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Effects of Multiple Supplementary Cementitious Materials on Workability and Strength of Lightweight Aggregate Concrete

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ABSTRACT

The use of supplementary cementitious materials (SCMs) in concrete has increased worldwide because of their economic and environmental benefits. Supplementary cementitious materials include silica fume (SF), blast furnace slag (BFS), fly ash (FA) and rice husk ash (RHA), which are generally derived from industrial byproducts and agro-wastes and can be mixed with blended cement to enhance concrete strength. The use of SCMs in concrete in conjunction with lightweight aggregate not only reduces the consumption of Portland cement, but also decreases the weight of structure, thus lessening the cost of construction. In the present experimental study, the effects of different SCMs (SF, BFS and FA) on mechanical strength properties and workability of lightweight aggregate concrete (LWAC) are tested with partial replacement of cement by SCMs in various proportions and combinations. From the test results and considering rheological and strength properties of concrete and economic benefits, the best combinations of SCMs obtained are the BFS–FA combination and the FA–SF–BFS combination.

KEYWORDS: Supplementary cementitious materials, Silica fume, Blast furnace slag, Fly ash, Lightweight aggregate concrete.

INTRODUCTION

Reducing the mass of the building or structure is of great importance, since earthquake forces which influence civil engineering buildings and structures are proportional to the mass of those buildings and structures. The use of lightweight concrete (LWC) in construction is one of the ways to reduce the dead weight or mass of a structure (Alduaij et al., 1999; Kilic et al., 2003; Ramadan and Balbissi, 2007).

Lightweight concrete (LWC) is usually characterized by low density, high porosity and relatively high strength in order to meet the requirements for buildings (Alduaij et al., 1999; Cabrillac et al., 2006; Mostafa, 2005). Buildings and structures constructed using LWC are environment friendly, economical, lightweight and cellular. LWC

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provides thermal and acoustic insulation as well as fire resistance (Narayanan and Ramamurthy, 2000). It has been found that LWC has better durability compared to normal concrete, such as better frost resistance, higher impermeability and fundamentally removing the risk of alkali-aggregate reaction (Bentz, 2009; Haque et al., 2004; Nilsen and Aïtcin, 1992; Shaikh, 2014; Yan et al., 2015). The most important part of LWC is the lightweight aggregate, because it makes concrete light in weight. In some cases, aggregate can regulate some concrete properties and influence workability of concrete (Boukli et al., 2009; Muhit et al., 2013b; Yaragal et al., 2016). Moreover, lightweight aggregate concrete (LWAC) exhibits many advantages, such as allowing low deformation for tensile strain, insulation for superior heat and better ratio of strength to weight. It also ensures lower thermal expansion coefficient (Balendran et al., 2002; Kayali and Haque, 1999; Mays and Barnes, 1991; Nilsen and Aïtcin, 1992; Rossignolo and Agnesini, 2002; Theodorakopoulos and Swamy, 1993). The use of lightweight aggregate in concrete can reduce the dead weight of a structure, resulting in decreased cross-section of columns, beams, plates and foundations (Theodorakopoulos and Swamy, 1993). Apart from that, for moderate to cold climates with outdoor temperature fluctuating frequently, it is an energy efficient choice (Qiao et al., 2008).

The partial replacement of cement in concrete industry by supplementary cementitious materials (SCMs) can be an essential key to sustainable global development (Demirboğa et al., 2001). Among SCMs, the most available materials are: silica fume (SF), fly ash (FA) and blast furnace slag (BFS). Silica fume (volatilized silica/micro-silica) is a byproduct in the production of silicon and ferrosilicon alloys, which are obtained by the reduction process of highly pure quartz with coal in electric furnaces (Mehta and Monteiro, 2014). It consists of very fine vitreous particles with a surface area ranging between 13,000 and 30,000 m^2/kg. Its particles are approximately 100 times smaller than the average cement particles (Elsayed, 2011; Mehta and Monteiro, 2014; Muhit et al., 2013a). This material is highly pozzolanic, but it increases considerably the water requirement in concrete if high range water reducers are not used (Muhit et al., 2013a; Muhit et al., 2014; Raihan and Muhit, 2014). Fly ash is found as a byproduct of thermal power stations during the combustion of powdered coal. When coal passes in the furnace through high temperature zone, the volatile matter and carbon are burned off and after agglomeration of mineral, some fine particles (fly ash) fly out with flue gas stream (Chen and Liu, 2008; Joisel and Amerongen, 1973; Malhotra and Ramezanianpour, 1994; Mehta and Monteiro, 2014). On the contrary, blast furnace slag is found as byproduct from still mill in the production of cast iron or pig iron (Chen and Liu, 2008). It is estimated that the world production of fly ash in the year 2000 was about 600 million tons, of which only 9% was utilized (Mehta and Monteiro, 2014).

The use of mineral additives in concrete, such as fly ash and/or silica fume, as well as calcined clay and natural pozzolan with metakaolin, has become widespread due to their pozzolanic reaction and environmental friendliness (Erdogan, 1997; Joisel and Amerongen, 1973; Malhotra and Ramezanianpour, 1994; Mehta and Monteiro, 2014). Along with being highly pozzolanic materials, fly ash and silica fume have significant effects to improve the packing of micro-pores of the mortar matrix and at the interfaces with the aggregate, which results in a denser concrete mix with finer pore structure (Erdogan, 1997; Mehta and Monteiro, 2014). Workability and water permeability of fresh concrete are affected by the addition of fly ash, unlike most other mineral admixtures (Hassan et al., 2000; Muhit et al., 2013a, Muhit et al., 2014). Generally, the water absorption (over 10%) for concrete with lightweight aggregate is considerably high, but the use of silica fume and a superplasticizer can solve this problem (Rossignolo and Agnesini, 2002).

