Drying Shrinkage Characteristics of Mortar Incorporating Different Mineral Admixture

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Abstract: This paper presents an experimental study of the effects of fly ash and ground granulated blast furnace slag (GGBS) on drying shrinkage of mortar. Two equations that can reasonably predict the drying shrinkage were also proposed. The test results reveal that mortar samples incorporating fly ash or GGBS exhibit greater lower drying shrinkage compared to the plain sample. The drying shrinkage decreases significantly with the increase in the fly ash content. While for GGBS, there is an optimal content of GGBS to restrain drying shrinkage. The prediction equations for the shrinkage strain of fly ash and GGBS mortar were proposed according to the dependent variable, which verified good accuracy compared to the test results.

1 INTRODUCTION

Drying shrinkage, one of the causes of cracks in concrete structures, can be defined as the volumetric change due to the drying of concrete (Zhang, et al., 2015). If not appropriately considered in the design state, the cracks can adversely affect the structural performance when environmental conditions are quite severe (e.g., high temperature, low humidity, high wind velocity) (Zhang, et al., 2012). Therefore, it is vital to study the shrinkage and shrinkage compensation of cement mortar or concrete.

Many methods(Han, et al., 2016; Sonebi, et al., 2015 have been proposed to restrain drying shrinkage such as using fibers, expansion admixture, mineral admixture, shrinkage reducing admixture and so on. Mineral admixtures are the by-product of some industries, which is specified as promoting green procurement for the global environment. Therefore, using mineral admixture such as fly ash and GGBS to replace part of the cement is the most economical and environmentally friendly method. Research results showed that the concrete with mineral admixture addition performed better in reducing drying shrinkage and improving workability compared to the plain concrete. Hu et al. found that the most obvious advantage in adding fly ash was not only a considerable reduction in shrinkage cracking width, but also a significant delay in first visible cracking. The shrinkage of mortar containing 25% fly ash decreased 12.6% and the initial cracking time was decreased by 28% compared with the control mortar.

The experimental program in this study was designed to assess the main drying shrinkage behavior involving the addition of mineral admixture. The objectives of this study are to (1) clarify and comparison the influences of GGBS powder and fly ash on the drying shrinkage evolution of cement mortar, (4) propose equations according to the dependent variable that can reasonably predict the drying shrinkage behavior.

2 EXPERIMENTAL PROGRAMS

2.1 Materials

Jiangnan Onoda Cement Plant provided Portland cement of Grade-52.5with a Bertrand specific surface area of 365m2/kg and a density of 3.13g/cm3. The natural river sand was used as fine aggregates. First grade fly ash, of fineness modulus5.2%, with a specific surface of 457 m2/kg and, density 2.22g/cm3produced by Huaneng

Thermal Power Plant production of primary fly ash was used in this study. And the GGBS of ZhongShan brand S95, of specific surface 425m2/kg and of density 2.84g/cm3 obtained was used in the experiment.

2.2 Mixing and Curing

The cement, river sand, fly ash or GGBS were initially mixed dry in a mixer for about 2 minutes until they were homogenous throughout. Then, the entire amount of mixing water was added and the mixing process lasted for another 3minutes, leading to a total mixing period of 5 minutes. Finally, the freshly mixed materials were cast in the molds and vibrated by a mechanical vibrating table for about 1min. After that, the samples produced were cured in air at 20 ± 3°Cin molds covered by a polyethylene film to prevent moisture loss. After 24 h, the samples were removed from the molds and transferred to a standard condition with T = 20 ± 3°Cand RH = 50 ± 4% until the testing age.

In the current study, equivalent substitution method was used to design mixing proportions. For all mixtures, the mixing proportions of samples are given in Table1.

Table 1: The mix proportions of mortars with mineral admixtures.

	Cement (kg/m³)	Fly ash (kg/m³)	GGBS (kg/m³)	Sand (kg/m³)	Water (kg/m³)
M0	450	-	-	1350	225
F1	360	90	-	1350	225
F2	315	135	-	1350	225
F3	270	180	-	1350	225
F4	180	270	-	1350	225
S1	360	-	90	1350	225
S2	315	-	135	1350	225
S3	270	-	180	1350	225
S4	180	-	270	1350	225

2.3 Testing Methods

The drying shrinkage is calculated from following equations respectively:

$$\varepsilon i = \frac{L0-Li}{250} \times 100\% \qquad (1)$$

$$L = \frac{G1-G2}{G2} \times 100\% \qquad (2)$$

where Si, εi and L are the mass loss rate, drying shrinkage and loss on ignition of the mortar sample respectively, W0 and L0 are the initial weight and initial length and of sample respectively, Wi and Li are the weight and length of sample after water loss at different days respectively, G1 is the weight of sample before combustion and G2 is the weight of sample after combustion.

