Effect of Curing Period on Properties of Steel and Polypropylene Fibre Reinforced Ultra-High Performance Concrete

Piotr Smarzewski
Lublin University of Technology, 40 Nadbystrzycka, 20-618 Lublin, Poland
p.smarzewski@pollub.pl

Abstract. This study has investigated the effect of curing period on the mechanical properties of straight polypropylene and hooked-end steel fibre reinforced ultra-high performance concrete (UHPC). Various physical properties are evaluated, i.e. absorbability, apparent density and open porosity. Compressive strength, tensile splitting strength, flexural strength and modulus of elasticity were determined at 28, 56 and 730 days. Comparative strength development of fibre reinforced mixes at 0.5%, 1%, 1.5% and 2% by volume fractions in relation to the mix without fibres was observed. Good correlations between the compressive strength and the modulus of elasticity are established. Steel and polypropylene fibres significantly increased the compressive strength, tensile splitting strength, flexural strength and modulus of elasticity of UHPC after two years curing period when fibre content volume was at least 1%. It seems that steel fibre reinforced UHPC has better properties than the polypropylene fibre reinforced UHPC.

1. Introduction
Ultra-high performance concrete (UHPC) is characterized by compressive strength above 120 MPa and high durability [1]. It is a known fact that the properties of concrete are improved with the addition of fibres [2]. The fibres added to the UHPC may overcome the limitations resulting from its low tensile strength and low ductility [3]. The polypropylene fibres are used to improve mechanical and physical properties, especially tensile splitting strength, flexural strength and long-term concrete shrinkage. The steel fibre is generally used for most structural purposes [4,5]. A lot of research revealed that the steel fibre in concrete could make effectively improve the interfacial transition zone between cement paste and aggregate, and constraint the occurrence and development of concrete crack [6-8]. A main advantage of steel fibre reinforced concrete is high energy absorption capacity and high toughness. The steel fibres are able to bridge the cracks and transfer the stress across the cracks. There are a lot of problems which need to be solved during the design and construction of fibre reinforced ultra-high performance concrete. The influence of the fibre content and the curing period on the physical and mechanical properties of steel and polypropylene fibre reinforced UHPC were studied by some researchers [9]. Nevertheless, no investigation in the literature is currently available on the properties of UHPC with steel or polypropylene fibres after long-term curing period.

The purpose of this study is to evaluate the effect of polypropylene or steel fibre volume content at two years of curing on the mechanical properties of UHPC. The investigations will help to answer the question whether delayed hydration of cement in the long-term curing period can affect the mechanical properties of the fibre reinforced UHPC.
2. Experimental program

2.1. Materials, mixtures, samples preparation

Portland cement CEM I 52.5 N-HSR/NA 670.5 kg/m³, silica fume 74.5 kg/m³, quartz sand 0/2 mm 500 kg/m³, basalt aggregate 2/16 mm 990 kg/m³, water 178 l/m³, superplasticizer 20 l/m³, polypropylene and steel fibres were used in the UHPC mixtures. A superplasticizer based on polycarboxylate ethers was applied in the amount of 1.5% in relation to the weight of cement and silica fume. The straight polypropylene fibres properties have the following parameters: length 12 mm, diameter 25 µm, density 0.9 g/cm³, tensile strength 0.35 GPa, modulus of elasticity 3.5 GPa. The hook-end steel fibres characteristics are: length 50 mm, diameter 1 mm, density 7.8 g/cm³, tensile strength 1.1 GPa, modulus of elasticity 200 GPa. These fibres are shown in figure 1.

Figure 1. a) Polypropylene fibres (PP), b) steel fibres (S).

The abbreviated concrete type and quantities of polypropylene (PP) and steel (S) fibres for various batches are displayed in table 1.

| Concrete type | C0 | CPP0.5 | CPP1 | CPP1.5 | CPP2 | CS0.5 | CS1 | CS1.5 | CS2 |
|---------------|----|--------|------|--------|------|-------|-----|-------|-----|
| Percentage (%)| –  | 0.5    | 1.0  | 1.5    | 2.0  | 0.5   | 1.0 | 1.5   | 2.0 |
| Mass (kg/m³)  | –  | 4.5    | 9.0  | 13.5   | 18.0 | 39.0  | 78.0| 117.0 | 156.0|

The mixtures were prepared using a concrete mixer. The basalt and sand were homogenized with a half of the amount of water. Afterwards, silica fume, cement, the remaining water and superplasticizer were added. At the end, polypropylene or steel fibres were applied by hand. Each of mixture was blended for 5 min at a high speed of mixer to provide homogeneity of the fibres in UHPC. When all the ingredients were thoroughly mixed, moulds coated with an anti-adhesive substance were filled and compacted on a vibrating table, and after that, the samples were covered with foil to minimize the loss of moisture. They were stored in moulds for 24–48 hours at a temperature of 20 °C ± 2 °C. Until demoulding, the samples were placed in a water tank for 14 days at 20 °C ± 2 °C, and at about 100% relative humidity. After this time, the samples were kept in constant room temperature in a laboratory environment.

