Compressive Strength and Drying Shrinkage of Alkali-activated Fly Ash/Slag Mortars

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***Abstract*— This study investigates the compressive strength and drying shrinkage of alkali-activated fly ash/slag mortars (AFSM). The liquid sodium silicate with modulus ratios (mass ratio of SiO_2 to Na_2O) of 2.5 were used as alkaline activators to alkali-activate fly ash and slag with various ratios of 50/50, 60/40, 70/30, 80/20 for fly ash to slag and liquid-to-binder ratios of 0.5 and 0.6. Test results showed that the compressive strengths decreased with an increase of FA and liquid-to-binder ratio for all AFSM. At the age 28 days, M5A (AFSM with fly ash/slag ratios of 50/50) has the highest compressive strength of 76.2 MPa. The drying shrinkage rate decreased with an increase of FA. At the age of 28 days, the drying shrinkage rate of M5D (AFSM with fly ash/slag ratios of 80/20) is 43.33 × 10^{-4}, which has the lowest drying shrinkage rate for all AFSM. Based on the test result, both the fly ash/slag ratio and the liquid-to-binder ratio have a significant influence on the compressive strength and drying shrinkage rate of AFSM.**

***Index Terms*—compressive strength, drying shrinkage, alkali-activated fly ash/slag, mortar**

I. Introduction

Over the last 2 decades, new binding materials instead of cement have been conducted by many studies [1-6]. Especially, alkali-activated slag (AAS) and fly ash (FA), metakaolin has been studied by many researchers [6-10]. Alkaline activation of slag or fly ash produced two types of cementitious materials, one is the case of the alkali-activated slag (Si and Ca) and the other is the alkali-activated class F fly ash (Si and Al)[11-14]. Fly ash and slag are two types of industrial by-products. Both are calcium aluminosilicate glasses but their reaction products are quite different. Its main reaction product of alkali-activated cements for slag is C-S-H while for class F fly ash it is the amorphous hydrated alkali-aluminosilicate[15-17].

Alkali-activated binders were reported by their superior mechanical properties and durability performance, however their drying shrinkage is still an important issue discussed by many researchers. Chi et al.[18]found that AAS mortars had higher compressive strength than Portland cement mortars and higher drying shrinkage was observed in AAS mortars than that observed comparable Portland cement mortars. Wang and Ma[19] investigated the drying shrinkage of alkali-activated fly ash/slag (AAFS) blended system and concluded that AAFS with 30 and 50% fly ash content by weight showed a lower drying shrinkage than AAS. Deb et al.[20] reported that shrinkage decreased with the increase of slag content and decrease of sodium silicate to sodium hydroxide (SS/SH) ratio in geopolymer concrete cured at room temperature. In addition, the shrinkage of geopolymer concrete was found to be comparable to that of OPC concrete of similar compressive strength at the age of 180 days. Despite the previous studies for AAFS binders, however the chemical composition of alkali activation is still the subject of much discussion in the scientific literature and depends on the physical-chemical nature of the raw materials, the nature and quantity of the activators and the curing condition. In this study, the compressive strength and drying shrinkage of AAFS mortars were investigated with various ratios of 50/50, 60/40, 70/30, 80/20 for fly ash to slag and liquid-to-binder ratios of 0.5 and 0.6.

II. Materials

The specimens were produced by alkali silicate activation of typical class F fly ash (FA) from Xingda Power Plant and ground granulated blast furnace slag (GGBFS) from CHC Resources Corporation, in Kaohsiung, Taiwan. The physical properties and chemical compositions of FA and GGBFS were as shown in Tables I and II. River sand was used as a fine aggregate in the production of mortars. The fineness modulus, bulk density and absorption of fine aggregate were 2.97, 2630 kg/m^3 and 2.51%, respectively. The most used alkaline activators are the mixture of sodium hydroxide (NaOH:99.1%, Na_2CO_3:0.5%) with sodium silicate (Na_2O: 50.41%, SiO_2:46.12%). The alkaline activation of the GGBFS and FA was performed by NaOH pellets with a density of 2130 kg/m^3 and sodium silicate solution ($Na_2O.\gamma SiO_2.nH_2O$) composed of 29.2% SiO_2, 14.8% Na_2O and 56.0% H_2O by mass. In addition,

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sodium hexametaphosphate (SHMP) was used as the retarder.