3 RESULTS AND DISCUSSION

3.1 The Influence of GGBS on Drying Shrinkage of Mortars

The drying shrinkage of cement mortars that increase with the age is presented in Fig.2. It can been observed that when the replacement amount of fly ash is 90kg/m3, 135kg/m3 and 180kg/m3, the drying shrinkage of mortar is 0.0639%, 0.0588% and 0.0539%,respectively, compared with the plain sample 0.0708% at 28 days. The obtained results show that the drying shrinkage of mortar decreases evidently with the increasing content of fly ash. This is mainly due to the content of cement reduces and content of fly ash increases in mortar incorporating fly ash. The hydration rate of fly ash is slower, so the hydration rate of mortar incorporating fly ash decreases. Moreover, the unreacted fly ash particles play a role to keep a stable skeleton and restrain deformation, which decreases the drying shrinkage of mortar significantly.

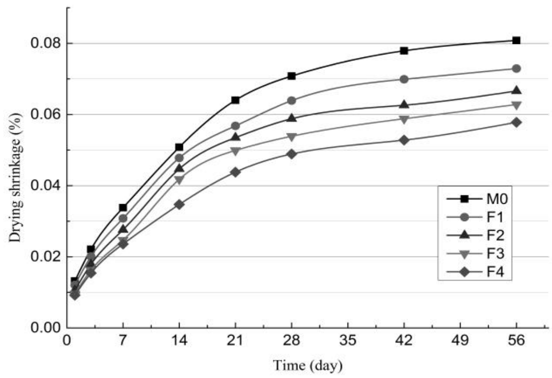

Fig. (a)

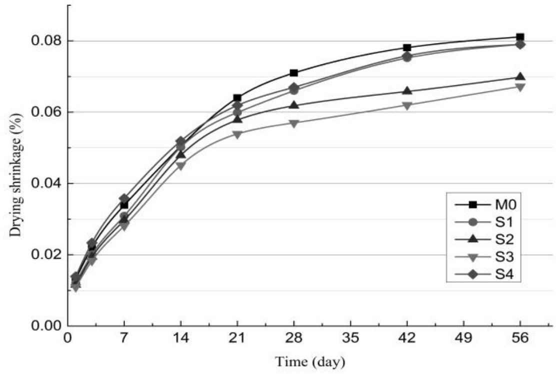

Fig. (b)

Fig.1: The effect of mineral admixture on the drying shrinkage of mortars: (a) fly ash and (b) GGBS.

Similarly, Fig.1 (b) shows that the drying shrinkage of mortar decreases with the increase of the replacement amount of GGBS within a certain range. When the replacement amount of GGBS is 90kg/m3. 135kg/m3 and 180 kg/m3, the drying shrinkage of mortar is 0.0660%, 0.0618% and 0.0570%, respectively, compared with the plain sample with a drying shrinkage of 0.0710% at 28 days. However, the drying shrinkage of mortar is 0.0670% at 28 days when the replacement amount of GGBS is 270kg/m3, which is slightly higher than that of the replacement amount of 135 kg/m3 and 180 kg/m3. The results reveal that there is an optimal content of GGBS to restrain drying shrinkage. It can be explained that the GGBS has potential activity and using the GGBS to replace cement will decrease the content of cement thus the total hydration rate of products of cementations materials will change. Furthermore, the part of the unreacted GGBS particles plays a role of micro-aggregate which restrains the drying shrinkage. However, when the content of GGBS exceeds a certain amount, the ability of autogenous shrinkage of mortar exceed the ability to restrain drying shrinkage of GGBS causing the drying shrinkage of mortar to increase, but is still lower than that of mortar without mineral admixture. This phenomenon has been analyzed by some previous research, which indicated that autogenous shrinkage of mortar incorporating GGBS increased with the increase content of GGBS. Tazawa et al. reported that the autogenous shrink age of mortar relatively rapid increased with the amount increasing of GGBS when the replacement content of GGBS between of 50 ~ 70%.