For constant strength of concrete, if a decrease in density can be achieved, it is possible to reduce the self-weight of the structure, required foundation size and at the end also the construction costs. In recent years, concrete technologies have been rocketing, which have resulted in the production of high-performance concrete (HPC) (Mehta and Monteiro, 2014; Sharmila and Dhinakaran 2015; Zaidi et al., 2017). After 1985, some research studies on high-performance lightweight concrete have been reported, but lacking in SCM various proportions (Alsharie, 2016; Balendran et al., 2002; Chen and Liu, 2008; Kilic et al., 2003; Malhotra, 1987; Mortazavi and Majlessi, 2012; Qiao et al., 2008; Rossignolo and Agnesini, 2002; Shoaei et al., 2017; Slate et al., 1986; Theodorakopoulos and Swamy, 1993).

Comprehensive research had been carried out in the past on the use of fly ash, pulverized-fuel ash, blast furnace slag, rice husk ash, silica fume,… etc. as cement replacement materials (Al-Ani and Hughes, 1989; Berry and Malhotra, 1980; Bilodeau and Malhotra, 1998; Hooton, 2000; Mehta, 1977; Swamy, 1983; Swamy, 1986). Nevertheless, studies incorporating both lightweight aggregate and supplementary cementitious materials (SCMs) are very limited. From literature, it is evident that most of the researchers focused neither on different dosages nor on several combinations of multiple cementitious materials. In the current study, the effects of different SCMs (SF, BFS and FA) on mechanical strength properties and workability of lightweight aggregate concrete (LWAC) are tested by adding the SCMs in various proportions. Moreover, in this research, maximum numbers of possible combinations and dosages were tested to investigate the exact percentages of SCMs. Through this research, the inclusion of best mineral admixture percentages for LWAC has been reported.

Materials and Mix Proportions

Materials of Specimens

Portland Cement

In this study, normal Portland cement (ASTM Type-I) is used. The initial and final setting times of this cement are 64 minutes and 121 minutes, respectively. According to ISO 679:2009, the compressive strength of cement for 28 days is determined as 49.5 MPa. Physical and chemical properties of the cement are obtained from lab test results and presented in Table 1.

Table 1. Chemical composition and physical properties of NPC and mineral admixtures

	NPC	SF	BFS	FA
Chemical composition (%)				
calcium oxide (CaO)	62.25%	1.1%	41%	8.1%
silicon dioxide (SiO_2)	21%	91.29%	25.5%	55.1%
aluminum oxide (Al_2O_3)	5.9%	0.9%	7.5%	24.5%
sulfur trioxide (SO_3)	2.4%	-	3%	3%
ferric oxide (Fe_2O_3)	3.4%	0.45%	2%	6%
magnesium oxide (MgO)	1.5%	0.22%	4.15%	1.9%
sodium oxide (Na_2O)	0.2%	0.02%	-	0.4%
potassium oxide (K_2O)	0.45%	-	0.3%	0.2%
loss on ignition	1.1%	2.1%	0.5%	0.15%
Physical and mechanical properties				
specific gravity (g/cm^3)	3.05	2.0	2.25	2.3
specific surface (cm^2/g)	3907	18000	5350	4400

Abbreviations; NPC: Normal Portland Cement; SF: Silica Fume; BFS: Blast Furnace Slag; FA: Fly Ash

Sand

Graded river sand is used with a fineness modulus (FM) of 3.00, which has been determined by standard sieve analysis as per ASTM C136-06 (ASTM, 2006).

Sieve analysis data is shown in Table 2. The sand has an apparent specific gravity of 2.69 g/cm^3 and to make sure that the sand is free from organic chemicals and unwanted clay, sand samples have been washed several times and dried.

Table 2. Sieve analysis data

Sieve size	Cumulative mass retained (g)	Cumulative percent (%) retained
4.75 mm (No. 4)	34	4.53
2.36 mm (No. 8)	160	21.33
1.18 mm (No. 16)	298	39.73
600 μm (No. 30)	468	62.4
300 μm (No. 50)	564	75.2
150 μm (No. 100)	726	96.8
Pan	750	100

Lightweight Aggregate

The lightweight aggregate used in this study has a particle dry density of 1.32 g/cm^3 and a bulk density of 725 ± 10 kg/m^3. The aggregate has water absorption of 5%, 8% and 10% at 1 hour, 24 hours and 7 days, respectively.

Supplementary Cementitious Materials (Mineral Admixture)

Silica fume (SF), blast furnace slag (BFS) and fly ash (FA) are three types of SCMs used in this study. Silica fume has been supplied by one of the commercial companies, which satisfies the requirements recommended by ASTM C1240-14 (ASTM, 2014a). ASTM Class C fly ash with high calcium content has been supplied by a commercial company, which satisfies the specifications of ASTM C618-12a (ASTM, 2012b). Moreover, the same company has supplied iron blast furnace slag, which fulfills the requirements of ASTM C989-99 (ASTM, 1999). The SiO_2 contents of SF, BFS and FA are 91.29%, 25.5% and 55.1%, respectively. Physical, mechanical and chemical compositions of SF, BFS and FA are presented in Table 1.

Water

Clean water collected from an available source is used for mixing.

Super Plasticizer (SP)

Because of the dosage of super plasticizer (SP), both cement paste and concrete can be affected (Cong et al., 1992). SP has an effect on concrete strength even at constant water–cement ratio (Mazloom and Miri, 2017; Neville, 2011). If the dosage of SP is varied with the replacement percentage of SCMs, the variation in concrete strength can be ambiguous to understand, since strength can fluctuate due to variation in SCMs as well as in the dosage of SP (Bhanja and Sengupta, 2003). Therefore, the dosage of SP is kept constant to identify the sharp effect of SCMs only. Nevertheless, the compaction energy is varied in order to obtain proper compaction for minimizing the variation in workability (Bhanja and Sengupta, 2002). In this study, melamine-based (non-surfactant) SP is used in a percentage of 1% by weight of binder as per previous experience (Muhit, 2013).

