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Compressive, flexural and splitting strength of fly ash and silica fume concrete

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ORIGINAL RESEARCH PAPER

ABSTRACT

Cement replacement materials are commonly used in concrete technology. Several researchers have examined high-performance concrete after adding mineral admixtures to it, but further studies are still needed to provide the optimum dosage of these materials for instance fly ash and silica fume. This study compares three types of concrete and the mechanical properties (compressive strength, flexural strength, and splitting tensile) of these types at the age of 28 and 90 days. The test results designate that adding the mineral admixtures commonly affects the mechanical properties of all the tested types. However, silica fume is more operative than fly ash. Furthermore, adding the fly ash and silica fume in the same concrete type slightly improves the mechanical properties.

KEYWORDS

fly ash, silica fume, high-performance concrete, compressive strength, flexural strength, splitting tensile

1. INTRODUCTION

High-Performance Concrete (HPC) is characterized by massive compressive strength and excellent durability compared to other types of concrete, which can be improved using additives such as fly ash and silica fume. HPC has become a widely used material that is widely used in engineering applications. A superplasticizer is also required in the mix to achieve the required properties. In addition, various types of additives are typically added to reduce porosity.

Silica Fume (SF) is a by-product of processing of simple silicone or silicone alloys in electric arc furnaces. The reduction of high-purity quartz to silicon at a temperature of about 2,000 °C produces silica fume, which changes its physical state at low temperatures and becomes silica smoke. SF has a solid surface and an extremely fine average size of 0.1–0.3 µm [1]. The early slump of fresh concrete should be increased to improve workability. D.Shen et al. [2] investigated the effects of different silica fume dosages (0, 5, 10 and 15% of cement weight) on High Strength Concrete (HSC). The results showed that with increasing SF dosage in HSC, (1) the crack resistance of HSC decreased at an early age; (2) the temperature drop, crack time, crack stress and crack stress to axial tensile strength ratio decreased; (3) the autogenous shrinkage and confined stress rate increased; and (4) the base tensile creep, specific tensile creep and creep-shrinkage ratio increased.

Fly Ash (FA) characteristically contains small carbon-burned fragments and has many practices. In several countries, FA, which is produced when coal is burned in power plants, is a major environmental and economic problem. It is an extremely popular mineral mixture that is only available in states with coal-burning facilities. In this study [3], concrete specimens were made with various mix ratios (0–70 percent) instead of normal Portland cement using FA. The steady increase in compressive strength and pulse velocity over 365 days is reflected in the high-volume FA concrete. The durability of concrete made with FA is significantly better by up to 50 percent. The scanning electron micrographs also support the

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Table 1. Chemical arrangements of materials (%)

Material	SiO_2	Al_2O_3	Fe_2o_3	Cao	MgO	NaO_2^{Eq}	Clinker
Cement CIM I 52.5 N	20.50	4.40	2.30	63.30	2.10	0.66	97.00
Fly ash	52.00	25.00	7.00	5.00	–	–	–
Silica fume	93.45	0.17	0.69	0.03	–	–	–

results and show that the substitution of cement with FA densifies the cement matrix as increased calcium silicate hydrate gels are formed.

Replacing part of the cement by supplementary materials is an advantageous solution to explicitly reduce the cost of HPC when the substitutes are waste or production by-products. These additional materials can also influence other weak points of HPC, namely the large heat of hydration and the high autogenous shrinkage. They can also help to reduce the environmental impact of cement production. Carbon capture, utilization, and storage allow fly ash to be used in a variety of ways, including as a capture material, as a medium for permanent CO_2 storage through mineralization, and as a catalyst or catalyst support for CO_2 utilization processes [4]. J. Junak et al. [5] used different types of waste materials including coal fly ash in their laboratory experiments which showed significant improvement in compressive strength of concrete. B. V. Kavyateja et al. [6] investigated the effect of FA (25%) and Alccofine (0, 5, 10, 15%) in reinforced self-compacting concrete beam as replacement material. Compared with the control concrete beam, fly ash and alccofine increased the bearing capacity and strength of the beam.

