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Effect of Silica Fume on High-strength Concrete Performance

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Abstract - Concrete is one of the most widely used construction and building materials. To produce high-strength concrete (compressive strength higher than 40 MPa) water/cement ratio has to be reduced up to 0.4 and more. Mineral admixtures (supplementary cementitious materials) are used as alternative to the increase in cement content. They either partially replace cement or is added additionally. The conducted studies show that silica fume is superior to other admixtures. However, there is lack of knowledge on overall mechanical performance of concrete mixtures with silica fume in terms of compression, tension, bending and cyclic loading and dependency between these characteristics. In addition to this, controversial findings regarding the optimal amount of silica fume exist. Therefore, the objective of this research is to comprehensively determine the effect of silica fume on high-strength concrete, which could be used for road pavement construction, performance. Three, the same type, concrete mixtures with different amount of silica fume (0%, 7% and 10%), but the same water/cement ratio (0.4) were produced and tested in compression, tension, bending and cyclic loading. In addition to this, density was determined to identify the difference in concrete microstructure due to presence of silica fume. The results showed that silica fume significantly enhances the performance of high-strength concrete in terms of compression, tension, bending and cyclic loading and 7% is an optimal amount.

***Keywords*:** Silica fume; Microsilica; Concrete; Admixture; Compressive strength; Flexural strength; Indirect tensile strength; Fatigue

1. Introduction

Concrete consists of cement, sand, coarse aggregate and water and is one of the most widely used construction and building materials. According to the compressive strength it is grouped as normal (ordinary) concrete, high-strength concrete or ultra high-strength concrete. High-strength concrete after 28 days has a strength above 40 MPa while compressive strength of ultra high-strength concrete is higher than 120 MPa. Compressive strength higher than 40 MPa is achieved by lowering porosity, i.e. reducing water/cement ratio up to 0.4 and more [1]–[3]. For this purpose, at least 450 kg/m^3 of cement is used to produce concrete while for normal concrete 280–360 kg/m^3 of cement is enough to reach the required compressive strength [4], [5]. Researchers paid their attention to this issue and conducted comprehensive studies. It was suggested to use mineral admixtures (supplementary cementitious materials) as partial replacement of cement or as additional material to enhance compressive strength through their hydraulic or pozzolanic activity or both without increasing cement content.

In general, mineral admixtures (e.g. slag, fly ash, natural pozzolans and silica fume also known as microsilica or condensed silica fume) are successfully used to produce high-strength concrete. Notwithstanding, several studies showed that silica fume is superior to other admixtures since it has significantly lower particles and twice higher amount of amorphous silica in comparison with other siliceous products [4], [6]–[8]. Eren and Çelik [9] demonstrated that the addition of 5% and 10% of silica fume increases the compressive strength after 28 days by 9.6% and 24.8%, respectively, However, higher amount of mineral admixture did not have a significant effect on indirect tensile strength while 5% of silica fume increased it even by 22.7%. Kou *et al.* [7] replaced 10% of cement with silica fume by keeping the same ratio of water and cementitious materials (0.5). It resulted in about 10% and 5% respectively higher compressive strength and indirect tensile strength. Valipour *et al* [8] also partially replaced cement with silica fume and concluded that 7.5–10% is an optimal replacement level in terms of compressive strength, electrical resistivity, gas permeability, sorptivity and water absorption. It reflects finding of Alexander and Magee [10] who also demonstrated that 10% of replacement leads to the optimum concrete performance. In some studies significantly higher amount of silica fume was used as a substitute to cement [11]–[15]. However, overall concluded that no more than 15–20% of cement replaced with silica fume positively influences the concrete performance [12], [13]. Very little was found in the literature on the effect of silica fume on resistance to fatigue. One study by Yan *et al.* [14] demonstrated that concrete mixture with 20% of replaced cement has 38% higher fatigue strength in comparison with control mixture as one million loads are applied. Consequently, specimens with silica fume had less number of cracks and those cracks were much shorter. However, this study fails to consider other mechanical properties such as compressive strength, indirect tensile strength and flexural strength as well as the effect of other amounts of silica fume on concrete resistance to fatigue.

In all the studies reviewed here, silica fume is recognised as appropriate mineral admixture to enhance performance of high-strength concrete without increasing cement content. However, no attempt was made to investigate the overall mechanical performance of concrete mixtures with silica fume in terms of compression, tension, bending and cyclic loading in the same study. Therefore, the objective of this research is to comprehensively determine the effect of silica fume on high-strength concrete performance in terms of compression, tension, bending and cyclic loading and find out the optimal amount. In addition to this, the effect of silica fume on physical property such as density was determined as well.