Mix Proportions and Preparation of Specimens

The mix proportions of all the test specimens are given in Table 3. The control specimen has no replacement of cement by silica fume, blast furnace slag or fly ash. To understand the effect of silica fume on lightweight concrete, 5%, 10%, 15% and 20% by weight of cement have been replaced by silica fume. Moreover, for individually investigating the effects of blast furnace slag and fly ash, 5%, 15%, 25% and 35% by weight of cement have been individually replaced by both blast furnace slag and fly ash (Table 3). Apart from that, to understand the combined effects of SCMs, additional four types of combinations have been selected. For all the test specimens, water–binder ratio has been kept constant (*w*/*b* = 0.4), where binder refers to the mixture of cement and SCM(s).

Table 3. Mix proportions

Specimen	**Cement (kg/m^3)**	**Silica Fume**		**Blast Furnace Slag**		**Fly Ash**		**Aggregates**		**Water (kg/m^3)**
		%	**kg/m^3**	**%**	**kg/m^3**	**%**	**kg/m^3**	**Lightweight (kg/m^3)**	**Fine (kg/m^3)**	
Control	480	0	0	0	0	0	0	410	336	192
SF-I	456	5	24	0	0	0	0	410	336	192
SF-II	432	10	48	0	0	0	0	410	336	192
SF-III	408	15	72	0	0	0	0	410	336	192
SF-IV	384	20	96	0	0	0	0	410	336	192
BFS-I	456	0	0	5	24	0	0	410	336	192
BFS-II	408	0	0	15	72	0	0	410	336	192
BFS-III	360	0	0	25	120	0	0	410	336	192
BFS-IV	312	0	0	35	168	0	0	410	336	192
FA-I	456	0	0	0	0	5	24	410	336	192
FA-II	408	0	0	0	0	15	72	410	336	192
FA-III	360	0	0	0	0	25	120	410	336	192
FA-IV	312	0	0	0	0	35	168	410	336	192
SF-BFS	360	5	24	20	96	0	0	410	336	192
SF-FA	360	5	24	0	0	20	96	410	336	192
BFS-FA	360	0	0	12.5	60	12.5	60	410	336	192
SF-BFS-FA	360	8.33	40	8.33	40	8.33	40	410	336	192

Standard cube specimens of 150 mm size have been cast for all specimen types. For each type of specimen, three samples have been cast for 7 days and three more for 28 days. Compressive strength test has been carried out and the average value of three samples has been taken as the final result. This means that a total of 51 samples have been cast for testing at 7 days and 51 samples more for testing at 28 days. During casting, compaction has been properly carried out and each layer has been compacted with not less than 35 strokes using a tamping rod. A steel bar having 16 mm diameter and 600 mm length with a bullet pointed at the lower end has been used as a tamping rod. Each time, the top surface has been leveled with the help of a trowel.

To ensure proper strength of concrete, curing is one of the most important things. Problem of freezing and thawing can be overcome by proper curing. The samples have been stored in a place free of vibration and in relatively moist air at temperatures ranging from 25ºC to 27ºC during the curing period as per standard (ASTM, 2014b). After 48 hours, the molds have been removed and the test specimens have been marked with symbols to be easily identified later. Finally, the specimens have been cured under clean fresh water. Moreover, humidity has been controlled by water nebulizers. To keep specimens undisturbed until crushing, special care has been taken.

Testing Methods

Slump and Slump Flow

The moisture content of the lightweight aggregate has been measured before mixing. 'Slump' and 'slump flow' tests have been carried out for each mixture before casting the specimens. Slump tests have been conducted according to ASTM C143M-12 (ASTM, 2012a) and cautions, like level base, filling concrete in three equal layers, rodding each layer to ensure compaction, lifting up carefully,… etc. have been taken. In case of adequately non-cohesive concrete, caution has been exercised for interpreting the results. The average diameter of the horizontal flow (the largest one and the one orthogonal thereto) after lifting Abrams' cone (top internal diameter = 102 mm and bottom internal diameter = 203 mm with a height of 305 mm) is taken as the "slump flow".

Compressive Strength

For compressive strength test, a digital compression testing machine with 3000 kN capacity at constant loading rate has been used in this study. The machine has enough ability to avoid the abrupt shock and to apply the load at a defined rate. Moreover, the rate of error is ±0.5% of the indicated load. From the test results of three samples of each type, the average is taken as the compressive strength.

RESULTS AND DISCUSSION

Physical and mechanical properties; i.e., density and compressive strength of concrete are presented in Table 4. Oven dry density and 28-day compressive strength of concrete are found to vary from 1,430 kg/m^3 to 1,546 kg/m^3 and from 43.5 MPa to 56.8 MPa, respectively.

The relationship between compressive strength and oven dry density of LWAC obtained in this study is depicted in Fig. 1. Moreover, results of material efficiency (ratio of compressive strength to density) of Brazilian lightweight aggregate investigated by Rossignolo et al. (2003) and lightweight aggregate with SCMs investigated by Chen and Liu (2008) are compared with the results of this study. It is clear from Fig. 1 that lightweight aggregate concrete with SCMs possesses higher material efficiency.