K. S. Rao et al. [7] studied high strength concrete using fly ash and steel fibers in different ratios (0–25%) and steel fibers in ratio (0, 0.3, 0.6, 0.9, 1.3, 1.5%). It was found that 20% fly ash replacement produced the maximum compressive strength parameters with 1.2% crimped steel fibers, but the splitting tensile and flexural strength of concrete was maximum at 25% fly ash along with 1.5% steel fibers.

2. EXPERIMENTAL PROGRAM

In order to understand the effect of the additives SF and FA on HPC and to verify the mechanical properties of this type of concrete, an experimental program was carried out in which SF, FA and both (12, 20, both 12 and 20%) were added to an HPC mix. The investigation included flow table test of fresh concrete, compressive strength, flexural strength and splitting tensile tests at 28 days of age. The results presented in this article will increase interest in improving the use of mineral mixes in HPC.

2.1. Materials

A CEM I 52.5 N cement [8] with a specific gravity of 3.13 g cm^{-3} and Blaine fineness of 410 kg m^{-2} was used in the test mix. SF is a powdered concrete admixture with highly effective fines to produce high-performance concrete. The specific gravity of silica fume is 2.2 g cm^{-3} as it is shown in Table 1. Microsite$_{20}$ FA was used in the experiment, which is an excellent latent hydraulic cement admixture type II for the production of concretes and mortars that meet high-quality requirements. Microsite$_{20}$ consists predominantly of SiO_2 and Al_2O_3 and thus belongs to the aluminosilicates. The specific gravity of fly ash is 2.5 g cm^{-3} as shown in Table 1.

The maximum size of the aggregate is 16 mm, the specific gravity for fractions 4–16 mm is 2.61 g cm^{-3} and the water absorption of the aggregate is 0.6%. Sieve analysis of the aggregate was carried out, which helped to distinguish two sizes of fractions 4–8 mm and 8–16 mm with proportions of 24.7 and 39.2%, respectively. The well-rounded natural fine aggregate was used as sand 0–4 mm with a specific gravity of 2.62 g cm^{-3} and water absorption of 0.2% with a proportion of 36.1%. All the sieve curvatures are shown in (Fig. 1). The superplasticizer (SP) used was Sika ViscoCrete-5-500, a third-generation superplasticizer used for the production of soft plastic concrete, as well as state-of-the-art, Self-Compacting Concrete (SCC) depending on the dosage amount, the specific gravity of the superplasticizer was 1.07 g cm^{-3}.

2.2. Mix amount

Three different mixes with different types of supplementary materials were prepared, to test the compressive strength, flexural strength, and splitting tensile strength of the concrete after 28 and 90 days. Nine specimens in each mix were used for these experiments. Mix1 contained 20% fly ash by weight of cement, Mix2 contained 12% silica fume by weight of cement and Mix3 contained 20% fly ash and 12% silica fume. The Water to Cement ratio (W/C) was kept at 0.4 while the cement weight was 360 kg m^{-3}. These cement quantities were selected according to different mixes with the modified value of W/C to obtain concrete with super performance and high strength as shown in Table 2.

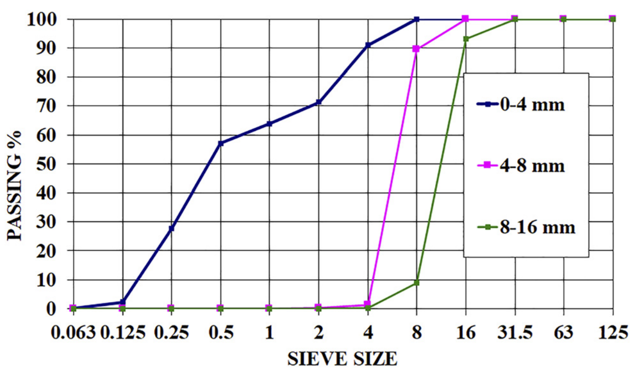

Fig. 1. Sieve analysis, curves of aggregate 4–16 mm and sand 0–4 mm

Table 2. Concrete admixture proportions

Criterion	Mix1	Mix2	Mix3
Cement (360 kg m^{-3})	288	317	245
Coarse aggregate (kg m^{-3})	1,209	1,209	1,209
Fine aggregate (kg m^{-3})	686	686	686
Water (kg m^{-3})	144	144	144
Silica fume (kg m^{-3})	–	43	43
Fly ash (kg m^{-3})	72	–	72
Superplasticizer (% binder)	1	1.2	1.1

