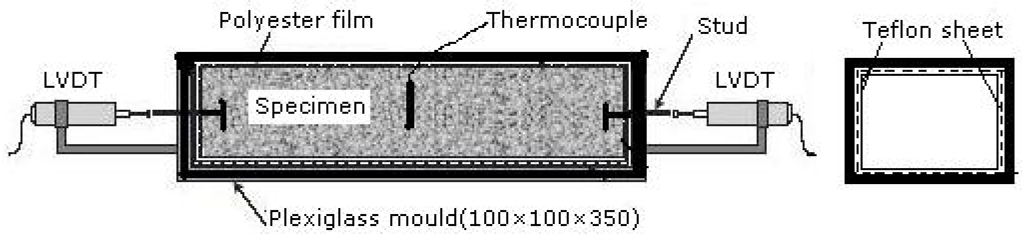

Fig.1 Experimental setup for the measurement of autogenous shrinkage of concrete

Polytetrafluoroethylene (Teflon) sheets were placed on the bottom and inside each end and side of the plexiglass mould. A polyester film was put between Teflon sheets and specimen with lubricant oil between Teflon sheet and polyester film in order to minimize the friction between the concrete and the mould. Teflon sheets at end and side were immediately pulled out when concrete reaches initial setting. A thermocouple is put in the center of the specimen to measure the temperature variation in concrete. The specimen is sealed with a tight cover against loss of water.

At each test the signals from the two LVDTs and the thermocouple were recorded continuously. The system demonstrated very good reproducibility for nominally identical mixes.

100mm×100mm×350mm prism specimens were prepared for autogenous shrinkage test. In each single case, at least 2 specimens were cast. The measurement of autogenous shrinkage was started from initial setting time of concretes[6]. Autogenous shrinkage is measured simultaneously on two identical samples.

3. Results and Discussions

3.1 Effect of the w/cm on autogenous shrinkage

Fig. 2 is a plot of autogenous shrinkage of concrete measured from initial setting time as a function of age up to 14 days for concrete prepared with pure Portland cement(C). It was observed that autogenous shrinkage of concrete increased as the w/cm decreased. Moreover, autogenous shrinkage of the concrete with low w/cm developed much more rapidly than that of the concrete with high w/cm. When the w/c ratio is low and no water can be further supplied during curing process, autogenous shrinkage in concrete occurs due to the “self-desiccation” in the pore structure of concrete as the moisture is consumed during the hydration process[7].

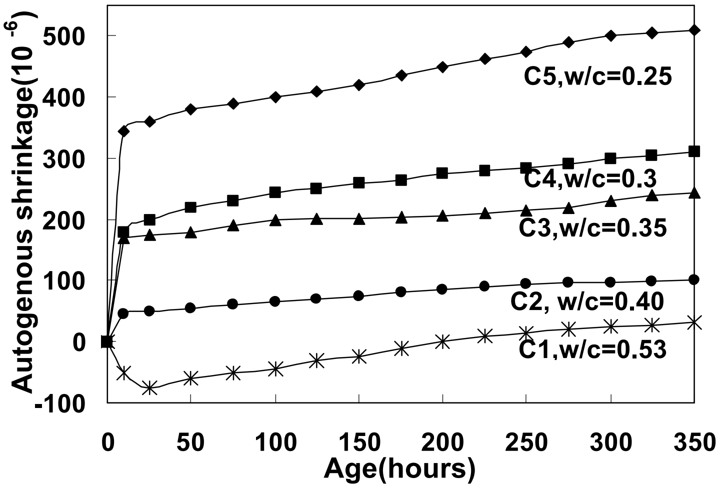

Fig. 2 Effect of w/cm on autogenous shrinkage for concrete prepared with pure Portland cement

It is interesting to see that the autogenous shrinkage curve for concrete with w/cm of 0.53(C1) exhibits dilating within first day then shrinkage permanently. It is probably the result of reabsorption of bleeding in concrete at early-age while overmuch free water existing in paste[8].

It was found that autogenous shrinkage of samples with high w/cm (mix C1 and C2) gradually increased and exhibited $40\text{-}100\times10^{-6}$ at 14 days. In contrast, Samples with low w/cm (mix C3, C4 and C5) showed much larger autogenous shrinkage compared with C1 and C2. For example, the concrete with the lowest w/cm of 0.25 (mix C5) showed 510×10^{-6} at 14 days. It was about ten times greater than that of C1. Also, autogenous shrinkage of mix C4 concrete at one day was approximately 74% of that at 14 days, implying that most part of autogenous shrinkage of HPC developed within first two days after casting. There is an obvious transiti on point on the autogenous shrinkage curve of concrete prepared with pure Portland cement and low w/cm at about the end of the first day. This rapid developing rate of shrinkage in early age may be responsible for the high cracking tendency in HPC.