Effects of Silica Fume (SF) on the Workability and Compressive Strength of LWAC

Effects of partial replacement of cement by SF on workability of LWAC are depicted in Fig. 2. It is evident that with replacement by SF, workability of LWAC decreases significantly. The rate of reduction in workability increases with the increase in SF content. The maximum reduction in slump is found to be 24% for 20% replacement of binding material by SF, compared to control specimen. Moreover, with the time of leaving the mixture, the specimens exhibit considerable slump loss. Slump flow results are also found to be conforming to the reduction in slump with the increase in SF content (Fig. 2).

However, significant increase of the strength of the specimens is obtained by the addition of SF, as shown in Fig. 3. For example, the 7-day and 28-day strengths of the specimens with 20% of SF are higher than those of the specimens without SF by almost 45% and 26%, respectively. Nevertheless, meeting the design requirements of slump and slump flow of concrete with addition of SF to LWAC is difficult without a high-quality super plasticizer, although it provides great improvement in strength. Therefore, taking both rheological and strength properties into consideration, it is not recommended to add only SF to LWAC (Chen and Liu, 2008).

Table 4. Physical and mechanical properties of concrete

Specimen	**Bulk density (kg/m^3)**		**Compressive strength (MPa)**		
	Fresh density	**Oven dry density**	**7 days**	**14 days**	**28 days**
Control	1586	1477	30.0	38.8	45.0
SF-I	1581	1469	36.1	44.0	50.3
SF-II	1585	1479	41.7	48.5	52.8
SF-III	1595	1485	43.0	50.2	56.0
SF-IV	1609	1490	43.5	51.0	56.8
BFS-I	1580	1488	33.5	42.0	48.8
BFS-II	1591	1485	37.2	45.5	52.0
BFS-III	1579	1465	40.5	50.0	56.6
BFS-IV	1581	1460	39.0	47.6	54.1
FA-I	1555	1430	28.8	39.1	49.0
FA-II	1536	1461	30.9	44.0	54.4
FA-III	1565	1469	26.6	38.5	48.0
FA-IV	1579	1476	23.5	34.9	43.5
SF-BFS	1610	1539	39.0	49.2	56.8
SF-FA	1600	1498	34.2	45.0	53.6
BFS-FA	1595	1505	37.5	47.3	52.9
SF-BFS-FA	1633	1546	43.5	51.9	57.0

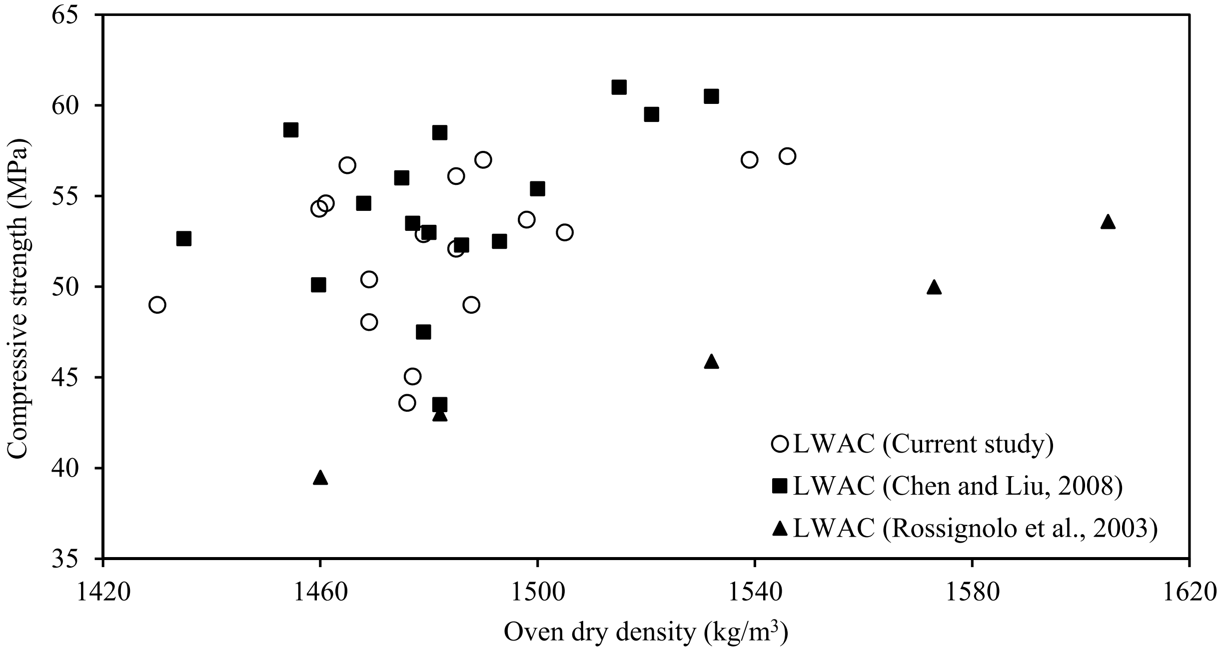

Figure (1): Relationship between 28-day compressive strength and oven dry density