2.3. Method of testing and specimen preparation

The dry materials were added to the pure water in the exact amount after one minute, when the mixture began to mix, the superplasticizer was added to obtain a perfect concrete mixture, reduce water amount and increase the strength of concrete. Mix the concrete for approximately 3–4 min until a uniform, workable consistency is achieved. Properly mixed concrete should look like thick oatmeal and hold its shape when squeezed in a gloved hand. The next step was a flow table test to check the fresh concrete and determine its workability of the concrete. Then the cube, cylinder, and prism molds were prepared for casting the concrete. After that, the specimens were stored in the room for 24 h, then cured in water for 7 days, and then left in the room until the day of testing. The manufacturing steps of the specimens are shown in (Fig. 2).

2.4. Compressive strength test

The number of cube-shaped specimens used for compressive strength testing was six for each mixture, 18 in total, with a size of 150 × 150 × 150 mm. For each mixture, three specimens were tested at 28 days of age and another three cube-shaped specimens were tested at 90 days of age, following the standard MSZ EN 12390-3:2019 [9] (Fig. 3).

2.5. Flexural strength test

The flexural strength test was performed with three prismatic specimens per mixture with a size of 70 × 250 × 250 mm at 28 days of age and the same number at 90 days of age following the standard MSZ EN 12390-5: 2019 [10] (Fig. 4).

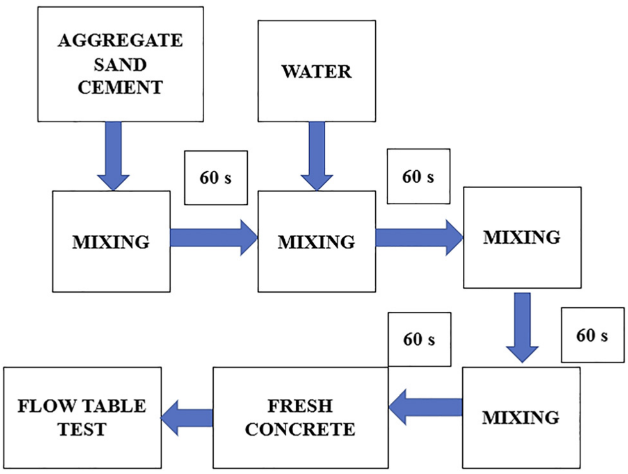

Fig. 2. Mix process

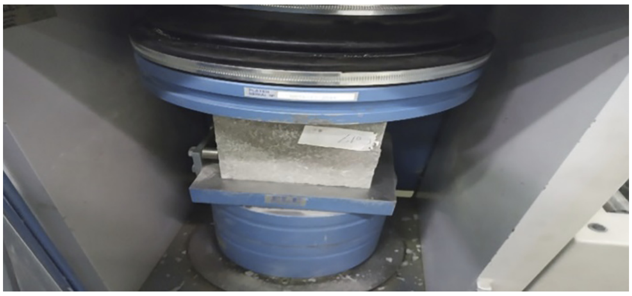

Fig. 3. Compressive strength test

2.6. Splitting tensile test

For the split tensile test, three plus three cylindrical test specimens with a size of 150 × 300 mm were prepared for each mixture at the age of 28 and 90 days following the standard MSZ EN 12390-6: 2010 [11] (Fig. 5).

3. RESULTS AND DISCUSSION

After reviewing many previous researches and several concrete experiments, especially the concrete supplemented with fly ash and silica fume, and how the high percentage of fly ash reduces the compressive strength and discovered that the perfect ratio of silica fume is between 10 and 15% of the

Fig. 4. Flexural strength test

Fig. 5. Splitting tensile test

cement weight, the expectation of having the best results by using the selected proportions of fly ash and silica fume is shown in this study.