2. Experimental research

2.1. Materials and mixture proportions

Sand (0/4 faction), crushed granite (5/16 fraction), ordinary Portland cement (CEM I 42.5 R), silica fume, water, air-entraining agent and superplasticizer was used to produce three high-strength concrete mixtures differing in the amount of silica fume (0%, 7% and 10%). 10% of silica fume was selected on the basis of literature review, however supplier recommended to use up to 7%. Thus, concrete mixtures with both amounts of silica fume were produced by additionally adding it. As a result, water/cement ratio in each mixture was constant (0.4). Details of the mixture proportions for concrete containing different levels of silica fume are given in Table 1. Fig. 1 shows a designed particle size distribution for concrete mixtures.

Table 1: Mixture proportions of concrete containing different levels of silica fume.

Mixture code	Cement, kg/m^3	Silica fume, kg/m^3	Water, kg/m^3	Sand, kg/m^3	Crushed granite, kg/m^3	Air-entraining agent, kg/m^3	Superplasticizer, kg/m^3
SF0	360	0	144	811.43	1079	0.72	1.8
SF7	360	25.2	144	797.58	1061	0.72	1.8
SF10	360	36.0	144	791.69	1053	0.72	1.8

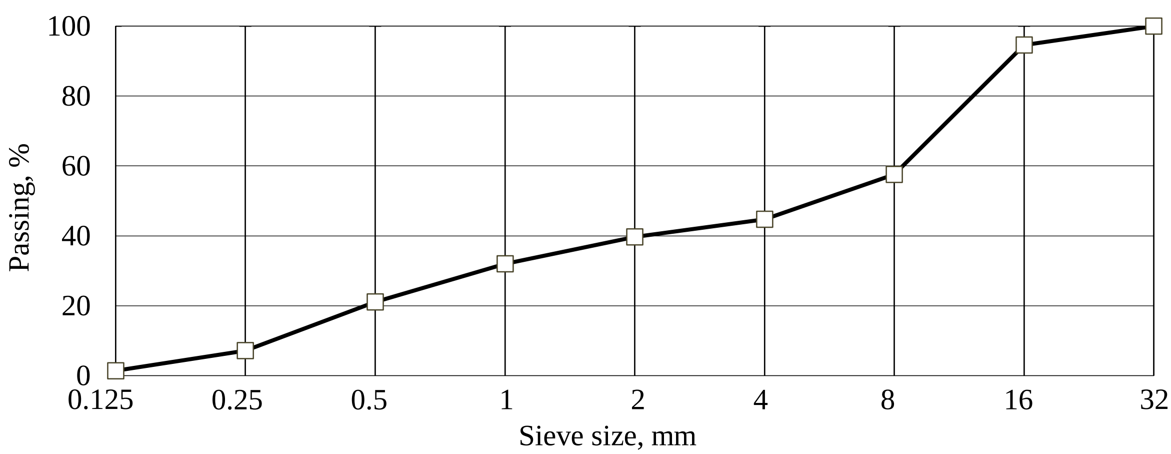

Fig. 1: Concrete mixture particle size distribution.

2.2. Test methods

Physical performance of SF0, SF7 and SF10 was evaluated by density after 28 days. It was determined in accordance with European standard EN 12390-7. Meanwhile, mechanical performance of SF0, SF7 and SF10 was evaluated in terms of compressive strength, indirect tensile strength, flexural strength and resistance to fatigue. All strength tests were carried out 28 days after casting by testing three specimens for each characteristic. Compressive strength was determined in accordance with European standard EN 12390-3 by compressing 100 × 100 × 100 (length × width × thickness) mm cubes. Indirect tensile strength test was conducted according to German technical regulations [16] by splitting 100 × 200 (diameter × length) mm cylinders. Flexural strength was determined in accordance with European standard EN 12390-5 by bending 400 × 100 × 100 (length × width × thickness) mm beams under four points: two loading points and two support points. Resistance to fatigue was evaluated under cyclic four-point bending at a frequency of 10 Hz. The cyclic loading was applied in a sinusoidal waveform under a load control up to the specimen failure or up to 2 million cycles depending on which occurred first. Each mixture was tested at three different load levels. Three 410 × 70 × 70 (length × width × thickness) mm beams were tested at each load level. Load level was selected so that the number of cycles to specimen failure would be in the range from 10^4 to 2×10^6. Fig. 2 presents different loading modes.

At all, 63 specimens were compacted with a vibrating table and stored in the laboratory at an ambient temperature of 20 °C and relative humidity of 95%. 1 day after casting, they were removed from the moulds and remaining 27 days were stored in the water at temperature of 20±2 °C.

Compression | Indirect tensile | Four-point bending

Fig. 2: Loading modes.