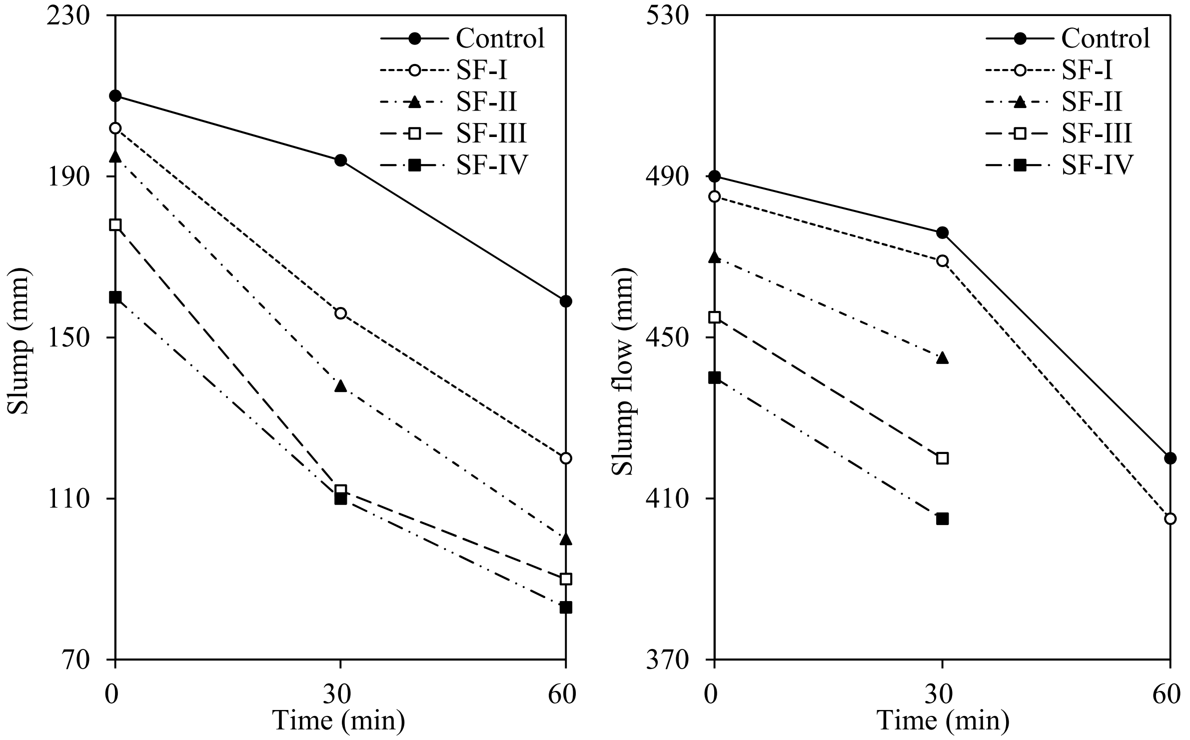

Figure (2): Slump and slump flow fluctuations of LWAC for silica fume (SF) volume fraction

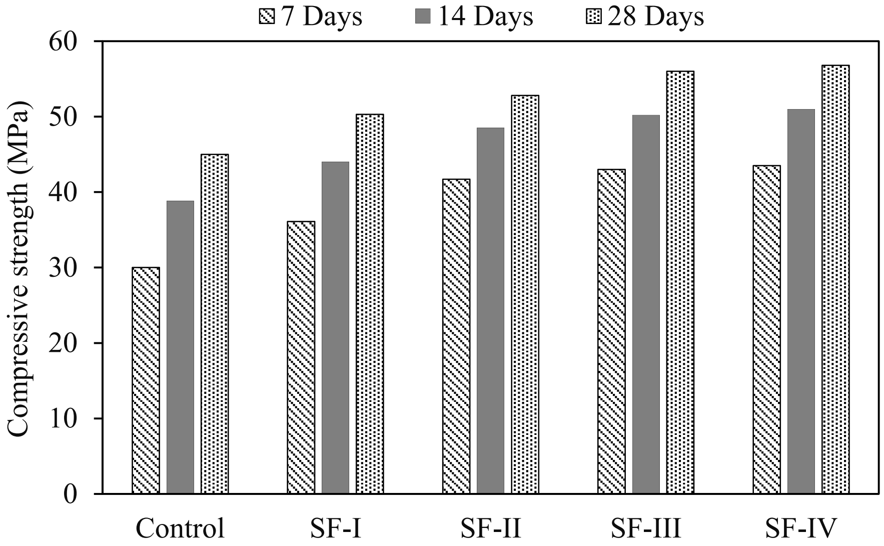

Figure (3): Compressive strength fluctuations of LWAC for silica fume (SF) volume fraction

Effects of Fly Ash (FA) on Workability and Compressive Strength of LWAC

The effect of supplementing FA as partial binder on workability of LWAC is shown in Fig. 4. Both slump and slump flow are found to be increased with the increase in FA content. The workability of the specimens is improved by the addition of FA due to its shape effect. Maximum increase in slump is 31% for 35% replacement of binding material by FA, compared to control specimen. However, during the experiment, bleeding has been observed for the specimens with FA, especially for those with 35% of FA content. In addition, with the time of leaving the mixture, slump losses are different with different amounts of FA. Slump flow results are found compatible with slump with the increase in replacement content by FA.

