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Methodology of Analysis of Fibre Sedimentation in HPC mixtures

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The aim of this work is to propose a methodology for evaluating inhomogeneity due to the sedimentation of fibres in High-Performnce Concrete (HPC) mixtures. HPC mixtures makes better mechanical-physical properties than ordinary concrete. To achieve higher strengths, the fine-grained matrix is reinforced with the reinforcement – fibres. The type of used fibres and their homogenization in mixture has an influence on the final mechanical properties of HPC mixture. Four concrete mixtures with same component proportion was chosen for experiments. Water was the only one component, that was changing in mixture recipes. Steel fibres with a ratio of the diameter to length = 0.3/20 were used as reinforcement. The fibre volume in mixture was 1.5 %. The microscopy analysis was used for evaluation of the fibre distribution in the test specimens. It was obtained, that the concentration of the fibres increases with distance from the surface to the bottom of the HPC structure and this non-homogeneity increases with higher water dosage. The dependence of sedimentation of fibres on composition of HPC mixtures can be used for evaluation and optimization of final mechanical properties of the HPC structures.

Keywords: HPC mixtures, Steel fibres, Sedimentation, Fibres distribution

1 Introduction

Fine-grained cementitious composites (High Performance Concrete HPC and Ultra-High Performance Concrete UHPC) are one of the most recently developed concrete mixtures. HPC mixtures belongs among the most modern material used in the construction industry (e.g. bridges, highways, buildings, industrial structures etc. [1]), Chillon Viaducts [2], pedestrian footbridge Passerelle des Anges [3], footbridge at Tabor [4] and recently finished Holešovice – Karlín Footbridge in Prague [5].

The HPC mixtures shows better mechanical-physical properties (high strength, high density high workability, low permeability and high resistance to chemical attack) than ordinary concrete mixtures. Mechanical properties of the HPC mixtures and its determination are well described in the literature, for example [6–9]. HPC mixtures are composed of fine aggregate, silica fume, slag, cement, water and superplasticizer. To achieve higher strengths, the fine-grained matrix is reinforced with the reinforcement – fibres. Fibres used in HPC mixtures are made from various materials (steel, glass, carbon, polypropylen, natural fibres etc.) [10-11]. The fibres has also different shape and size. Steel fibers used as reinforcement are the most studied type of fibers in HPC mixtures. Influence of the steel fibres contents, shape and size on the mechanical properties is described in literature e.g. [12-19]. Polypropylene fibres are used as reinforcement in HPC mixtures to enhance higher mechanical properties, toughness, shrinkage properties and impact resisence. On the other hand, the properties of these fibres are influenced by temperature. Mechanical properties od HPC mixtures with polypropylene fibres exposed to high temperature are shown in [20-22]. In recent years, the natural fibres are also used as reinforcement of the HPC mixtures due to the recyclability, e.g. [23-27]. In literature are also mentioned comparative studies describing mechanical properties of HPC mixtures with diffrent fibres [28-32]. It is evident that properties of the HPC mixtures, both at fresh and hardened state, depends not only on mixture composition but also on type of used dispersed fibres and production technology of HPC structures.

Fibres used in HPC mixtures has impact on rheology and workability of fresh state of these mixtures. The content of the fibres used in HPC mixtures is chosen according to this bondary conditions. During hardening, the fibres having high density settle due to gravity. As a result of this sedimentation, there is an inhomogeneous distribution of fibers in the HPC structure. Data mentioned in literature and our practical experiences obtained during experimental tests held in laboratories of the Klokner Institute CTU in Prague [33-35] shows that the final mechanical properties of HPC structures depend not only on mixture composition but also on homogeneity of the fibre distribution. Due to this, the compaction of HPC mixture is reduced during production of HPC elements to prevent fibre segregation. Non-homogeneity of fibre distribution and its concentration at specific areas leads to several problems of structure elements. Areas with minimum or without non-uniform reinforcing (fibres) cause structure deformation (e.g. cracks). These areas have a critical impact on load bearing capacity of elements that is impacted by homogeneity of the fibre distribution and orientation of the fibres. It is evident that final mechanical properties of the HPC structures (e.g. compressive strength, modulus of elastic, tensile strength and especially residual tensile and bending strength) depend on the fibre homogeneity in the structure. Influence of the fibres distribution on mechanical properties of the HPC mixtures could be both positive [33], and negative [36].