3. Results

3.1. Density after 28 days

Density after 28 days of concrete mixtures containing different amount of silica fume are given in Fig. 3. Error bars represent the minimum and maximum values. As can be seen from the figure below, results are stable and consistent. Coefficient of variation for each concrete mixture is less than 0.6%.

The addition of silica fume resulted in 4.6–5.4% higher density. The density increased as amount of silica fume increased. It is caused by presence of high amount of amorphous silica in silica fume, which reacts with lime present in cement and as a result, denser microstructure of concrete is formed.

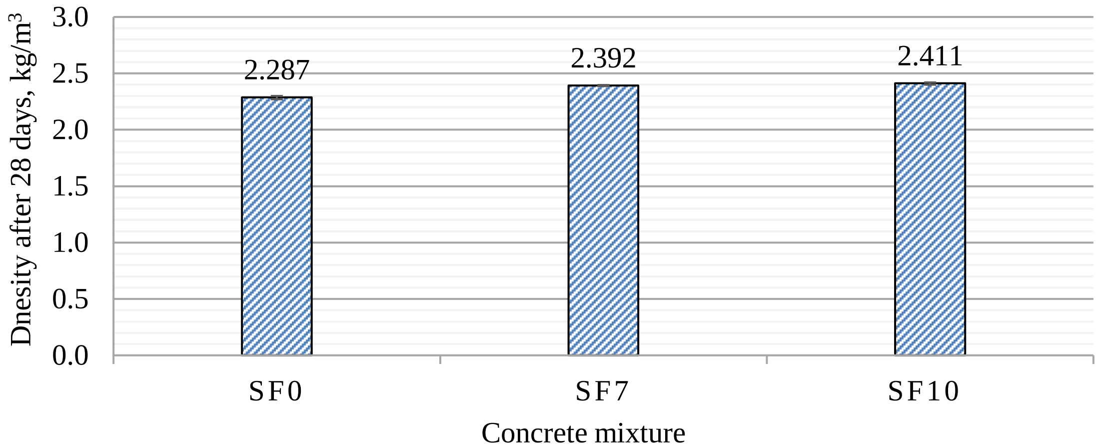

Fig. 3: Density after 28 days of concrete mixtures containing different amount silica fume.

3.2. Strength after 28 days

Compressive strength, indirect tensile strength and flexural strength after 28 days of concrete mixtures containing different amount of silica fume are given in Fig. 4. Error bars represent the minimum and maximum values. Closer analysis of the results showed that coefficient of variation for each concrete mixture is less than 5–7% depending on the tested characteristic and the addition of silica fume did not affect the repeatability of the results.

In all cases strength increased as silica fume was additionally added. It is in agreement with results of previous studies [7]–[10]. Closer inspection of the graph shows that compressive strength increased the most (33.9–37.6%) and reached about 60 MPa irrespective of the amount of silica fume. The lowest effect of silica fume was on indirect tensile strength. Nevertheless, it increased by 16% and 3% when 7% and 10% of silica fume was added, respectively. Meanwhile, flexural strength from 5.4 MPa increased up to 6.9–7.7. MPa depending on the amount of silica fume. However, the increase is not proportional to the amount of silica fume since 10% of mineral admixture gave lower flexural strength than 7%. Overall, these results indicate that 7% of silica fume is an optimal amount to enhance performance of high-strength concrete in terms of compression, tension and bending.

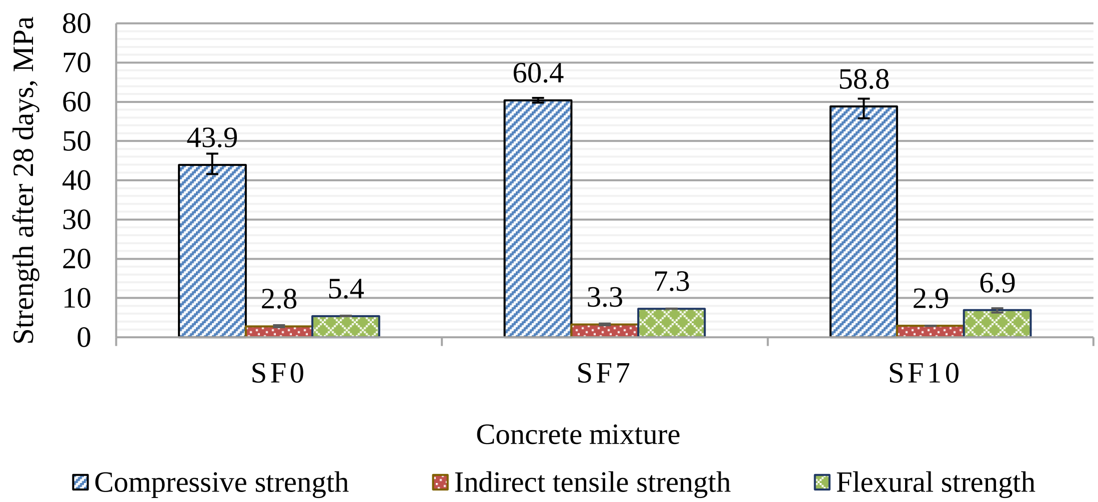

Fig. 4: Strength after 28 days of concrete mixtures containing different amount of silica fume.