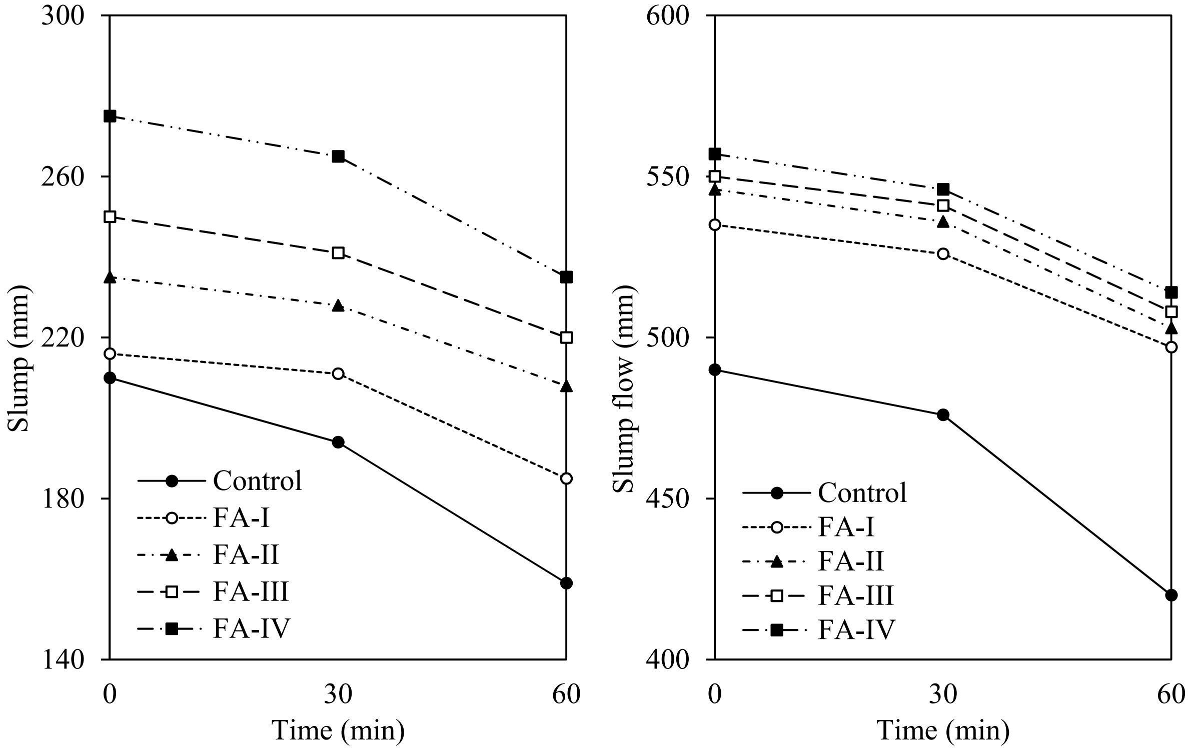

Figure (4): Slump and slump flow fluctuations of LWAC for fly ash (FA) volume fraction

Strength properties of LWAC with different amounts of FA are presented in Fig. 5. The figure shows that the 7-day strength of LWAC with FA decreases with the increase in FA. The decrease of strength gets more intensive with the increase in FA content. In case of the 28-day strength, the highest strength is obtained when FA content is 15% and strength decreases with more increase in FA content. This is primarily due to the fact that pozzolanic reaction of FA is a slow process at low temperatures. However, the addition of only FA to LWAC is not suggested by taking both rheological and strength properties into consideration.

Effects of Blast Furnace Slag (BFS) on Workability and Compressive Strength of LWAC

Figure 6 shows the effect of BFS as supplementary cementitious material on workability of LWAC. It is apparent from the figure that workability of LWAC improves with the increase in BFS content. Maximum slump occurred for 25% replacement of cement by BFS and this increased the slump by 14% compared to the control specimen. Also, it has been reported that the presence of slag eases compaction by vibration and eventually results in better workability (Hooton, 2000). Moreover, for the same volume content of replacement, LWAC with BFS shows less workability than that with FA, which is probably due to the rough texture of the BFS. No significant bleeding has been observed for the specimens with BFS. In addition, specimens with BFS show less slump loss than those with FA. Slump flow shows similar increasing trend as slump with the increase in replacement fraction by BFS.

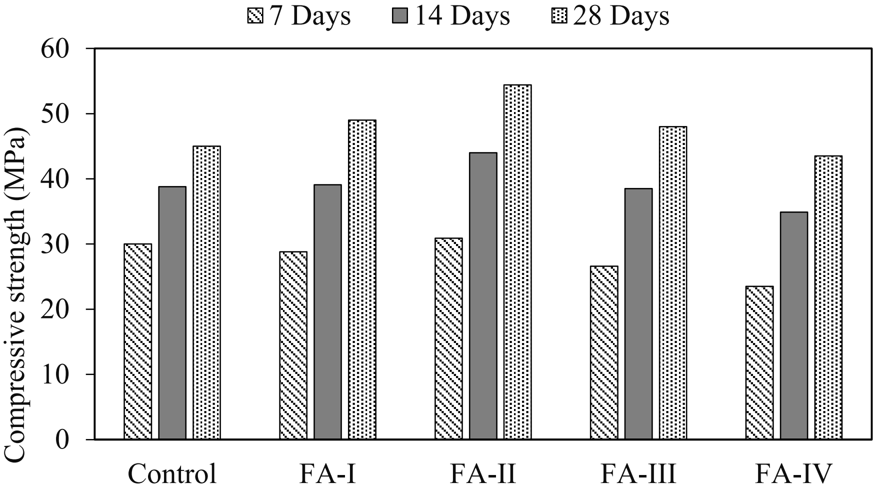

Figure (5): Compressive strength fluctuations of LWAC for fly ash (FA) volume fraction

