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Technical Note

PROPERTIES OF ALKALI-ACTIVATED FLY ASH CONCRETE BLENDED WITH SLAG

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Abstract:*The current research aims to investigate alkali-activated fly ash (AAFA) concrete/mortar modified with granulated ground blast-furnace slag (slag). FA was partially replaced with slag at levels of 0, 5, 10 and 15%, by weight. The workability and mechanical properties of alkali-activated concretes were studied. Drying shrinkages of alkali-activated mortars were investigated. All results of alkali-activated FA/slag concretes/mortars were compared to control concretes/mortars based on plain AAFA. The results indicated that the workability decreased as the slag content increased. Mechanical strengths and drying shrinkages increased with increasing slag content.*

Keywords: *Alkali-activated FA, Alkali-activated FA/slag, Workability, Mechanical strengths, Drying shrinkage*

1. INTRODUCTION

Each year, the concrete industry produces approximately 12 billion tonnes of concrete and uses about 1.6 billion tonnes of Portland cement (PC) worldwide. Indeed, with the manufacture of one tonne of cement approximately 0.8 tonnes of CO_2 are launched into the atmosphere. The cement industry accounts for 5-8% of worldwide CO_2 emission [1]. In addition, cement industry consumes considerable amounts of virgin materials (limestone and sand) and energy (energy demand about 1700-1800 Mj/tonne clinker), producing each tonne of PC requires about 1.5 tonnes of raw material [1]. In light of these problems, the scientific community has undertaken to seek new processes, technologies and materials to provide the construction industry with alternative binders. One avenue that is expected to significantly reduce cement industry is the use of blended cement [2-8]. The second alternative is the use of alkali-activated FA [1], slag [9-11] and other alumina-silicate materials.

Different additives have been used to modify AAFA. Some authors blended AAFA with another material, as slag, aiming to produce new composite material with superior properties in comparison with pure AAFA system. In the following, a short summary of some investigations addressed the behavior of AAFA blended with slag in alkali activation system.

Puertas and Fernández-Jiménez [12] studied the mechanical, mineralogical and microstructural characterisation of cement pastes obtained by activation of FA/slag mixtures cured at different temperatures. The cement pastes were prepared in prismatic moulds of 1×1×6 cm. The FA/slag ratio was 50/50 wt%. NaOH 10 M was used as activator solution. Two curing temperatures were used 22 and 65 °C. The results indicated that at 7 days the mechanical strengths are similar in both curing conditions, the obtained compressive strength value was 30 MPa. At 28 days the mechanical values are higher in the pastes cured at 22 °C, the obtained compressive strength was 60 MPa. Puertas et al. [13] replaced FA with slag at levels of 0, 30, 50, 70 and 100%. They activated the composite pastes with NaOH at concentration levels of 2 M and 10 M. They concluded that as slag content in the pastes increased, compressive strength also increased. Higher strengths were obtained when 10 M of activator was used.

García et al. [14] studied the compressive strength of the alkali-activated FA/slag composites at ratios of 100/0, 75/25, 50/50, 25/75 and 0/100. Sodium silicate with modulus (SiO_2/Na_2O) of 0, 0.75, 1, 1.5 and 2 was used and the $\%Na_2O$ was added at 4, 6 and 8%, relative to the binder weight. The pastes were cured for 24 h at 75 °C and then 28 days at 20 °C. The results indicated that for 0/100 pastes, the highest strengths were for 4% Na_2O (80-85 MPa); the optimum modulus was 1.5. For 100/0 pastes, the higher % Na_2O, the better the strength, whereas the highest strength of 25 MPa was reached using modulus 1. For the composite of 25/75 the strengths were (56-60 MPa) at 4% Na_2O and the modulus 1 and 1.5. For the composite of 50/50 pastes, the strengths were (45-48 MPa) at 4% Na_2O and the best modulus was 1-1.5. For the composite of 25/75 pastes, the strength reached (30-35 MPa) at 4% Na_2O and modulus 1.5. Bakharev et al. [15] studied alkali-activated Australian slag mortar using different activators. In addition, they prepared mixture of alkali-activated slag/FA. The inclusion of FA was 30% and slag was 70%. They concluded that FA introduced in alkali-activated slag (AAS) at 30% reduced the compressive strength of the mortar. Wang et al. [16] reported that the addition of FA (below 10%) in AAS mortar often caused slight reduction in compressive strength under normal curing.