TABLE I. PHYSICAL PROPERTIES OF FA AND GGBFS

Physical properties	FA	GGBFS
Specific gravity	2.26	2.90
Specific surface area (m^2/g)	0.297	0.585

TABLE II. CHEMICAL COMPOSITIONS OF FA AND GGBFS.

Chemical compositions (%)	FA	GGBFS
Calcium oxide, CaO	4.51	39.96
Silicon dioxide, SiO_2	57.18	34.24
Aluminum oxide, Al_2O_3	20.34	14.19
Ferric oxide, Fe_2O_3	5.58	0.20
Sulfur trioxide, SO_3	0.25	0.18
Sodium oxide, Na_2O	0.33	0.15
Potassium oxide, K_2O	0.8	0.32
Magnesium oxide, MgO	1.52	7.88
Loss on ignition, L.O.I.	2.76	0.02
Others	8.68	1.41

A. Mixes Design and Specimens Preparation

Alkali-activated fly ash/slag mortars (AFSM) with 837 kg of binder per cubic meter in accordance with ASTM C 192 was designed. The liquid/binder ratios of 0.5 and 0.6 were selected. The liquid sodium silicate with modulus ratios (mass ratio of SiO_2 to Na_2O) of 2.5 were used as alkaline activators to alkali-activate various ratios of fly ash to slag. The fly ash/slag ratios were 50/50, 60/40, 70/30, 80/20 with symbols A, B, C, and D, respectively. The alkali solution of NaOH and Na_2SiO_3 was done 24 hours prior mixing to the dry mix. Meanwhile, FA, GGBFS and fine aggregate were mixed in dry state for 2 minutes. Then the calculated quantity of alkali liquid was added and mixed totally. Alkali-activated fly ash/slag mortars were produced and kept in steel molds for 24 hours, and then they were demolded and moved into a curing room at the temperature of 25℃ and relative humidity of 80% RH until testing. Cubic specimens with 50×50×50 mm^3 dimensions were cast for compressive strength test and prismatic specimens with 285×25×25 mm^3 dimensions were prepared for drying shrinkage test. The mixes design was listed in Table III. The specimens were tested in triplicate sets until the time of testing.

TABLE III. MIX PROPORTIONS OF AFSM(KG/M^3)

Mix No.	Water	FA	GBFS	Fine Agg.	Na_2SiO_3	NaOH
M5A	325	419	419	751	51.5	20.6
M5B	325	503	335	739	51.5	20.6
M5C	325	586	251	708	51.5	20.6
M5D	325	670	168	686	51.5	20.6
M6A	390	419	419	559	61.8	24..7
M6B	390	503	335	537	61.8	24.7

B. Methods

Compressive strength test. The compressive strength test of the specimens were conducted according to ASTM C109. An average of three specimens of each mix were tested under the compressive testing machine to determine the compressive strength at the ages of 7, 14, and 28 days.

Drying shrinkage test. The drying shrinkage test was done in accordance with ASTM C596. The prismatic specimens were prepared and then demolded after 24 hours. Specimens were placed in the humidity cabinet in the 80% RH at the temperature of 25℃. After 3 days, the initial length (L_i) of the shrinkage specimens was measured before placing them in the humidity cabinet. The length (L_x) of the shrinkage specimens was measured at the age of 7, 14, and 28 days, respectively. The length change was then calculated by the following formula:
Drying Shrinkage (mm/mm):

