Influence of Selected Factors on HPC Strength Properties

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Abstract. The paper presents the results of research, the objective of which was an evaluation of the influence of selected factors related to content on the resistance properties of high performance concrete. These factors were the water/binder ratio (W/S), the sand/binder ratio (P/S) and the PVA fibre content (Vf). An 18-point experiment plan was used. The mortars were made of the following ingredients: CEM I 52,5R cement, silica fume, silica sand, PVA fibres, polycarboxylate superplasticiser. The testing programme covered: tests of compressive strength per standard PN-EN 1015-11:2001 and tests of flexural strength per standard PN-EN 14651+A1:2007. Such an ingredient ratio was sought that will permit the achievement of the most advantageous strength properties (flexural strength and compressive strength). The conducted research shows that among the analysed factors, the greatest influence on flexural strength is exhibited by the content of PVA fibres. The highest values of flexural strength were achieved for a fibre content of Vf=3-3.7%. The addition of PVA fibres has lesser influence on compressive strength than the W/S ratio. The increase of the fibre content causes worsening of the workability of the concrete mix.

1. Introduction

HPC is a derivative of ordinary concrete achieved by way of modification of its ingredients in terms of quality and quantity, aimed at the reduction of disadvantages of ordinary concrete. High performance concrete is made of high-quality cement with a maintained low water/cement (water/binder) ratio and with the utilisation of highly effective chemical admixtures, mainly those influencing rheological properties (plasticisers and superplasticisers), mineral additives, in particular silica fume and fibres. The achievement of special properties of the concrete mix and the solidified HPC may require the use of other types of chemical additives as well, e. g. air-entraining admixtures, admixtures speeding up binding and hardening, etc.

HPC is most commonly defined as concrete with a compressive strength over 60 MPa determined after 28 days of curing. HPC, due to compressive strength, are subdivided as: UHPC > 150 MPa, VHPC 100-150 MPa, HPC 60-100 MPa.

The use of high performance concrete in structures brings with itself a range of advantages that permit the construction of multi-storey buildings. Thanks to the use of HPC, it is also possible to reduce the own load of a structure, while maintaining the load-bearing capacity of structural components. When designing the content of HPC the following technological assumptions must be used:
- the lowest possible W/C (W/S) ratio, for HPC 0.35-0.45, for VHPC 0.25-0.35,
- high-quality cement, of stable, repeatable properties, strength class ≥ 42.5,
- aggregate of very high mechanical strength and high quality (no contaminants in the form of dust),
- additives that aim at the sealing of micropores by filling the aggregate stack with a microfraction phase,
- improvement of tightness and filling of the zone at the paste-aggregate border, e.g. silica fume,
- use additives that strongly reduce the water content.

The additive most commonly used for HPC is silica fume. It modifies a range of properties both of the concrete mix as well as of the cured HPC (strength, porosity, watertightness, chemical aggression resistance). It is recommended to use silica fume as an ingredient in concrete, at 10% according to the cement mass.

Additionally, to improve the mechanical properties of HPC, several different types of fibres are used, e.g. steel [1-4], polypropylene [5-7], PVA fibre [8], glass [9] or carbon fibre for UHPC. For each type of fibre, there is an optimal amount [10]. The fibres cause an increase in compressive strength and flexural strength, a drop in the volume of microfractures emerging during loading, a reduction of initial contraction, a reduction in own stress inside fresh concrete. Of significant importance is also the shape of the fibres (straight, hooked, wavy) and the geometrical parameters of the fibres (length, diameter and sleekness).

The research of Bhosale et al. [11] shows that steel fibres exhibit better performance, followed by hybrid and macro-synthetic fibres. Steel fibres also provide higher toughness than the hybrid and macro-synthetic fibres for the same fibre dosage. The hybrid combination of steel and synthetic polyolefin fibres offers a very good solution for the improvement of the residual strengths at smaller crack openings. A hybrid combination of two different fibres of various mechanical and physical properties leads to a synergistic effect on the overall performance improvement at both service and ultimate states. The research of Abbass et al. [12] shows that the compressive strength of the concrete with a steel fibre content of 0.5 to 1.5% was slightly increased by no more than 10% for high strength concrete (W/C = 0.25), while for the moderately high strength concrete the increase in compressive strength reached 25%. The direct tensile strength of concrete increases to about 12% for the case of 0.5% fibre content and the length of 50 mm in high strength concrete (W/C = 0.25). Such an increase is higher and reaches 47% in the case of a 1.5% fibre content and the length of 60 mm in lower strength concrete (W/C=0.45). Badogiannis et al. [13] examined the influence of the use of steel and polypropylene fibres in the mechanical properties of lightweight concrete. Concerning the compressive strength, as concluded from the experimental results, both fibre types seemed to lead to a significant increase of the compressive strength, measured from 16% up to 76%, in comparison to plain concrete. For both steel and polypropylene fibres the magnitude of the compressive strength was found to be strongly dependent on the term $V_f*(l/d)$. On the other hand, in terms of the modulus of elasticity and Poisson’s ratio, the influence of fibre addition was proved to be rather negligible. As far as the flexural behaviour is concerned, all mixtures exhibited higher values of flexural strength, measured from 47% up to 110%, in comparison to plain concrete. As also observed in compressive strength, the flexural strength was found to be dependent on the term $V_f*(l/d)$.