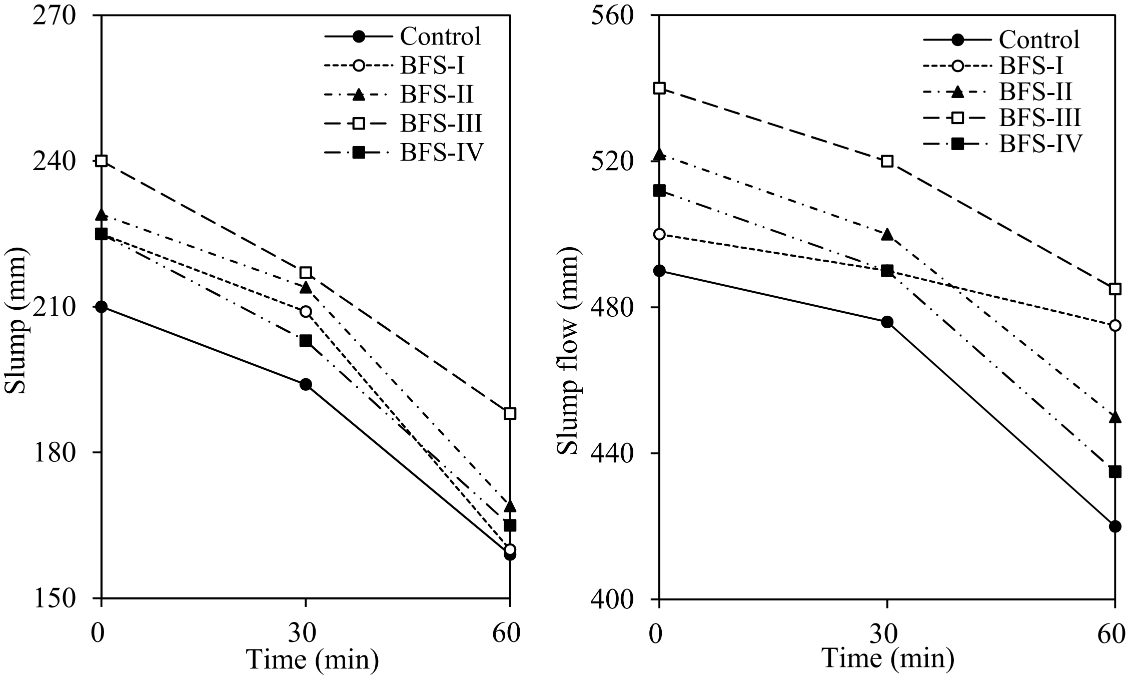

Figure (6): Slump and slump flow fluctuations of LWAC for blast furnace slag (BFS) volume fraction

The effect of BFS content on the strength of LWAC is shown in Fig. 7. The strength of LWAC with BFS at early ages is higher than that with FA due the higher pozzolanic reaction. Moreover, at each BFS content, 28-day strength is higher than 7-day strength. Both workability and compressive strength of LWAC with BFS show their highest values at 25% BFS content (Fig. 6 and Fig. 7). Hence, considering both rheological and strength properties, it is feasible to add BFS to LWAC for both high workability and strength purposes.

Effects of Combinations of SCMs on Workability and Compressive Strength of LWAC

The effect of different combinations of supplementary cementitious materials on workability of LWAC is shown in Fig. 8. It is observed from Fig. 8 that use of SF in combination with FA produces more workable concrete than concrete with only SF (Fig. 2). Due to the addition of SF, workability of LWAC decreases. But, the addition of FA retards the decrease in workability of LWAC due to the addition of SF. In addition, during the experiment, bleeding was effectively controlled.

All the other combinations (i.e., SF-BFS, BFS-FA and SF-BFS-FA) considered in this study provide uniform concrete mixture with good workability and without bleeding. Also, best improvement of slump and slump flow is provided by BFS-FA combination (increase in slump by 18%) compared to control specimen.

Compressive strength of concrete with different combinations of SCMs is shown in Fig. 9. It is obvious from the figure that both highest 7-day and 28-day strengths are provided by the combination of all three mineral admixtures.

According to Fig. 9, the order of strengths of LWAC with different SCM combinations is: SF-BFS-FA>SF-BFS>BFS-FA>SF-FA. Therefore, considering both rheological and strength properties of concrete and taking economic benefit into account, the best combinations would be the BFS-FA combination and the SF-BFS-FA combination.

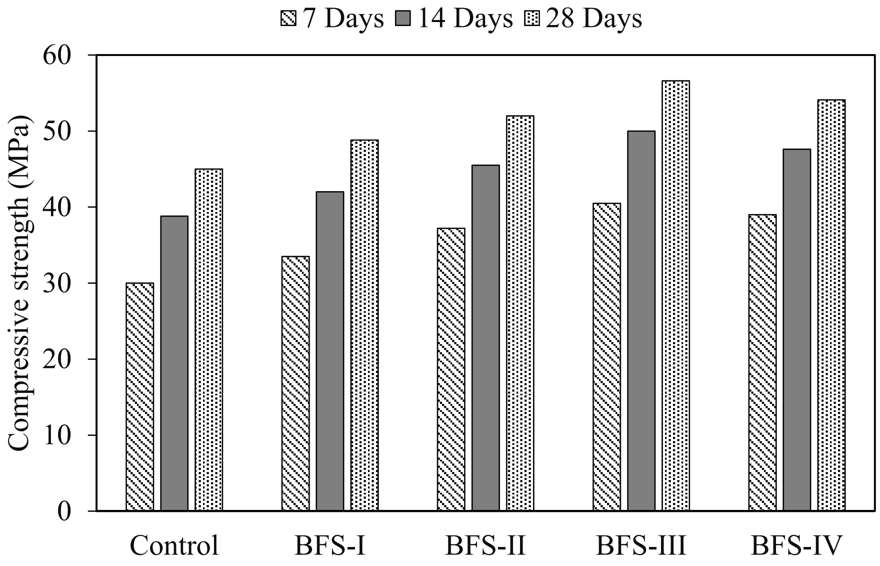

Figure (7): Compressive strength fluctuations of LWAC for blast furnace slag (BFS) volume fraction