$$DS(\%) = (L_i - L_x)/250 \times 100\% \qquad (1)$$

III. RESULTS AND DISCUSSION

A. Compressive Strength

The compressive strength development of AFSM with liquid/binder ratio of 0.5 at the ages of 7, 14 and 28 curing days is shown in Fig. 1. The compressive strengths increased with an increasing age and decreased with an increase of FA for all AFSM. At the age 28 days, M5A (AFSM with fly ash/slag ratios of 50/50) has the highest compressive strength, with 76.2 MPa of the compressive strength, followed the M5B (AFSM with fly ash/slag ratios of 60/40), with 72.7 MPa of the compressive strength, and then the M5C (AFSM with fly ash/slag ratios of 70/30), with 54.0 MPa of the compressive strength, M5D (AFSM with fly ash/slag ratios of 80/20) is on the other end of the scale, with 34.4 MPa of the compressive strength. The compressive strength of alkali-activated fly ash/slag based-materials is attributed to the amorphous hydrated alkali-aluminosilicate produced for fly ash and the calcium silicate hydrate gel (C-S-H) formed for slag. The compressive strength of AFSM decreased with an increasing quantity of FA because of the lower activity of FA. It can be explained as following: (1) the particle size of fly ash is higher than that of slag; (2) its glassy surface layer of glass beads is dense and stable; (3) its silica-alumina glassy chain of high Si, Al, and low Ca is firm. Therefore, the compressive strength is reduced with an increasing ratio of fly ash/slag.

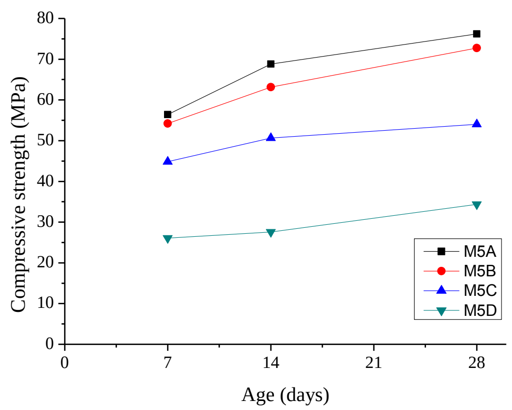

Figure 1. Compressive strength development of AFSM with liquid/binder ratio of 0.5

Fig. 2 shows the compressive strength development of AFSM with fly ash/slag of 50/50 and 60/40 at the liquid/binder ratios of 0.5 and 0.6, respectively. The compressive strengths decreased with an increase of liquid-to-binder ratio. At the age 28 days, M6A (AFSM with fly ash/slag ratios of 50/50) has the compressive strength of 63.6 MPa, which is higher than that of M6B (AFSM with fly ash/slag ratios of 60/40), with 56.1 MPa of the compressive strength. The trend of compressive strength development of AFSM is similar with that of ordinary Portland cement (OPC) concrete.

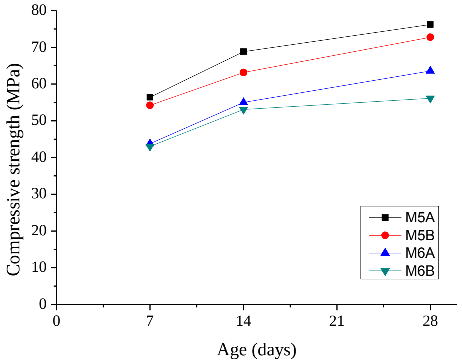

Figure 2. Compressive strength development of AFSM with fly ash/slag of 50/50 and 60/40 at the liquid/binder ratios of 0.5 and 0.6