The research of Teng et al. [14] shows that the double hooked-end steel fibres exhibit the best performance compared to the other fibres. An addition of 1.2% double hooked-end steel fibres resulted in an increase of up to 161% of the 28-day modulus of rupture and 43.3 times for the flexural toughness compared to those of the plain concrete. The substitution of double hooked-end steel fibres with another type of fibre caused a reduction in the flexural strength of concrete. The incorporation of polyvinyl alcohol (PVA) fibres substantially reduced the flexural performance of the fibre-reinforced concrete specimens, even though these specimens with PVA fibres still show better performance when compared to similar concrete specimens without fibres. The tensile strength, length, modulus of elasticity, and the particular anchorage shape of the double hooked-end steel fibres are parameters that remarkably affect the properties of the resulting fibre-reinforced concrete.

The three main roles of polypropylene fibre in PFRC lie in improving strength, toughness and resistance to split effect of concrete. First, the strength-reinforced effect is seen in the improvement of
tensile strength, flexural strength and shear strength. Second, the toughness enhancement embodies the post-cracking residual strength. Third, split resistance reflects the bridging joint action and cohesive action between polypropylene fibre and concrete matrix [15].

The total crack width and the number of cracks decrease when 1% synthetic fibre is added to the concrete mix. At a specific load, higher amounts of synthetic fibres reduce the beams’ mid-span deflection [16]. Studies by Khan and Ali [17] show that compared to a control mix, the compressive, flexural and splitting-tensile strengths of hair fibre-reinforced concrete are improved by 12.4%, 16.2% and 19.1%, respectively, and that those of wave polypropylene fibre reinforced concrete are increased by 11.7%, 21.5% and 17.5%, respectively.

Research by Wang [18] shows that compared to HPC without fibre, the flexural strength of HPC reinforced with a single fibre was increased by 1.1%-24.5%, and the splitting tensile strength was increased by 21.9%-44.5%; the effect of polypropylene fibre on the flexural strength and splitting tensile strength of HPC is superior to that of basalt fibre. The research of Falliano et al. [19] as well as Wu et al. [20] shows that the addition of fibres had a slight impact on compressive strength, but significantly increased flexural strength and splitting tensile strength.

A high volume of fibre used (1-1.5%) can cause problems with even mixing of ingredients, the blocking of fibre, etc. Mixes with a lower yield limit and elastic viscosity, hence, lower stability, exhibit an increased tendency to segregate and settle. The research of Ayub et al. [21] shows that the optimum compressive strength at 2% basalt fibre volume is higher, whereas at 3% fibre volume compressive strength reduced probably due to the presence of voids caused by the use of higher fibre volume of basalt fibres. Baričević et al. [22] concluded that a higher superplasticiser content at higher fibre dosages, for the same workability class, showed that fibres decrease workability of fresh concrete.

The paper presents the results of research, the object of which was an evaluation of the influence of selected factors related to the content on the strength properties of high performance concrete. These factors were the water/binder ratio (W/S), the sand/binder ratio (P/S) and the PVA fibre count (V_f).

2. Materials and Methods

The testing programme covered the preparation of 18 mortar samples. The objective of the research was the evaluation of influence of the water/binder ratio (W/S), the sand/binder ratio (P/S) and the PVA fibre count (V_f) on strength properties of high performance concrete. The W/S ranged between 0.22 and 0.35, the sand/ binder ratio ranged from 0.8 to 1.2, and the fibre content was between 0.3 and 3.7%.

