Influence of mixing procedure on mechanical properties of high-performance concrete

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Abstract. Mechanical parameters of cementitious composites are primarily determined by the composition of cement matrix. In case of high performance concrete (HPC), high-quality compounds and increased amounts of cement are exploited to obtain the best possible properties of the material. As these components are expensive, the aim is to use them with maximum efficiency. With optimized procedure of homogenization of compounds, parameters of concrete can be improved without changing the composition of the mix. Several mixing procedures were applied to a selected HPC mix. Compressive and flexural strength of particular batches were compared. The results showed that the compressive strength of HPC made of the same compounds can vary by almost 30% just due to amendments of the mixing procedure, while the flexural tensile strength was almost indifferent to the homogenization technique used.

1. Introduction
The exploitation of high-performance concrete (HPC) in real applications becomes more common in the recent years thanks to their extraordinary mechanical properties and durability. The limiting factor is still the unit price of the material which is in average four times higher than in case of normal strength concrete, mainly due to increased amount of cement and the use of high-quality compounds. Mechanical parameters of concrete can be influenced not only by the composition of the mix, but also by the way the compounds are mixed. The parameters of homogenization procedure, such as the type of the mixer, mixing speed, air pressure in the mixer, sequence of addition of the compounds, mixing times or temperature, can also affect the properties of both fresh and hardened concrete significantly, as shown in the detailed review carried out by Dils et al [1].

The main objective of the research presented in this paper was to compare the effect of selected parameters of the mixing procedure, namely the order of addition of the components and the mixing times, on compressive and flexural tensile strength of a selected HPC mix.

2. Experimental program
The experiments were carried out on 40x40x160 mm prismatic specimens that were subjected to four-point un-notched bending test according to ČSN EN 12390-5 standard [2]. The remnants of the specimens were used for compressive strength test according to ČSN EN 12390-3 [3]. The tests were performed in the age of 28 days. All the samples were made of the same mix (see table 1) and
prepared in the same mixer (standard laboratory concrete mixer, nominal volume of 80 liters, mix prepared at atmospheric pressure and room temperature).

Table 1. Composition of concrete mix.

| Component                        | Amount (kg.m⁻³) |
|----------------------------------|-----------------|
| Cement CEM I 42.5                | 650             |
| Water                            | 152             |
| Aggregate 0-4 mm                 | 1710            |
| Aggregate type                   | basalt          |
| Superplasticizer (polycarboxylate)| 27              |
| Silica fume                      | 80              |

Mixing procedures for mixes M1 to M5 differed according to tables 2 to 6. For mix M1, standard mixing procedure for HSC was used. At first, aggregate was homogenized, than cement was added, followed by silica fume and water with superplasticizer. In mix M2, silica fume was added before cement and mixing time of silica fume was extended from 180 s to 300 s. In case of mix M3, silica fume was added as the last component (after the water with superplasticizer). The mixing procedure of M4 mix was the same as standard (M1), but the mixing time of silica fume was increased from 180 s to 600 s. In the last mixture (M5), the effect of aggregate pre-wash (removal of dust by washing the aggregate by water) was tested. The mixing procedure was the same as standard with extended mixing time of silica fume (300 s).

Table 2. Mixing procedure – mix M1.

| Step            | Mixing time (s) |
|-----------------|-----------------|
| Aggregate       | 10              |
| Cement          | 60              |
| Silica fume     | 180             |
| Water + superplasticizer | 30        |

Table 3. Mixing procedure – mix M2.

| Step            | Mixing time (s) |
|-----------------|-----------------|
| Aggregate       | 10              |
| Silica fume     | 300             |
| Cement          | 60              |
| Water + superplasticizer | 30        |

Table 4. Mixing procedure – mix M3.

| Step            | Mixing time (s) |
|-----------------|-----------------|
| Aggregate       | 10              |
| Cement          | 60              |
| Water + superplasticizer | 30        |
| Silica fume     | 300             |
Table 5. Mixing procedure – mix M4.

| Step                  | Mixing time (s) |
|-----------------------|-----------------|
| Aggregate             | 10              |
| Cement                | 60              |
| Silica fume           | 600             |
| Water + superplasticizer | 30            |

Table 6. Mixing procedure – mix M5.

| Step                     | Mixing time (s) |
|--------------------------|-----------------|
| Aggregate (pre-washed)   | 10              |
| Cement                   | 60              |
| Silica fume              | 300             |
| Water + superplasticizer | 30              |

3. Results and discussion

Average flexural tensile strength and compressive strength of particular mixes is given in table 7. Plot in figure 1 presents the mean load-deflection curves from the bending test.