3.2 Shrinkage Model

Quantification of concrete shrinkage allows the designer to design concrete that meet the construction requirements based on the shrinkage model. So it is necessary to find the most suitable shrinkage model. There have been some American and European empirical models that predict the shrinkage strain of Portland cement concrete. These models were developed and calibrated based on some experimental measurements involving different types of concrete mixes. The objective of these models was to predict the long-term shrinkage strain based on few short-term measurements. There are two well-known models, ACI 209 and CEB-FIB 1990 that were considered in this study to validate and/or adapt their use for compared cement mortar. Fernandez-Gomez and Lands berger confirmed that these methods were applicable.

3.2.1 56 Days Shrinkage Measurements

Shrinkage of the four mortar samples shown in Table 3 were monitored over a 56 days period and the results are shown in Fig.1. In those figure, the x-axis represents the age of the samples at which the shrinkage measurement are taken, while the y-axis shows the measured shrinkage strain for the different samples. Fig.1 (a) shows that the shrinkage strains of fly ash mortar for the four samples were in the same order of magnitude and varied between 570 and 730μm/m for an age of 56 days. The figure shows also that shrinkage strain increases rapidly during 56 days. Fig.1 (b) indicates that the GGBS mortar has similar tendency.

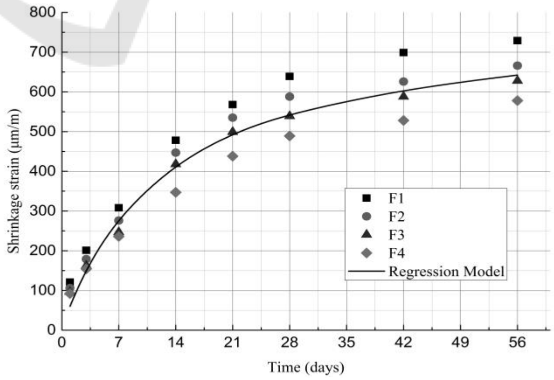

Fig. (a)

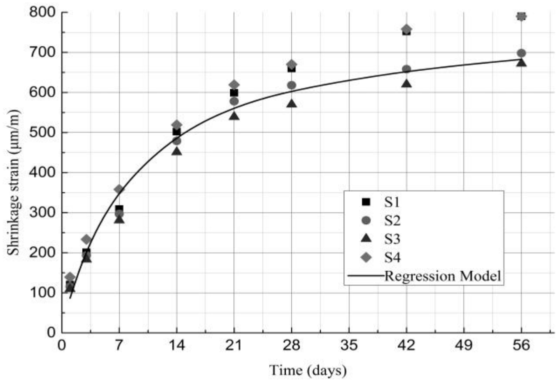

Fig. (b)

Fig.2: Average measured shrinkage strain over a 56 days period: (a) fly ash and (b) GGBS.

Since the four mixes presented roughly the same trend for their shrinkage strain evolution with respect to time, two regression models were developed to fit all measured date. For mortar incorporating fly ash and GGBS, the models are shown by solid curve in Fig.2 (a) and (b) and are represented by Equation(3) and Equation(4).

$$\varepsilon\,(t) = \frac{t}{12+t}\,\varepsilon_{max} \tag{3}$$

$$\varepsilon\,(t) = \frac{t}{8+t}\,\varepsilon_{max} \tag{4}$$

Where t is the mortar concrete age in days, and εmax represents the long-term shrinkage strain, which is found to be equal to 780μm/m. For fly ash mortar, the model had a coefficient of determination R2 of 0.997 and a standard error of 20μm/m. For GGBS mortar, with a coefficient of determination R2 of 0.990 and a standard error of 34μm/m was obtained. These mean that Equation(3) and Equation (4) describe well the shrinkage behaviour of mortar incorporating fly ash or GGBS.

3.2.2 ACI 209 Shrinkage Model

The American Concrete Institute proposed the ACI 209 shrinkage model in 1992. The shrinkage strain as a function of time, εsh (t), is calculated as follows:

$$\varepsilon_{sh}(t) = \frac{t}{32+t}\,\varepsilon_{sh\,(u)} \tag{5}$$

Where εsh(u) is the ultimate shrinkage strain, which is equal to 780μm/m for ordinary Portland cement concrete. The Portland cement concrete ACI 209 model did not fit well with mortar incorporating fly ash or GGBS experimental shrinkage date. However, when two correction factor of 1.54 for fly ash mortar and 1.75 for GGBS mortar were applied to the model, the corrected ACI 209 model fit well the measured experimental data as shown in Fig.3 (a) and (b). Therefore, for mortar incorporating fly ash or GGBS, the adapted ACI 209 model could be represented by Equation (6) and Equation (7). The calculated coefficient of determination, R2 ,for this model of fly ash mortar was 0.986 while the calculated standard error was 67μm/m , for GGBS mortar, the model had a coefficient of determination R2 of 0.986 and a standard error of 79μm/m.