An 18-point plan was assumed, wherein the investigated factors were: X1 – water/binder ratio W/S; X2 – sand/binder ratio P/S; X3 – PVA fibre content; V_f. Code values of the variables:

\[
X_1 = (W/S-0.3)/0.05 \\
X_2 = (P/S-1.0)/0.1 \\
X_3 = (V_f-2.0)/1.0
\]

The coded and real values of the studied factors are shown in table 1.
Table 1. Coded and real values of investigated factors.

| No. | X1  | X2  | X3  | W/S | P/S | Vf |
|-----|-----|-----|-----|-----|-----|----|
| 1   | 1   | 1   | 1   | 0.35| 1.1 | 3  |
| 2   | 1   | 1   | -1  | 0.35| 1.1 | 1  |
| 3   | 1   | -1  | 1   | 0.35| 0.9 | 3  |
| 4   | 1   | -1  | -1  | 0.35| 0.9 | 1  |
| 5   | -1  | 1   | 1   | 0.25| 1.1 | 3  |
| 6   | -1  | 1   | -1  | 0.25| 1.1 | 1  |
| 7   | -1  | -1  | 1   | 0.25| 0.9 | 3  |
| 8   | -1  | -1  | -1  | 0.25| 0.9 | 1  |
| 9   | -1.682 | 0  | 0   | 0.22| 1.0 | 2  |
| 10  | 1.682 | 0   | 0   | 0.38| 1.0 | 2  |
| 11  | 0   | -1.682 | 0  | 0.30| 0.8 | 2  |
| 12  | 0   | 1.682 | 0   | 0.30| 1.2 | 2  |
| 13  | 0   | 0   | -1.682 | 0.30| 1.0 | 0.3|
| 14  | 0   | 0   | 1.682 | 0.30| 1.0 | 3.7|
| 15  | 0   | 0   | 0   | 0.30| 1.0 | 2  |
| 16  | 0   | 0   | 0   | 0.30| 1.0 | 2  |
| 17  | 0   | 0   | 0   | 0.30| 1.0 | 2  |
| 18  | 0   | 0   | 0   | 0.30| 1.0 | 2  |

The relationship is described by the regression function in the form of an incomplete second degree polynomial:

\[ y = a_0 + a_1 \cdot X1 + a_2 \cdot X2 + a_3 \cdot X3 + a_{12} \cdot X1 \cdot X2 + a_{13} \cdot X1 \cdot X3 + a_{23} \cdot X2 \cdot X3 \]  (1)

A measure of adaptation of the function to the measurement results is the correlation coefficient R. On the basis of the experiment, it is possible to determine the relationship between the analysed factors X1, X2, X3 and a specific property of concrete.

The following materials were used in the tests:
- CEM I 52,5R cement,
- silica fume,
- quartz sand 0.1-0.5 mm,
- PVA fibre (length 12 mm, diameter 38 μm, density 0.9 g/cm³),
- polycarboxylate superplasticiser.

The mortar mixes did not require compaction. The execution of the investigation saw the preparation of samples sized at 4 x 4 x 16 cm. After forming, the samples were placed for 24 hours in a chamber over water under a cover at 20 °C ± 2 °C. Then, the samples were extracted from moulds and placed for 48 hours in a thermal chamber, in water, at 65 °C ± 2 °C. Upon extraction from the chamber, the samples were cured over up to 28 days in laboratory conditions, at 20 °C ± 2 °C and 65% ± 5% humidity.

The testing programme covered:
- tests of compressive strength per PN-EN 1015-11:2001 [23],
- tests of flexural strength per PN-EN 14651+A1:2007 [24].

Testing of flexural strength was carried out on three samples using a hydraulic press connected to a computer with special software. Three-point bending test was performed to measure the flexural strength \( f_{cf} \) of the beams.

The compressive strength tests were carried out on a hydraulic press with an inlay to study the standard strength of mortar. Samples were used (six half-beams) that were subject to the flexural strength test. Half of a sample was placed in the press so that the centre of the compression surface
overlapped with the centre of the half-sample (Figure 1). In this way, two results were obtained for each sample.