3.2 Effect of fly ash partially substituting Portland cement on autogenous shrinkage of concrete

Autogenous shrinkage of concrete containing fly ash of 0, 20, 30, 40 and 60% by weight percentage of cementitious material as a function of age up to 14 days are shown in Fig. 3. Clearly, all FA concretes showed lower autogenous shrinkage at given ages than that of concretes prepared using pure Portland cement(C) at same w/b. The higher replacement percentage of fly ash, the lower the autogenous shrinkage. At 14 days, when w/b was 0.25, autogenous shrinkage of FA20 was reduced by about 5-10% compared with the C5, while those of FA30, FA40 and FA60 were 15-25%, 30-40% and 80-100%, respectively. This reduction in autogenous shrinkage could be attributed to a dilution effect caused by a reduction in Portland cement content because part of the Portland cement was replaced by fly ash with low hydration activity.

The autogenous shrinkage of concrete in the first hydrating day decreases along with the increase of replacing percentage of fly ash. There are still obvious transition points on the autogenous shrinkage curves of concrete in which the replacing percentage of fly ash is not more than 30%. The autogenous shrinkage of concrete in which the replacing percentage of fly ash is higher than 30% reduces greatly in the first day. There is no occurrence of autogenous shrinkage when the placement percentage of cement by fly ash reaches to 60%. In this case there is a lot of unhydrated fly ash in concrete because fly ash does not hydrate on the first day. The unreacted fly ash may act like a microaggregate that does not shrink. Therefore, the total autogenous shrinkage of concrete can be reduced.

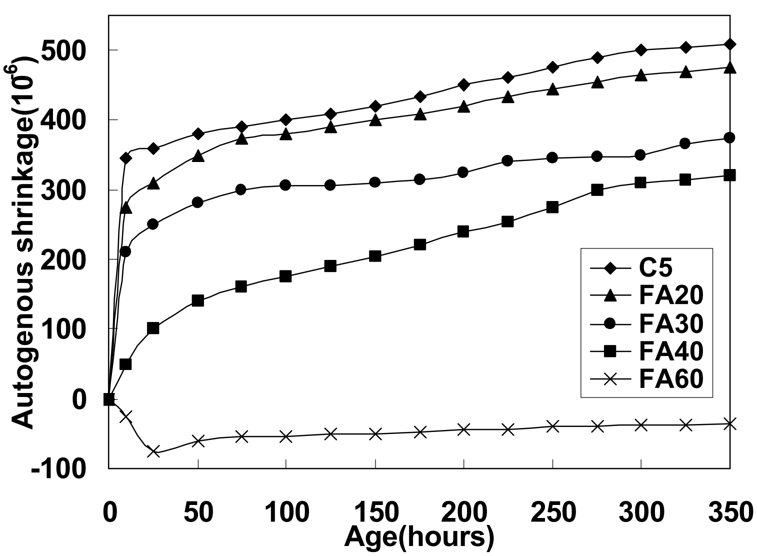

Fig. 3 Effect of fly ash content on autogenous shrinkage of concrete with w/b of 0.25

Chan et al.[9] proposed that fly ash would be used to reduce autogenous shrinkage because it is more effective than other mineral admixtures, such as silica fume and GGBS. When fly ash is used as a supplementary cementitious material in concrete, not only does it lead to less hydration, but also its pozzolanic reaction can only occur when calcium hydroxide is produced from the hydration process of Portland cement. Furthermore, fly ash particles can retains much more free water than cement particles because of its spherical shape. As autogenous shrinkage is the result of water consumption during the hydration process of binder, the large free water content results in low autogenous shrinkage.

In fact, fly ash, like other mineral admixtures, contributes to the properties of concrete as to both the filler effect and the pozzolanic effect. In paste with a high replacement ratio of fly ash and considerably low water-binder ratio, unreacted fly ash particles behave like a part of the microaggregates.

3.3 Effect of GGBS partially substituting Portland cement on autogenous shrinkage of concrete

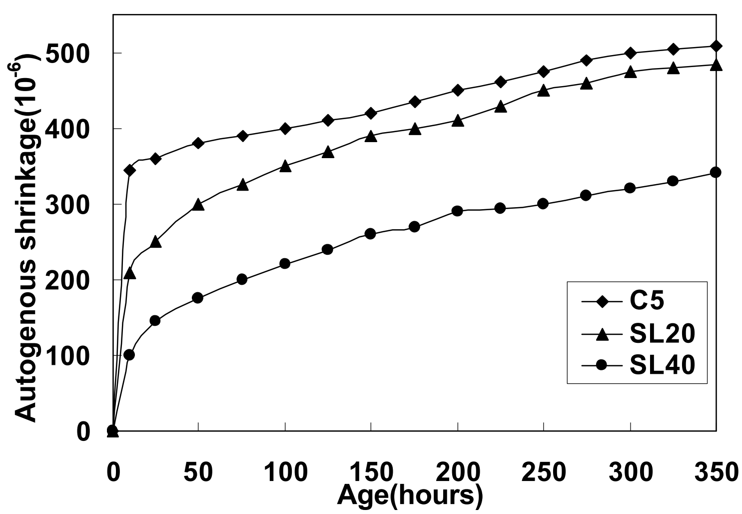

Fig. 4 Effect of GGBS content on autogenous shrinkage of concrete with w/b of 0.25