3.3. Resistance to fatigue

Number of cycles when specimens containing different amount of silica fume failed depending on the initial strain is is given in Fig. 5. It can be seen that in general specimens fail faster as initial strain increases. To determine the fatigue equations for each concrete mixture, the data was fitted to the power regression model. A strong correlation was found for concrete with the highest amount of silica fume (SF10). Other two concretes also showed a moderate correlation, however data was much more scattered.

Table 2 presents the initial strain after 1,000,000 cycles that was calculated on the basis of fatigue equations. Overall, the addition of silica fume enhanced the resistance to fatigue by 21–45%. Concrete mixture with 7% silica fume showed the best behaviour; its initial strain after 1,000,000 cycles was the highest (42 με).

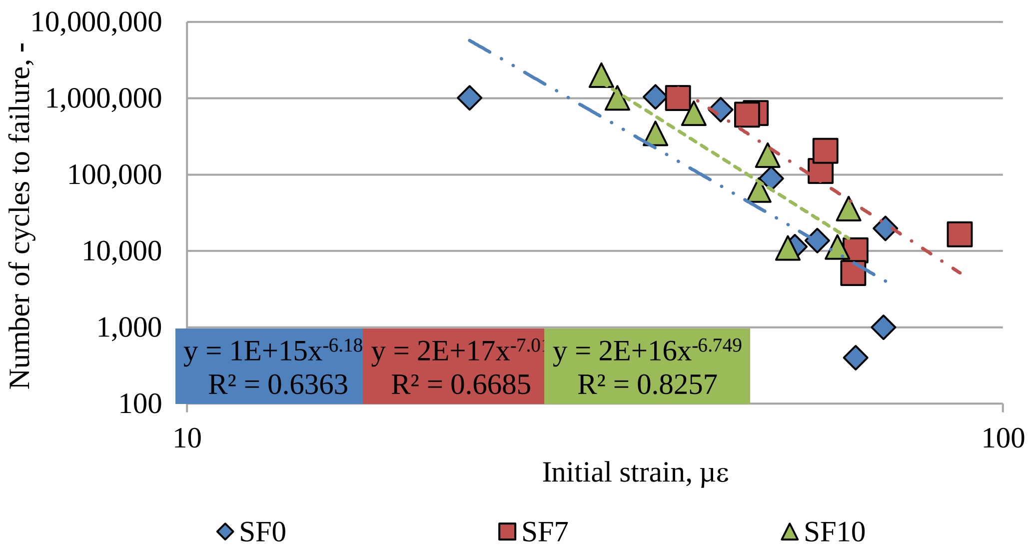

Fig. 5: Number of cycles to failure depending on the initial strain.

Table 2: Calculated initial strain after 1,000,000 cycles.

Mixture code	Initial strain after 1,000,000 cycles, με
SF0	29
SF7	42
SF10	35

4. Conclusions

The findings of this research indicates that silica fume significantly enhances the performance of high-strength concrete in terms of compression, tension, bending and cyclic loading and it may be related to the increased concrete density since about 5% denser microstructure of concrete was formed by the addition of silica fume. It happens because silica fume is rich in amorphous silica that reacts with lime present in cement.

The analysis of concrete mixture' behavior depending on the amount of silica fume showed that 7% is an optimal amount. It results in 37%, 16% and 35% higher strength in compression, tension and bending, respectively and 45% higher resistance to fatigue. An increase of silica fume up to 10% has almost the same effect on compressive strength; however, indirect tensile strength and flexural strength are 5–11% lower than those determined for concrete mixture containing 7% of silica fume.

The research has also shown that 7% addition of silica fume to the particle size distribution analyzed in this particular case lead to the saturation point (2.392 kg/m^3) and gave the compressive strength of 60.4 MPa, flexural strength of 7.3 MPa, indirect tensile strength of 3.3 MPa and initial strain after 1,000,000 cycles of 42 με. Meanwhile, further increase in silica fume content had negligible effect on density. Therefore, an optimal amount of silica fume depends on the particle size distribution and has to be determined in each case individually.

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