2.2. Test methods

Tests of the apparent density, open porosity and wettability were carried out on cubic samples with sides of 100 mm in accordance with EN 12390-7:2009 and EN 13755:2008.

Strength tests were conducted in a Walter-Bai AG and Controls hydraulic presses within 3 MN, at 28, 56 ± 2, 730 ± 7 days of curing. The compressive strength test was realized on the basis of EN 12390-3:2002 (figure 2a) on nine cubes with the dimensions 100×100×100 mm, while the tensile splitting strength test was performed according to the recommendations in standard EN 12390-6:2011 (figure 2b) on nine cubes with sides of 100 mm. The flexural strength was carried out according to EN 12390-5:2011 normative. Nine beams 50×63×350 mm (for each of C0, CS series) and nine beams with the dimensions 50×50×250 m (CPP series) were centrally loaded (three-point bending test) at a rate of 0.05 MPa/s (figure 2c).
3. Results and discussion

3.1. Physical properties

The obtained average results of the absorbability, apparent density and open porosity are shown in Table 2.

| Concrete type | C0 | CPP0.5 | CPP1 | CPP1.5 | CPP2 | CS0.5 | CS1 | CS1.5 | CS2 |
|---------------|----|--------|------|--------|------|-------|-----|-------|-----|
| Absorbability (%) | 0.6 | 0.9 | 0.9 | 0.8 | 0.7 | 1.8 | 2.0 | 2.1 | 2.5 |
| Apparent density (g/cm³) | 2.56 | 2.41 | 2.37 | 2.30 | 2.27 | 2.50 | 2.54 | 2.58 | 2.60 |
| Open porosity (%) | 4.3 | 4.7 | 4.0 | 3.9 | 3.8 | 4.6 | 5.1 | 5.5 | 5.7 |

The results show that the increase in volume content of polypropylene fibres (from 0.5 to 2%) has an influence on the increase in absorbability and the decrease in density of UHPC. The addition of 0.5 and 1% PP fibres causes the highest increase in absorbability by 33%. The decrease in density is from 6 to 11%. Above 0.5% PP fibre content, the decrease in open porosity was noted within the range of 7-12%. On the other hand, the increase in volume content from 0.5 to 2% of steel fibres affects the increase in UHPC absorbability – from 27 to 48%, and open porosity – from 7 to 25%. The increase in density by 2% was observed above 1.5% of steel fibre content. It was found that the increase in volume content of steel fibres causes a gradual increase in absorbability, density and open porosity. Micro-cracks formed...
in transition zone and weaker adhesion between the fibres and cement paste affected the increase in absorbability of fibre reinforced UHPC.

3.2. Mechanical properties

Figure 3 shows the average compressive strength determined at 28, 56 and 730 days.

![Figure 3](image)

**Figure 3.** Average compressive strength at 28, 56 and 730 days of curing

An adverse effect of the addition of polypropylene fibres on compressive strength at 28 and 56 days can be found. The polypropylene fibre volume content from 0.5% to 2% results in the compressive strength decrease from 6 to 19% compared to the compressive strength of plain UHPC at 56 days. The addition of steel fibres above 1.5% resulted in the compressive strength increase from 3 to 7% at 56 days compared to the plain UHPC. It can be seen that the differences are minor and are within the limits of statistical error. Therefore, the steel fibres do not affect the compressive strength of UHPC. On the other hand, the beneficial effect of the curing period on the compressive strength of UHPC with a fibre volume content of at least 1% can be seen. The increase in compressive strength at 730 days ranged from 16 to 25% compared to the strength at 56 days that was observed. Such a high increase in the compressive strength of UHPC after 730 days of curing when the fibre content was at least 1% can be explained by delayed hydration of the cement, mainly at the interface of the fibres and the cement mortar, and the improvement the adhesion properties.

The tensile splitting strength of the UHPC was determined at 28, 56 and 730 days of curing. Figure 4 shows the effects of fibre content and curing period on the average tensile splitting strength of the UHPC.