Fig.4 demonstrates that concretes containing GGBS behaved in a similar manner as concretes containing fly ash, although GGBS concretes showed slightly higher autogenous shrinkage than FA concretes under the same replacing percentage of cementitious materials.

The GGBS plays an important role in the autogenous shrinkage behavior of concrete not only due to its high activity but also due to the possibly refined pore structure because its high fineness that enhance self-desiccation process.

3.4 Effect of silica fume partially substituting Portland cement on autogenous shrinkage of concrete

Fig.5 shows autogenous shrinkage of concrete containing silica fume of 0, 10 and 20% by weight of cementitious material. SF10 concrete shows higher autogenous shrinkage than the C concrete, while SF20 concrete shows a slightly low amount of autogenous shrinkage compared with the C concrete.

The use of silica fume will lead to reduction in porosity and pore size of the interface transition zone and produces a dense microstructure. The finer porosity causes the water meniscus in capillary to have a greater radius of curvature. These menisci cause a large compressive stress on the pore walls, thus having a greater autogenous shrinkage as the paste is pulled inwards[10]. The pozzolanic reaction of silica fume with the calcium hydroxide liberated during the hydration of Portland cement helps consumption of free water and formation of bonds between the densely packed particles in the interface transition zone, which leads to further increase the degree of self-desiccation, and this is sometimes attributed, at least partly, to autogenous shrinkage.

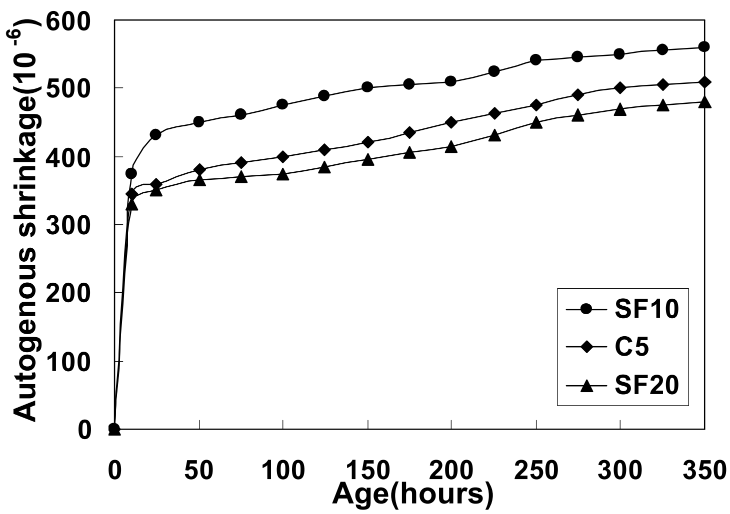

Fig. 5 Effect of silica fume content on autogenous shrinkage of concrete with w/b of 0.25

4. Predication Model for Autogenous Shrinkage

A prediction equation for estimating shrinkage strain of concrete has been proposed by Japan Society of Civil Engineers (JSCE)[11]. The equation is expressed as the product of the ultimate autogenous shrinkage value, $\varepsilon_\infty(w/cm)$, and coefficients of $\beta(t)$ and γ, which describe the development rate of autogenous shrinkage with time and the effect of cement and mineral admixture type, respectively.

Based above testing result, an experiential model was developed to simulate the autogenous shrinkage strain of concrete prepared with complex binders. It is similar to the model proposed by JSCE.