All the tests in the experimental program were carried out using the three types of admixtures. These included the table flow test of the fresh concrete and the compressive, flexural and splitting tensile tests on the specimens at 28 and 90 days of age, separately. In the following, the results of the tests are presented and compared with the results of parallel investigations from the literature.

3.1. Fresh properties

The flow table test was the main test on all concrete admixtures, trying to achieve the plastic consistency of class F3 (420–480 mm) according to the standard MSZ EN 12350-5:2019 [12] by adding different amounts of SP. Therefore, the range of flow table test for all concrete mixes was 420–430 mm. Here, the SP amount was different depending on the concrete mix type. The concrete mix with 20% fly ash as cement replacement had lower SP than the concrete mix with 12% silica fume. This result is confirmed by other researchers [13, 14]. Based on their results, the excessive adsorption of SP is due to the large surface zone of silica fume particles, which reduces the volume obtainable in solution on the outer surface of the cement particles, thus reducing the liquidity of the cementitious mixes.

3.2. Compressive strength

For reference, the compressive strength of the control concrete was tested, and the values were 43.7 and 54.2 MPa at 7 and 28 days of age. But the main result of Compressive Strength (CS) test of all mixes at the age of 28 and 90 days is shown in (Fig. 6). The range of this test of all types was 59–77 MPa at the age of 28 days and 57–81 MPa at the age of 90 days.

The maximum 28 days old CS test was obtained for Mix2 with 76.8 MPa, which contained 12% silica fume. In contrast, the lowest value of CS at 28 days of age was 59.9 MPa for Mix1 formed with 20% cement replacement by fly ash. However, the addition of 12% silica fume and 20% fly ash in Mix3 improved CS to 67.1 MPa. The same behavior results were obtained at 90 days of age, which shows that Mix2 has the largest CS value with 81.2 MPa, then Mix3 with 78.2 MPa and Mix1 77. 8 MPa.

In general, the addition of these supplementary materials to concrete has a different behavior depending on the percentage of these materials added. Guneyisi et al. [15], Gesoglu et al. [16] investigated the compressive strength of concrete after adding fly ash in different mixes and the result showed a decrease in the strength of concrete after increasing the percentage of fly ash from 20 to 60%. Compared with the result, 20% fly ash is the optimum percentage as a replacement material in concrete mix. S. Jagan et al. [17] also studied CS of SF concrete with different replacement proportions of 0, 5, 10 and 15% at the age of 7, 14, 28 and 90 days. The result showed an increase in CS and other properties, confirming that silica fume has a great influence on concrete admixture.

3.3. Flexural strength

The Flexural Strength (FS) test showed the same behavior as the compressive strength test. At the age of 28 days, the concrete with 20% FA showed a slight decrease in FS test compared to the concrete with 12% silica fume. Compared to the concrete containing (20% fly ash + 12% silica fume), the FS averaged 7.8 MPa. The FS values for Mix1 and Mix2 were 6.2 and 8.9 MPa, respectively, confirming that the effect of silica fume was still greater than the effect of fly ash in the FS test.

Continuously, for the FS results at 90 days of age compared to concrete 20% fly ash, the concrete with 12% silica fume showed the greater value 10.44 MPa, while the mean value of FS was for the concrete with 12% silica fume + 20% fly ash, which was 8.53 MPa. The addition of fly ash Mix1 had a slightly negative effect on FS, when compared with Mix3 as shown in Fig. 7.