Although the literature has numerous articles on AAFA and alkali-activated FA/slag pastes [13, 14] and mortars [15, 16], up to now, there is no any publication studied the mechanical strengths of AAFA concrete blended with slag. The current study aims to investigate a number of composition and processing conditions on workability, compressive, splitting and flexural strengths of AAFA concretes when FA was partially replaced with slag at levels of 0, 5, 10 and 15%, by weight, activated with a combination of sodium silicate and sodium hydroxide. In addition, the drying shrinkage of alkali-activated mortars manufactured with FA and FA/slag was investigated. Moreover, this study aims to provide solutions for the extra four issues of: lower emission of pollutants into atmosphere by replacing PC system with another system, reduction in consumption of natural resources required in PC industry, reduction in the amount of fuel required in PC industry and eliminating the problems related with FA and slag disposals. However, this investigation will therefore add valuable knowledge to the alkali activation system.

2. EXPERIMENTAL

2. 1. Materials

The FA used in the current investigation was obtained from disposal waste resulting from the combustion of pulverised coal in the coal-fired furnaces. It complies with the requirements of BS3892: Part 1 (BSI 1992) and is classified as low calcium Class F fly ash in ASTM-C618. Specific gravity of the FA was 2.4 g/cm^3. Its Blaine specific surface area was 3500 cm^2/g. The slag was delivered from the disposal waste of Helwan steel factory (in Cairo-Egypt) in the form of water quenched fine grains. The slag was then finely ground in a laboratory ball mill to satisfy Blaine specific surface area of 3200 cm^2/g. The specific gravity of the slag was 2.8 g/cm^3. The slag classified as a category 80 slag according to ASTM C 989 hydraulic activity index. The chemical composition of the FA and slag were evaluated by X-ray fluorescence (XRF) and are given in Table 1. Liquid sodium silicate, which had a density of 1.38 g/cm^3 and a composition comprising of 8.2% Na_2O, 27% SiO_2 and 64% H_2O and NaOH in pellet-form with purity of 98% were used as alkali activators.

The employed sand was natural siliceous with a fineness modulus of 2.47. Its particle size distribution was within the range of medium grading zone according to the classification of the Egyptian Standard Specification ES 1109/ 2002.

Table 1. Chemical composition of cementitious materials

Oxide Composition	FA (%)	slag (%)
SiO_2	60	30.38
Al_2O_3	22.7	9.05
Fe_2O_3	4.6	3.82
CaO	4.5	45.88
MgO	1	5.39
Na_2O	0.7	0.52
K_2O	2	0.31
SO_3	0.5	1.78
L.O.I.	4	1.41

Table 2. Details of alkali-activated concrete mixtures

Mix	%FA	%GGBS	Stone/sand	C/aggregates	Solution/C
M1	100	0	1.33	0.285	0.5
M2	95	5	1.33	0.285	0.5
M3	90	10	1.33	0.285	0.5
M4	85	15	1.33	0.285	0.5

C Cementitious

The coarse aggregate was crushed limestone; 40% of its particles was in the size range of 10 – 14 mm, and the rest was finer than 10 mm size.

2. 2 Mixture Proportions

The activator was prepared by mixing 15% sodium silicate with 85% 12.2 M NaOH (SiO_2/Na_2O ratio = 0.16) and left until the temperature of the solution got down to the room temperature. The ratios of FA (or FA+slag): fine aggregate: coarse aggregate were taken as 1: 1.5: 2; and the alkaline solution/cementitious materials was adjusted at 0.5. The mixing proportions details are shown in Table 2. In the case of mortar production, the ratio of cementitious materials / sand and the dissolution alkaline / cementitious materials were controlled at 0.5 and 0.4, respectively.