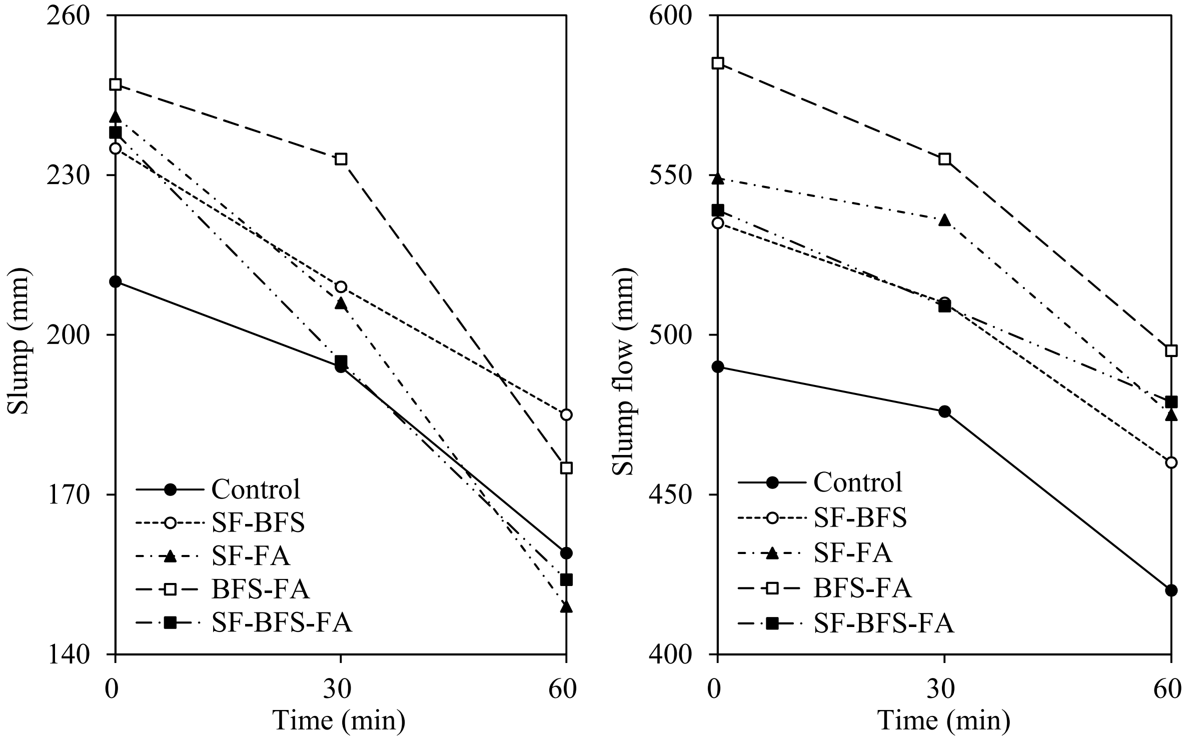

Figure (8): Slump and slump flow fluctuations of LWAC for different combinations of SCMs

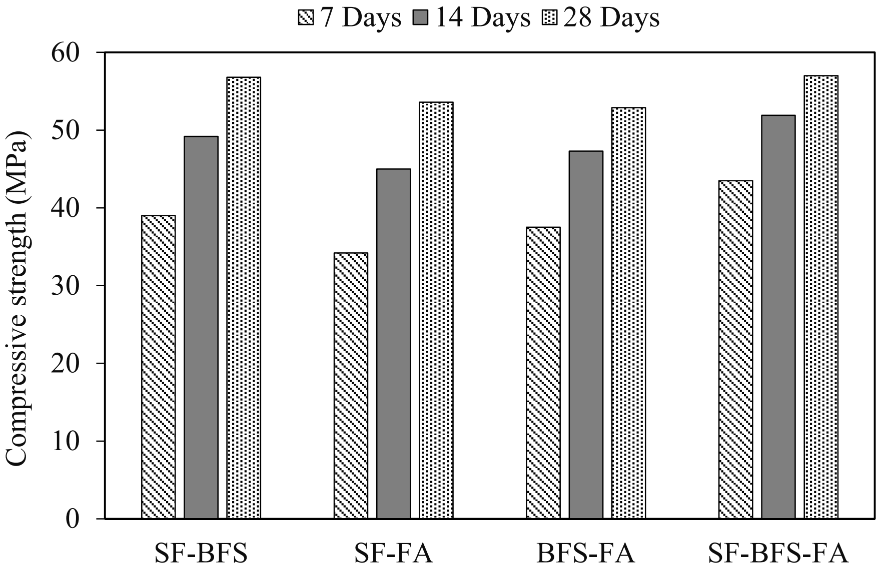

Figure (9): Compressive strength fluctuations of LWAC for different combinations of SCMs

CONCLUSIONS

High workability and strength can both be achieved by the addition of mineral admixture and superplasticizer into LWAC. Addition of different supplementary cementitious materials (SCMs) shows different effects on workability and strength properties of LWAC.

In case of FA, when added individually, it improves workability of LWAC better than other SCMs. A maximum of 31% increase in slump is obtained by replacing 35% of the cement by FA. But, in this case, the early age strength substantially decreased with the increase in FA content. So, considering both rheological and strength properties, it is not suggested to add only FA into LWAC. Addition of SF into LWAC showed some advantages, such as: considerable improvement in early age strength, increase in bonding of concrete mixture and control of bleeding and up-floating of aggregates. But, rapid reduction of workability of concrete is caused due to the addition of SF into LWAC. So, from the above considerations, the addition of only SF into LWAC is not recommended either. Considering both rheological and strength properties, it is feasible to add BFS to LWAC for high workability and strength purposes. 35% and 25.7% increase in 7-day and 28-day compressive strength, respectively, together with 14% increase in slump compared to the control specimen are achieved by 25% replacement of cement by BFS.

Better improvement of both rheological and strength properties is shown by LWAC when SCMs are added into it in combinations. The BFS-FA combination increases 7-day strength and 28-day strength by about 25% and 17.6%, respectively along with 18% increase in slump, whereas the SF–BFS-FA combination increases 7-day strength and 28-day strength by about 45% and 26.7%, respectively along with 13% increase in slump. Considering both rheological and strength properties of concrete and taking economic benefit into account, the best combinations suggested are the BFS–FA combination and the SF–BFS-FA combination.

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