3.4. Splitting tensile strength

The results of Splitting Tensile Strength (STS) for all concrete mixes at 28 and 90 days of age are shown in Fig. 8. Compared to concrete with 12% SF, the concrete with 20% FA showed different behavior in terms of flexural strength at age 28 days, which had a significant effect on the STS test. Meanwhile, the addition of 20% FA +12% SF as

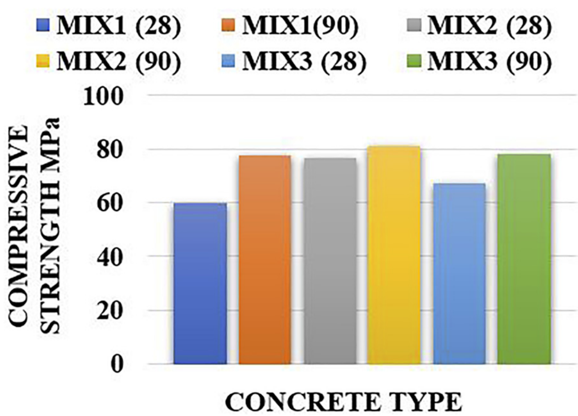

Fig. 6. Compressive strength results at age 28 and 90 days

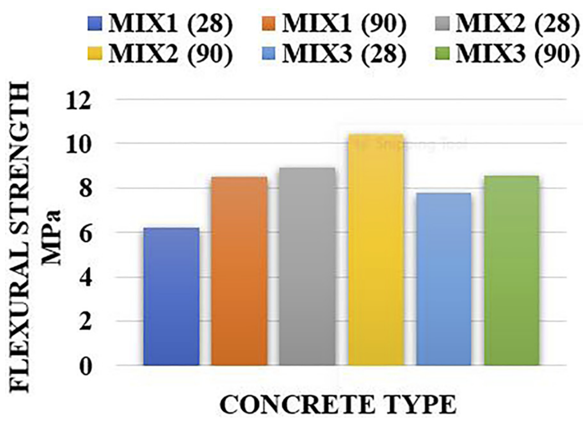

Fig. 7. Flexural strength result at age 28 and 90 days

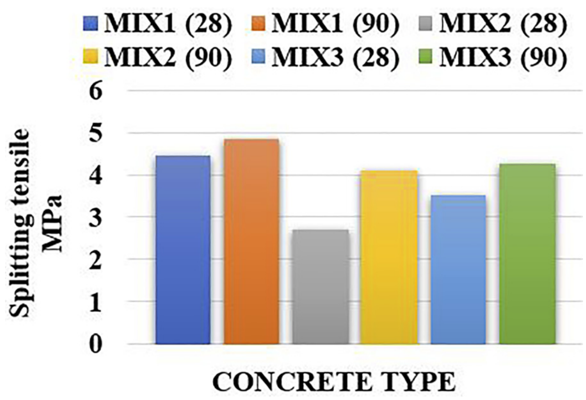

Fig. 8. Splitting tensile results at age 28 and 90 days

replacement materials in the concrete provided a lower value compared to the concrete with 20% FA in the STS. The STS for all concrete mixes were 4.45, 2.7 and 3.51 MPa for Mix1, Mix2, and Mix3, respectively.

At the age of 90 days, when comparing the three values of STS, which is shown in Fig. 8, the concrete with 20% FA had the highest value of 4.83 MPa in STS. Accordingly, fly ash could be a good admixture material to increase the splitting tensile strength of concrete at both 28 and 90 days of age.

4. CONCLUSION

This paper presents an experimental program describing the effect of treatment conditions on the HPC with two percentages of FA and SF to determine the best mix of FA, SF, or their combination in terms of concrete compressive strength, flexural strength, and splitting tensile strength. Based on the results, the following conclusions can be drawn:

- The superplasticizer requirement of HPC with 20% fly ash was lower than the superplasticizer requirement of HPC with 12% silica fume. The reason for this result is the large surface area of silica fume particles. This reduced the surface area of the cement elements obtained;
- The compressive strength was at the peak values of 76.8 and 81.2 MPa at the age of 28 and 90 days, respectively, for the concrete type with 12% silica fume, and the influence of 20% fly ash as an admixture in the concrete mix provided the lowest values at both ages. However, the combination of both minerals with the same percentages has improved compressive strength compared to Mix1;
- This study had investigated the flexural strength of the three types of concrete. The result has confirmed that the effect of concrete with 12% SF is better than concrete with 20% FA;
- The third mechanical property tested in this study was the splitting tensile strength. This test showed different results depending on the type of concrete. The highest value of 4.45 MPa was the concrete containing 20% FA, while the addition of 12% silica fume in Mix2 caused a significant reduction of 2.70 MPa compared to the first type. Meanwhile, the combination of the two additional materials in Mix3 improved the STS with a value of 3.51 MPa. The results of the concrete at 90 days of age had the exact sequence of ranking values.