2. 3. Casting, Curing and Testing

Cementitious materials and aggregate were mixed in a pan mixer for 5 minutes, then the liquid component of the material was added and mixed for extra 5 minutes. Just after mixing, the slump of fresh concrete was determined in accordance with ASTM C173. Then the mixture was cast into 15 × 15 × 15 cm moulds, cylinders of 15 cm diameter and 30 cm height moulds and prisms of 10 × 10 × 50 cm, in three layers. Each layer was vibrated for 15 seconds using vibrating table. Immediately after casting, the specimens were wrapped with thin vinyl sheet to avoid loss of water then cured at 80 ± 1 °C and 95 ± 5% RH for 48 h. The specimens were then demould and left at room temperature until testing. In similar way, the mortar was mixed. After mixing, the mortar was cast into 2.5 × 2.5 × 28.5 cm moulds in three layers. Each layer was vibrated in similar way. Immediately after casting, the mortar specimens were covered with plastic sheets then cured at 80 ± 1 °C and 95 ± 5% RH for 48 h. The specimens were then demould and left at 20 ± 1°C and 50 ± 5% RH.

The compressive strength of cube specimens was measured in triplicate after ages of 3, 7, 28 and 91 days. The testing machine employed for this test complies with British Standard (BS 1881: Part 115). The splitting tensile strength was determined using cylinder specimens according to ASTM C 496 at ages of 3, 7, 28 and 91 days. The flexural strength tests were carried out on the prisms of 10 × 10 × 50 cm at ages of 3, 7, 28 and 91 days using simple beam with center-point loading according to ASTM C293. Three specimens of each mixture were tested and the mean value was reported. Dry shrinkages were determined on mortar specimens in agreement with standard ASTM C596-09. The drying shrinkage measurements started at the third day from casting then repeated every 7 days. The drying shrinkage measurements continued up to 91 days.

3. RESULTS AND DISCUSSIONS

3. 1. Fresh Properties

Figure 1 shows that the alkali-activated concretes give good workability. The degree of workability decreased as the replacement of FA with slag increased. It's worth mentioning that Yang et al. [17] used sodium silicate powder to activate either FA or slag mortars. They used constant w/b ratio of 0.5 and sand to binder of 3. They reported that the AAS mortars had lower workability than AAFA mortars.

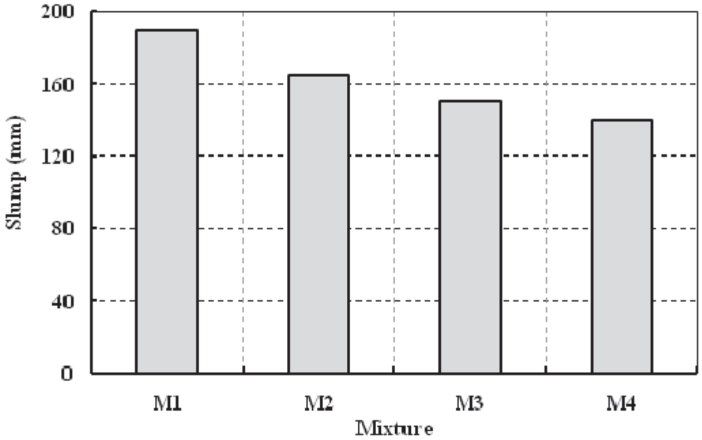

Fig. 1. Initial slump of different concrete mixtures

3. 2. Mechanical Strength Development

Figures 2-4 show the compressive strength, splitting tensile strength and flexural strength development at different ages of different concrete mixtures. The compressive, splitting and flexural strengths of concretes increased with increasing hydration time. The obtained results indicate that this type of concrete reaches good compressive strength at early ages. Only after three days, the compressive strength of 27 MPa was obtained, for AAFA. Replacing FA with slag led to increasing strength. Figure 2 illustrates that as the amount of slag increased in concrete matrix as the gain in strength obtained. However, after 3, 7, 28 and 91 days of hydration, the compressive strengths of M4 were 1.11, 1.16, 1.09 and 1.109 higher than those of M1, respectively. Figure 3 shows the splitting tensile strength of different mixtures. Apparently, similar findings of splitting strengths were found as compressive strengths. The splitting tensile strength of AAFA concretes blended with slag is still higher than those of plain AAFA concrete. Figure 4 illustrates the flexural strength results. However, it is known that there is a relationship between the flexural strength and compressive strength of concrete, such that the higher the compressive strength the higher the flexural strength of concrete. The flexural strengths of concretes were dependant on the amount of slag. As the amount of slag increased as the flexure strength increased.