The average tensile splitting strength decreases with increasing addition of the polypropylene fibres regardless of the UHPC curing period. However, the strength increases with a higher content of steel fibres up to 1.5%. The concrete without fibres at 730 days obtained a tensile splitting strength which was 15% higher than at 28 days. An increase in strength by 7% for CPP0.5 and 20% for CS1, CS1.5, and CS2 at 730 days of curing can be seen, compared to the strength at 56 days.
Figure 4. Average splitting tensile strength at 28, 56 and 730 days of curing

The flexural strength and the elastic modulus of UHPC were determined at 28, 56 and 730 days. The average results are illustrated in figures 5 and 6.

Figure 5. Average flexural strength at 28, 56 and 730 days of curing
The average flexural strength decreases with increasing addition of the polypropylene fibres at 28 days. However, with an increasing addition of fibres the flexural strength significantly increased at two years of curing. An increase in flexural strength from 3% for CS0.5 to 23% for CS2 at 730 days of curing is visible, compared to the strength at 56 days. Very large variations in flexural and tensile splitting strength of UHPC containing fibres 1.5 and 2% can be observed. These errors can be caused by random orientation of fibres. The addition of PP fibres resulted in the increase of elastic modulus after two years of curing. It can be observed that the differences are minor. Therefore, the fibres do not affect the UHPC modulus of elasticity.

The relationships between the compressive strength and modulus of elasticity for UHPC with polypropylene fibres and steel fibres are shown in figure 7. These correlations are presented in the form of the polynomial $ax^2 + bx + c$. The high correlation coefficients equal to 0.91 and 0.86 indicate that the data have been matched by the best $R^2$ value. A higher correlation coefficient values indicate that
modulus of elasticity has a strong association with compressive strength. There is a clear grouping of the results depending on the curing period.

4. Conclusions

Based on the results and analysis presented in this paper, the following conclusions can be drawn:

- The fibre volume content of at least 1% in ultra-high performance concrete significantly increased the compressive strength, tensile splitting and flexural strength, and elastic modulus after two years of curing period. This can be explained by delayed hydration of the cement and the improvement the adhesion properties between the fibre and cement mortar.
- Good correlations between the compressive strength and modulus of elasticity for the fibre reinforced ultra-high performance concrete are established. The results depend on the curing period. It observed that the results for UHPC with highest content of steel fibres differ significantly from other results.

Acknowledgments

This work was financially supported by Ministry of Science and Higher Education – Poland, within the statutory research number S/15/B/1/2017.

References

[1] fib, Structural Concrete, “Textbook on behaviour, design and performance,” 2nd edn, vol. 1, fib Bulletin 51, fédération internationale du béton, Lausanne, 2009.
[2] A. M. Brandt, “Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering,” *Compos. Struct.*, vol. 86, pp. 3–9, 2008.
[3] P. Smarzewski, and D. Barnat-Hunek, “Property Assessment of Hybrid Fibre-Reinforced Ultra-High-Performance Concrete,” *Int. J. Civ. Eng.*, pp. 1–14, 2017, DOI 10.1007/s40999-017-0145-3.
[4] S. J. Foster, “The application of steel-fibres as concrete reinforcement in Australia: from material to structure,” *Mater. Struct.*, vol. 42(9), pp. 1209–1220, 2009.
[5] D. M. Özcan, A. Bayraktar, A. Şahin, T. Haktanir, and T. Türker, “Experimental and finite element analysis on the steel fibre-reinforced concrete (SFRC) beams ultimate behavior,” *Constr. Build. Mater.*, vol. 23(2), pp. 1064–1077, 2009.
[6] M. Nili, and V. Afroughsabet, “Property assessment of steel-fibre reinforced concrete made with silica fume, *Constr. Build. Mater.*, vol. 28(1), pp. 664–669, 2012.
[7] M. Pająk, and T. Ponikiewski, “Effect of the shape of steel fibres on the mechanical properties of reinforced self-compacting concrete,” *Cement Lime Concrete*, vol. 18, pp. 335–342, 2013.
[8] V. Afroughsabet, and T. Ozbakkaloglu, “Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibres,” *Constr. Build. Mater.*, vol. 94, pp. 73–82, 2015.
[9] H. S. Arel, “Effects of curing type, silica fume fineness, and fibre length on the mechanical properties and impact resistance of UHPFRC,” *Results in Physics*, vol. 6, pp. 664–674, 2016.