For $t \le t_0$ $$\varepsilon_{as}(t) = 0 \quad (1)$$

For $t > t_0$ $$\varepsilon_{as}(t) = \gamma \varepsilon_M (w/cm) \beta(t) \quad (2)$$

$$\varepsilon_M(w/cm) = 5936 \exp(-9.45 w/cm) \quad (3)$$

$$\gamma = \left(1 - 2.8 x_{FA}^2\right) \quad \text{(for FA concrete)}$$

$$= \left(1 - 2.5 x_{SL}^2\right) \quad \text{(for GGBS concrete)}$$

$$= \left(1 + 1.3 x_{SF} - 3 x_{SF}^2\right) \quad \text{(for SF concrete)}$$

$0.25 \le w/cm < 0.53$, $x_{FA,}$ x_{SL} and x_{SF} are replacement ratio of cement by fly ash, GGBS and silica fume, respectively.

$$\beta(t) = a \exp\left[1 - \left(\frac{350 - t_0}{t - t_0}\right)^b\right] \quad (4)$$

Table 3 Coefficient, γ, in Eq.2 and constants, a and b, in Eq.4

NO.	C1	C2	C3	C4	C5	FA20	FA30	FA40	FA60	SL20	SL40	SF10	SF20
w/cm	0.53	0.40	0.35	0.30					0.25				
γ	1	1	1	1	1	0.888	0.748	0.552	-0.008	0.9	0.6	1.1	1.01
a	0.81	0.73	1.13	0.89	0.91	0.96	0.89	1.04	8.06	0.96	1.02	0.91	0.85
b	1.62	0.22	0.13	0.14	0.13	0.13	0.12	0.28	-0.33	0.19	0.24	0.10	0.11
R	0.91	0.98	0.97	0.99	0.98	0.997	0.996	0.985	0.904	0.995	0.997	0.998	0.984

Where ε_{as} is the autogenous shrinkage strain of concrete at age of t (hours) in microstrain; $\varepsilon_M(w/cm)$ the autogenous shrinkage strain at 350 hours, which was obtained by regression with autogenous shrinkage at 350 hours versus w/cm; $\beta(t)$ the coefficient to describe the development rate of autogenous shrinkage strain with time; γ the coefficient to express the effects of types of cement and mineral admixture(in the case of ordinary Portland cement, γ=1); t_0 the initial setting time in hours; a,b the constants that depend on the cement and admixture type; t the age of concrete in hours.

Compared with the JSCE model, $\varepsilon_\infty(w/cm)$ was substituted by $\varepsilon_M(w/cm)$ at age of 350 hours because it can be more easily obtained. Moreover, corresponding $\beta(t)$ function was modified as shown in Eq.4.

By applying the test data to the autogenous shrinkage model, coefficient, γ, in Eq.2 and constants, a and b, in Eq.4 were determined, as given in Table 3. Table 3 shows that γ decrease with the increasing of fly ash and GGBS content, i.e. the presence of fly ash and GGBS reduces autogenous shrinkage, while γ increases for addition of silica fume.

For comparison, the autogenous shrinkages of concretes containing (and without) GGBS with w/b of 0.25 gotten from numerical model and measurement are given in Fig. 6. The correlation coefficients R between numerical computation and experimental results for all samples are higher than 0.98, which means that the model could predict famously autogenous shrinkage strain. However, the effects of temperature on the rate and ultimate value of autogenous shrinkage should be investigated more.

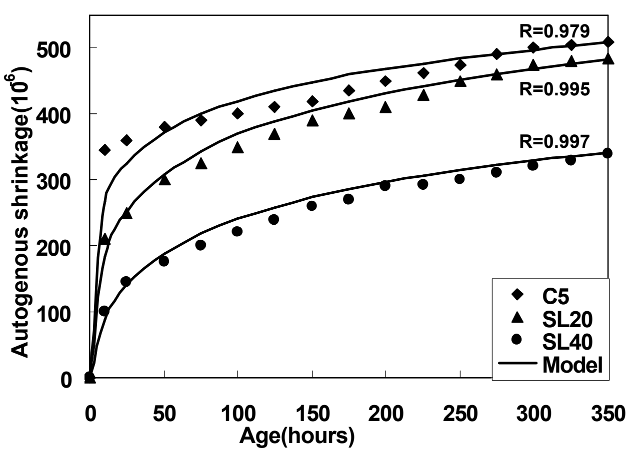

Fig. 6 autogenous shrinkage curves of concretes containing GGBS with w/b of 0.25 gotten by numerical model and measurement results

5. Conclusion

(a) The autogenous shrinkage of concrete increases with decrease of w/b ratio, and with the presence of silica fume. Incorporating fly ash and GGBS considerably reduced autogenous shrinkage of HPC; the higher admixtures content, the lower autogenous shrinkage. It is hypothesized that the intrinsic characteristics of fly ash and GGBS, such as their spherical particle shape and delayed hydration, contribute to reduction of autogenous shrinkage of HPC.

(b) The autogenous shrinkage of the concrete with low w/cm developed rapidly at early ages. For most of the concretes studied, 70% or more of the autogenous shrinkage up to 14 days occurred in the first 2 days after concrete casting. There is an obvious transiti on point on the volume changing curve of concrete prepared with pure Portland cement at about the end of the first day.

(c) A model for predicting autogenous shrinkage including the effect of mineral admixture was proposed.

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