$$\varepsilon_{sh}(t) = 1.54\,\frac{t}{35+t}\,\varepsilon_{sh\,(u)} \tag{6}$$

$$\varepsilon_{sh}(t) = 1.75\,\frac{t}{32+t}\,\varepsilon_{sh\,(u)} \tag{7}$$

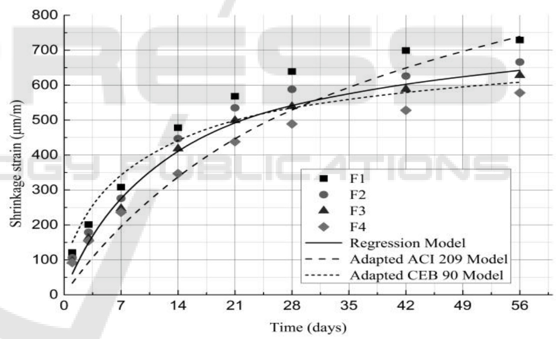

Fig. (a)

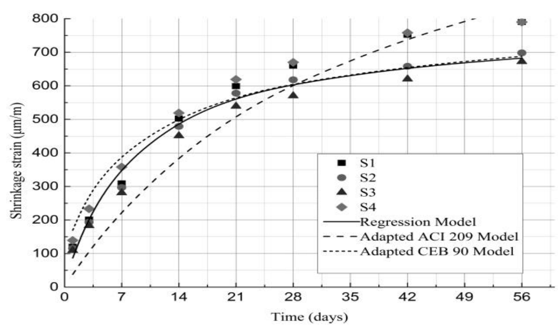

Fig. (b)

Fig.3: Experimental shrinkage data with developed prediction models: (a) fly ash and (b) GGBS.

3.2.3 CEB 90 Shrinkage Model

For CEB-FIP model, the shrinkage strain as a function of time is given by

$$\varepsilon(t) = \varepsilon_{cs0}\beta_s(t) \tag{8}$$

Where t is the concrete age in days, εcs0 is the ultimate shrinkage strain, and βs (t) is given by Equation (9).

$$\beta_s(t) = \left[\frac{t}{t+0.035\, h_0{}^2}\right]^{0.5} \tag{9}$$

Where h0 is the effective thickness of the specimen in mm. Two correction factor of 0.92 for fly ash mortar and 1.04 for GGBS mortar were applied to the model, the adapted CEB-FIP model could be represented by Equation(10) and Equation(11). The calculated coefficient of determination, R2 , for this model of fly ash mortar was 0.992 and the calculated standard error was 49μm/m, for GGBS mortar, the model had a coefficient of determination R2 of 0.993 and a standard error of 51μm/m.

$$\varepsilon(t) = 0.92\varepsilon_{cs0}\left[\frac{t}{t+0.035\, h_0{}^2}\right]^{0.5} \tag{10}$$

$$\varepsilon(t) = 1.04\varepsilon_{cs0}\left[\frac{t}{t+0.035\, h_0{}^2}\right]^{0.5} \tag{11}$$

3.2.4 Interpretation of Results

The figures from Fig.3 (a) and (b) show that the measured experimental date and the three models developed to fit the date. It is noted that the two regression models predict better the average measured shrinkage strain over time than the ordinary Portland cement concrete adapted models. This observation is proved by the calculated standard errors of three models. For fly ash or GGBS mortar, the regression models had the lowest standard error of 20μm/m and 34μm/m, respectively.

4 CONCLUSIONS

The mortar samples incorporating fly ash or GGBS exhibits greater lower drying shrinkage compared to that of the mortar samples without mineral admixture.

The result shows that the drying shrinkage of mortar decreases obviously with the increasing content of fly ash. While there is an optimal content of GGBS to restrain drying shrinkage, a replacement content of 180kg/m3for GGBS, the sample presents the lowest drying shrinkage. The drying shrinkage became greater with the increase in water evaporation. A greater mass loss resulted in a greater drying shrinkage.

Shrinkage strain of mortar incorporating fly ash or GGBS could be predicted using the well-known ACI 209 and CEB 90 shrinkage models after applying minor correction factors. Two rational equations (Equation (3) and Equation (4)) can predict the shrinkage strain of mortar incorporating fly ash or GGBS. And two regression models predict better than the ACI 209 and CEB 90 shrinkage models.

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