![Figure 1. Strength tests of the beams.](image)

### 3. Results and discussions

Table 2 shows the results of determination of flexural strength and compressive strength for 18 mortar samples. The regression and correlation coefficients are shown in Table 3. Figure 2 shows the influence of the W/S ratio and the addition of PVA fibres (Vf) on flexural strength fcf, and Figure 3 shows the influence of the W/S ratio and the addition of PVA fibres (Vf) on compressive strength fcm.

| Series | fcf MPa | Standard deviation SD | fcm MPa | Standard deviation SD |
|--------|---------|-----------------------|---------|-----------------------|
| 1      | 12.1    | 1.52                  | 99.4    | 3.70                  |
| 2      | 6.0     | 2.35                  | 108.1   | 3.54                  |
| 3      | 9.0     | 1.11                  | 98.8    | 2.83                  |
| 4      | 7.2     | 0.15                  | 108.8   | 3.39                  |
| 5      | 11.4    | 1.94                  | 110.0   | 2.51                  |
| 6      | 5.3     | 0.64                  | 105.3   | 2.30                  |
| 7      | 12.8    | 0.12                  | 110.9   | 3.96                  |
| 8      | 4.7     | 0.93                  | 110.1   | 2.81                  |
| 9      | 10.9    | 1.16                  | 109.2   | 3.17                  |
| 10     | 5.3     | 1.43                  | 99.3    | 3.82                  |
| 11     | 8.2     | 1.24                  | 100.9   | 1.38                  |
| 12     | 8.6     | 1.07                  | 102.2   | 2.39                  |
| 13     | 4.4     | 0.90                  | 93.5    | 3.76                  |
| 14     | 16.2    | 3.16                  | 113.7   | 3.88                  |
| 15     | 7.2     | 1.89                  | 97.4    | 2.46                  |
| 16     | 6.1     | 0.38                  | 104.2   | 4.42                  |
| 17     | 7.3     | 1.22                  | 102.3   | 2.73                  |
| 18     | 7.7     | 1.36                  | 103.7   | 3.08                  |

The achieved flexural strength fits in the range between 4.4 to 16.2 MPa and compressive strength in the range from 93.5 to 113.7 MPa. Among the analysed factors, the greatest influence on flexural strength was exhibited by the PVA fibre content. For the addition of fibre at 1%, flexural strength is between 4.7 and 7.2 MPa, an increase of fibre content to 2% causes an increase of flexural strength to a level of 5.3-10.9 MPa. A fibre content of 3% permits the achievement of flexural strength between
9.0 and 12.8 MPa. The lowest flexural strength value of 4.4 MPa was achieved for mortar no. 13, which had the lowest fibre content (0.3%), and highest (16.2 MPa) for mortar no. 14, which had the highest fibre content (3.7%). It must be considered, however, that an increase in fibre content causes a reduction of the workability of the concrete mix.

The addition of PVA fibres has a smaller effect on compressive strength than the W/S ratio. The volume of sand (P/S ratio), the fibre volume (Vf) and the W/S ratio influence the concrete mix texture. For samples with a fibre content of Vf=3% for W/S=0.35, observed was compressive strength reduced probably due to the presence of voids caused by the use of higher fibre volume. This confirms the conclusions of other researchers.

Figure 4 shows the relationship between compressive strength and flexural strength of mortar samples. The analysis of the obtained results shows that there is no simple relationship between the investigated strength properties.

The diversified air content and the random distribution of fibres in the samples greatly influences their strength properties.

| Table 3. Derived regression and correlation R coefficients. |
|-----------------------------------------------------------|
| Variable | Regression coefficient |
|          | f_cf MPa | f_cm MPa |
| A:W/S   | -0.63     | -2.78    |
| B:P/S   | 0.20      | -0.26    |
| C:Vf    | 3.02      | 1.51     |
| AB      | 0.23      | 0.71     |
| AC      | -0.69     | -3.03    |
| BC      | 0.39      | 0.65     |
| R       | 0.80      | 0.50     |

Figure 2. Influence of the W/S ratio and the addition of PVA fibres (Vf) on flexural strength $f_{cf}$. 
**Figure 3.** Influence of the W/S ratio and the addition of PVA fibres ($V_f$) on compressive strength $f_{cm}$.

**Figure 4.** Relationship between compressive strength and flexural strength.

### 4. Conclusions

On the basis of the analysis of the test results for 18 mortar samples with different PVA fibre content, water/binder ratio and sand/binder ratio values, the following conclusions were formulated:

1. Among the analysed factors, the greatest influence on flexural strength is exhibited by the PVA fibre content. Highest flexural strength values were obtained for a fibre content of $V_f=3-3.7\%$.
2. The addition of PVA fibres has lesser influence on compressive strength than the W/S ratio.
3. For samples with a fibre content of $V_f=3\%$ for W/S=0.35, observed was a reduction of compressive strength probably due to the presence of voids caused by the use of higher fibre volume.

4. An increase of fibre content causes worse workability of the concrete mix.

5. An analysis of the obtained results of compressive strength and flexural strength tests shows that there is no simple dependence between the investigated strength properties.

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