Table 7. Experimental results.

| Mix | Flexural tensile strength (MPa) | Flexural tensile strength relative to M1 (%) | Compressive strength (MPa) | Compressive strength relative to M1 (%) |
|-----|---------------------------------|---------------------------------------------|-----------------------------|----------------------------------------|
| M1  | 14.5                            | 100.0                                       | 156.9                       | 100.0                                  |
| M2  | 14.6                            | 100.7                                       | 164.3                       | 104.7                                  |
| M3  | 15.4                            | 106.2                                       | 142.0                       | 90.5                                   |
| M4  | 15.5                            | 106.9                                       | 119.0                       | 75.8                                   |
| M5  | 14.4                            | 99.3                                        | 121.1                       | 77.2                                   |

Figure 1. Load-deflection curves from the bending test.

The flexural behavior of materials was almost unaffected by the mixing procedure. Mix M5 had slightly lower elastic modulus than the remaining ones, but the variance of flexural strength of all the mixes was insignificant (less than 7%).
In case of compressive strength, the process of homogenization was found to have significant effect on the results. Mix M2 reached the best results. Comparison with mix M1 shows that it is more suitable to add the silica fume before cement. A possible explanation is that the silica particles covered the surface of aggregate grains and functioned as microfiller, leading to higher density and strength of the interfacial transition zone (ITZ) between the aggregates and cement paste. ITZ is the weakest part of the composite, therefore the improvement of ITZ may significantly enhance the overall characteristics of the composite. Another contributing factor might have been a phenomenon described by Mazanec et al. [4]. The gaps between the coarser cement grains and aggregate particles are normally filled by water. If small silica fume particles are present, they fill the gaps and the water which would otherwise have filled the gaps is used to reduce the friction between the particles. This leads to better compaction of the mix, higher bulk density and higher compressive strength.

When silica fume was added to the wet mix M3, compressive strength was lower by 10 % compared to M1, probably due to the fact that the silica fume could not be properly dispersed in the wet mix and clusters of silica fume grains were created. This result was anticipated by the authors, but the decrease in compressive strength was lower than expected.

Extending the mixing time of silica fume from 180 s to 600 s (mix M5) led to deterioration of compressive strength of hardened concrete, the decrease was almost 25 % in comparison with the basic mixing procedure (M1). This results was surprising, it was expected that the strength will be higher due to more thorough dispersion of the components in the mix, or the same at worst. The authors assume that longer mixing allowed silica fume particles to adsorb more water; this resulted in lack of water for the hydration of cement. Another possible explanation can be deduced from the finding of Schitzel et al. [5] who observed that the number of fine particles in the mix is raised by increased abrasion of the coarse aggregate when mixing time is extended. As a consequence, specific surface of aggregate is increased, leading to higher adsorption of water to the surface of aggregates, lower amount of water available for hydration of cement and reduced compressive strength. In any case, it can be clearly stated that extending the mixing time of silica fume above 300 s has no point as it only not only decreases the mechanical properties, but increases the consumption of energy, wear of the mixer and time required for preparation of fresh concrete at the same time.

In case that aggregate pre-wash was applied to remove the fine particles (mix M6), compressive strength was decreased. The authors expected an increase in compressive strength, but the effect of fines content in aggregate on concrete properties is a subject of constant debates. The fines content would increase the surface area and thus the water demand, but also increase the packing density. Hence, the fines content has both undesirable and desirable effects [6]. The mineralogy of fines is also important – if they are of a clay nature, their influence is negative, but silt type fines can function as mineral filler with positive effect [7]. Another important factor is the amount of fines; Topçu and Uğurlu [7] have shown that the content of 7 – 10 % of mineral filler (less than 0.15 mm) that is not of a clay type increases the compressive strength of concrete, while at 15 % dosage the effect becomes negative. The mineralogy and exact content of fines in the aggregate used in the experimental program presented in this paper were determined neither before nor after the aggregate pre-wash. This step should be undertaken in the future to clarify the observed negative effect of aggregate pre-wash.

4. Conclusions
The main conclusions of the work can be summarized as follows:

- Flexural tensile strength of HPC of the given composition seems to be almost indifferent to the mixing procedure applied, the variance of the results was 7 %.
- Compressive strength was significantly affected, the difference between the best and the worst results was almost 30 %.
- It was found that addition of silica fume before cement can increase compressive strength compared to the standard procedure when silica fume is added after cement.
• Extension of mixing time of silica from 300 s to 600 s led to significant reduction of compressive strength.
• Aggregate pre-wash did not lead to the expected improvement of material parameters. This result will be further analyzed.

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