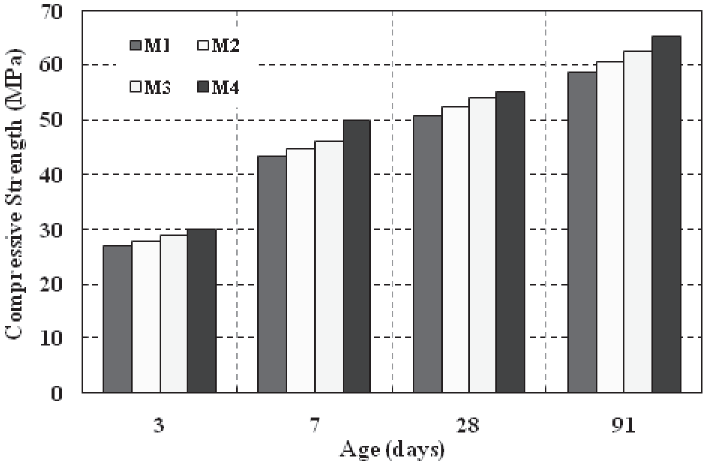

Fig. 2. Compressive strength developments of different concrete mixtures

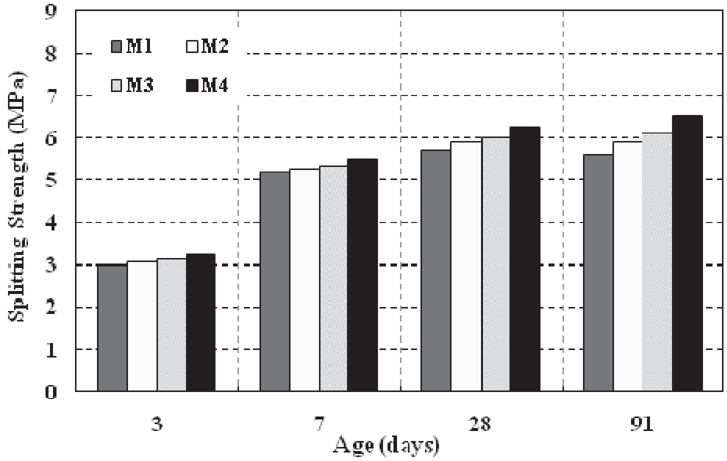

Fig. 3. Splitting tensile strength developments of different concrete mixtures

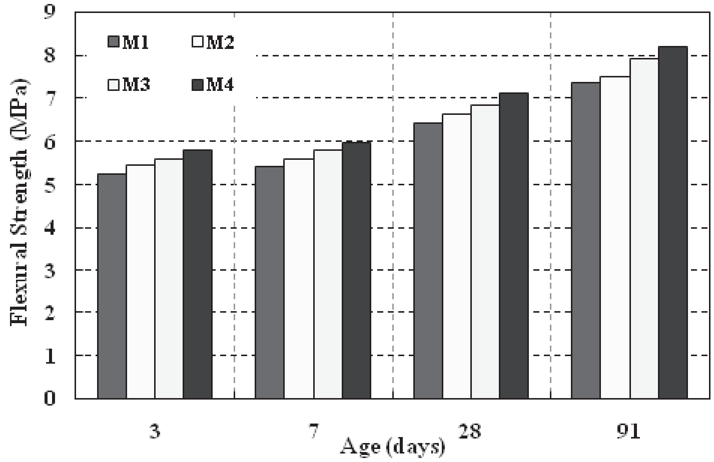

Fig. 4. Flexural strength developments of different concrete mixtures

Apparently, the compressive, splitting and flexural strengths increased as the percentage of FA replaced with slag increased. The increasing in mechanical strengths with increasing slag content may be related to many factors. The first factor, attributed to the difference in chemical composition of the slag and FA, significantly affects the process of alkali activation of the binders [18]. The second factor, as known,the reaction of slag is extremely higher than those of FA and reacts almost completely. On the contrary, the FA partially dissolved and participates in the reaction process [19]. The third factor, as the slag content increased in the FA concrete matrix, as a compacted and denser matrix was obtained. The fourth factor, as known, is that in alkali-activated binder materials, the pH value of solution plays an important role in the hydration process [20] determining the nature of CSH hydration product formation [21]. The value of pH should be higher than 11.5 to effectively activate the hydration [20] where this is impossible below pH 9.5 [20]. The formation of CSH is depending on the types of silicate in solution which is affected by pH. It has been reported that when the pH value was higher, the activator showed better hydration capacity activation [22], accelerated setting times and increased the mechanical strengths [20]. However, the measured pH value of the pure slag was 11.5 is higher than that of pure FA which was 8.5. Furthermore, the increasing in mechanical strengths due to increasing slag content may be

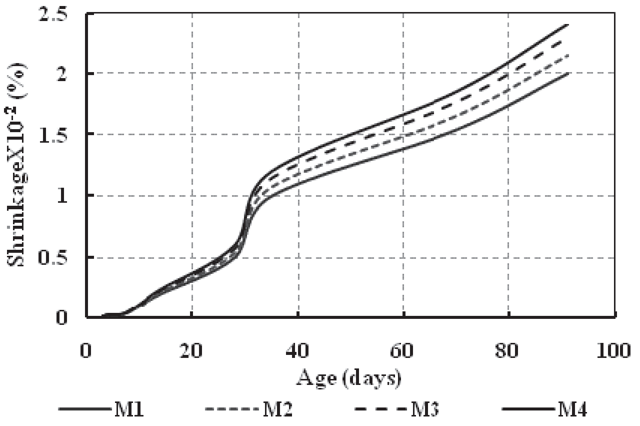

Fig. 5. Dry shrinkage of different mortar mixtures

related to the amount of crystalline material in FA is much higher and much of it usually occurs as spherical particles, while slag is typically in the form of broken particles. FA is relatively rich in Al_2O_3 while slag in CaO [23]. However, the mechanical strengths of M4 were approximately 10% higher than those of M1. The previous work by other authors reported similar findings and concluded that the slag systems with no addition of FA achieved the highest compressive strength [24]. The current results seemed to be similar to the previous results conducted by Li and Liu [25] where they reported that the addition of 4% slag to the FA based geopolymer (10% metakaolin and 90% FA) led to more amorphous products and accelerated the rate of reaction, refined the pore size and reduced pore volume.