REFERENCES

[1] D. K. Panesar, “Supplementary cementing materials,” in *Developments in the Formulation and Reinforcement of Concrete*, 2nd ed., S. Mindess, Ed., 2019, pp. 55–85.

[2] D. Shen, J. Kang, Y. Jiao, M. Li, and C. Li, “Effects of different silica fume dosages on early-age behavior and cracking resistance of high strength concrete under restrained condition,” *Constr. Build. Mater.*, vol. 263, 2020, Paper no. 120218.

[3] M. Kumar, A. K. Sinha, and J. Kujur, “Mechanical and durability studies on high-volume fly-ash concrete,” *Struct. Concrete*, vol. 22, no. S1, pp. E1036–E1049, 2020.

[4] A. Dindi, D. V. L. F. Vega, E. Nashef, and M. R. M. Abu-Zahra, “Applications of fly ash for CO_2 capture, utilization, and storage,” *J. CO_2 Utilization*, vol. 29, no. 2, pp. 82–102, 2019.

[5] J. Junak, N. Stevulova, and M. Ondova, “Concrete samples prepared with different types of wastes,” *Pollack Period.*, vol. 9, Supl. 1, pp. 95–104, 2014.

[6] B. V. Kavyateja, J. G. Jawahar, C. Sashidhar, and N. R. Panga, “Moment carrying capacity of RSCC beams incorporating alccofine and fly ash,” *Pollack Period.*, vol. 16, no. 1, pp. 19–24, 2021.

[7] K. S. Rao and K. S. Rao, “Study of HSC by using fly ash as partial replacement of cement & incorporating of steel fibers,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1006, 2020, Paper no. 012037.

[8] M. Boumaaza, P. Turcry, B. Huet, and A. Aït-Mokhtar, “Influence of carbonation on the microstructure and the gas diffusivity of hardened cement pastes,” *Constr. Build. Mater.*, vol. 253, 2020, Paper no. 119227.

[9] *MSZ EN 12390-3: 2019*, Examination of hardened concrete, Part 3: Compressive strength of specimens, Hungarian Standard Committee, 2019.

[10] *MSZ EN 12390-5: 2019*, Examination of hardened concrete, Part 5: Flexural tensile strength of specimens, Hungarian Standard Committee, 2019.

[11] *MSZ EN 12390-6: 2010*, Examination of hardened concrete, Part 6: Tensile strength of specimens, Hungarian Standard Committee, 2010.

[12] *MSZ EN 12350-5: 2019*, Examination of fresh concrete, Part 5: Area measurement, Hungarian Standard Committee, 2019.

[13] F. A. Sabet, N. A. Libre, and M. Shekarchi, "Mechanical and durability properties of self-consolidating high-performance concrete incorporating natural zeolite, silica fume and fly ash," *Constr. Build. Mater.*, vol. 44, pp. 175–184, 2013.

[14] C. K. Park, M. H. Noh, and T. H. Park, "Rheological properties of cementitious materials containing mineral admixtures," *Cement Concrete Res.*, vol. 35, no. 5, pp. 842–849, 2005.

[15] E. Güneyisi, M. Gesoğlu, and E. Özbay, "Permeation properties of self-consolidating concretes with mineral admixtures," *Mater. J.*, vol. 108, no. 2, pp. 150–158, 2011.

[16] M. Gesoğlu, E. Güneyisi, and E. Özbay, "Properties of self-compacting concretes made with binary, ternary, and quaternary cementitious blends of fly ash, blast furnace slag, and silica fume," *Constr. Build. Mater.*, vol. 23, no. 5, pp. 1847–1854, 2009.

[17] S. Jagan and T. R. Neelakantan, "Effect of silica fume on the hardened and durability properties of concrete," *Int. Rev. Appl. Sci. Eng.*, vol. 12, no. 1, pp. 44–49, 2021.