B. *Drying Shrinkage*

Drying shrinkage of cement-based composites is an important index to evaluate the structural properties and durability of concrete. The drying shrinkage rate of ASFM with liquid/binder ratio of 0.5 at 7, 14 and 28 curing days is shown in Fig. 3. The drying shrinkage rate of all specimens increased with an increasing ages and decreased with an increase of FA for all AFSM. At the age of 28 days, the drying shrinkage rate of M5D (AFSM with fly ash/slag ratios of 80/20) is 43.33 × 10^{-4}, which has the lowest drying shrinkage rate for all AFSM. The greater the amount of fly ash the lower the drying shrinkage rate of AFSM. It indicates the fly ash/slag ratio has a significant influence on the drying shrinkage rate of AFSM and the addition of fly ash can reduce drying shrinkage rate. Chemical shrinkage is a reduction in volume resulting from the chemical reaction between the reagent and water. The main products of alkali-activated are hydrotalcite and C-S-H gel, which lead to an increase in the total amount of chemical shrinkage.

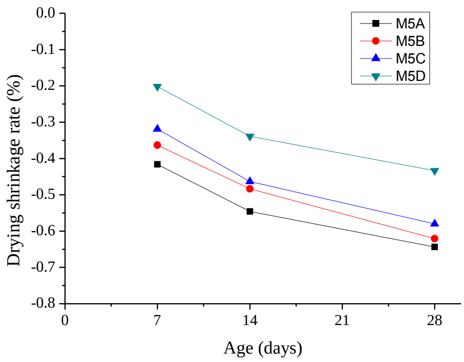

Figure 3. Drying shrinkage of ASFM with liquid/binder ratio of 0.5

Fig. 4 shows the drying shrinkage rate of AFSM with fly ash/slag of 50/50 and 60/40 at the liquid/binder ratios of 0.5 and 0.6, respectively. Slight difference was observed in drying shrinkage rate for AFSM with liquid/binder ratios of 0.5 and 0.6 at the same age. The drying shrinkage rate of AFSM with liquid/binder ratio of 0.5 reduces by approximately 10% as compared with that of AFSM with liquid/binder ratio of 0.6 at the age of 28 days. It indicates that the liquid/binder ratio has also an influence on the drying shrinkage rate of AFSM. The higher the liquid-to-binder ratio, the more the pore water. Thus, the drying shrinkage rate increased with the pore water evaporated for AFSM.

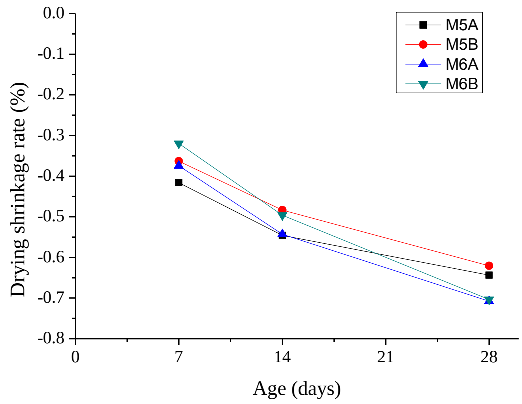

Figure 4. Drying shrinkage of ASFM with fly ash/slag of 50/50 and 60/40 at the liquid/binder ratios of 0.5 and 0.6

IV. CONCLUSIONS

This study investigates the compressive strength and drying shrinkage of alkali-activated fly ash/slag mortars. The main conclusions extracted from the present study are following:

- The compressive strengths increased with an increasing age and decreased with an increase of FA and liquid-to-binder ratio for all AFSM. At the age 28 days, M5A (AFSM with fly ash/slag ratios of 50/50) has the highest compressive strength of 76.2 MPa.
- The drying shrinkage rate of all specimens increased with an increasing ages and decreased with an increase of FA for all AFSM. At the age of 28 days, the drying shrinkage rate of M5D (AFSM with fly ash/slag ratios of 80/20) is 43.33 × 10-4, which has the lowest drying shrinkage rate for all AFSM.
- Both the fly ash/slag ratio and the liquid-to-binder ratio are significant factors influencing the compressive strength and drying shrinkage rate of AFSM.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Maochieh Chi, Weichung Yeih conducted the research and wrote the paper; Jiangjhy Chang and Kuochung Tsou did the test and analyzed the data. All authors had approved the final version.

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