3. 3. Drying Shrinkage

As known, shrinkage is the reduction in volume at constant temperature without external loading. It is an important material property that significantly affects the long-term performance of designed structures. It also influences structural properties and durability of the material. However, Fig 5 shows the drying shrinkage of different mortar mixtures. Apparently, the AAFA mortar specimens experienced a very slight shrinkage when they were dried. It can be noted, from Fig 5, that the drying shrinkage increases as the slag content increases in the mortar matrices. The current results give an idea of the great dimensional stability of AAFA mortar compared to alkali-activated FA/slag mortars. This is due to the spherical shape of FA particles that acted as the micro-aggregate and increased the volume stability. It's worth mentioning that Weiguo et al. [26] activated neat slag and slag blended with FA by waterglass with SiO_2/Na_2O ratio of 2.4 and sodium hydroxide used to adjust the SiO_2/Na_2O ratio to 1.0. They studied the drying shrinkage up to 60 days compared to PC shrinkage. They reported that the drying shrinkage of PC paste was the lowest, while neat AAS was the highest and FA lowered the drying shrinkage of pure AAS paste. Other authors [27-31] reported that the drying shrinkage of AAFA binders could be lowered than that of PC binders.

4. CONCLUSIONS

1. The main benefits of using AAFA concrete or AAFA concrete blended with slag are at least two fold: reduction in the environmental impacts resulting from cement production and reduction in stockpiling of common wastes.
2. Compared to PC, this kind of binder material may be economical because the source material is an industrial by-product.
3. Although the workability of fresh AAFA concrete decreases with incorporation of slag, the mechanical strengths significantly increase. The higher the slag content, the

higher the increase in mechanical strengths.

4. Drying shrinkage of alkali-activated mortars mainly depends on the source of materials, its increased as the percentage of slag increased in FA matrix.

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