The aim of this work was focused on the design of methods describing the sedimentation of non-spherical particles in High-Performance Concrete (HPC) mixture during hardening concrete structure casted from this mixture. Four HPC concrete mixtures were used for the experiments. Water content was the only one component, that was changing in mixture recipes. Other components content were same. Steel fibres with a ratio of d/l = 0.3/20 were used as reinforcement in the experimental HPC mixtures. The fibre volume in mixtures was 1.5 %. The laser confocal microscope Olympus LEXT OLS 3000 was used for sedimentation monitoring. Two methodologies for evaluating the distribution of fibers in the HPC structure have been proposed and experimentally verified.

2 HPC sample preparation

Four HPC concrete mixtures (A, B, C and D) were used for the experiments. Content of the dry components (cement, silica fume, slag and aggregate), supesplasticizer and steel fibres was same for all HPC mixtures. Water content was the only one component, that was changing in mixture recipes. For the proposing of the methodology were prepared same mixtures in different days (January 9, 2023, April 12, 2023 and September 14, 2023).

As part of the experiments, material developed at the Klokner Institute classified as HPC (UHPC) was used for the experiments. To simplify the preparation of the fresh material that is the subject of this research, the dry components (cement, silica fume, slag and aggregate) were mixed by an external company and stored in an airtight bags. For the experiments, siliceous aggregate fraction 0.063-0.63 mm, siliceous aggregate fraction 0.63-1.2 mm, CEM II 52.5 N with strength 52.5 MPa after 28 days of the hardening were used. Scattered steel fibres with ratio d/l = 0.3/20 were used as reinforcement of the HPC mixtures. Water content was in the range from 160 kg/m^3 to 210 kg/m^3. This range was chosen due to the required behavior of the HPC mixture. Fibers sedimentation occurs in HPC mixtures with minimal value of the yield stress 5 Pa. From the previous experiments [37] it was established that this minimum yield stress value occurs at water content 160 kg/m^3. Maximal water content 210 kg/m^3 was chosen so that the HPC mixture was still workable and usable for the real HPC structures. Mixtures compositions described by mass concentration of all components, i.e. the mass of component related to the total volume of the mixture is shown in Tab 1.

Tab. 1 *Mixtures compositions described by mass concentration of all components*

Component	A	B	C	D	unit
Siliceous aggregate fraction 0.063-0.63 mm	486	486	486	486	kg of component/m^3
Siliceous aggregate fraction 0.63-1.2 mm	739	739	739	739	kg of component/m^3
CEM II 52.5 N	700	700	700	700	kg of component/m^3
Microsilica	100	100	100	100	kg of component/m^3
The finely ground slag	80	80	80	80	kg of component/m^3
Water	**160**	**180**	**190**	**210**	**kg of component/m^3**
Superplasticizer	40	40	40	40	kg of component/m^3
Scattered steel reinforcement d/l = 0.3/20	120	120	120	120	kg of component/m^3

For the production of fresh HPC material, the required amount of components was prepared on laboratory scales, specifically the mentioned dry component, water, superplasticizer and steel fibers. A planetary laboratory mixer designed for mixing cement pastes and mortars was used to mix the components. The standard procedure for mixing fine-grained HPC was followed. Water and superplasticizer were added to the dry component. After the activation of the superplasticizer and subsequent liquefaction of the material, the steel fibres was added. Mixing of the material with the steel fibres took place for a one minute. It means, the homegenisation of the steel fibres in the entire volume was obtained.

After mixing the material, fresh HPC tests such as consistency test and temperature determination were performed. The workability of the fresh HPC mixtures was measured by a small mortar cone (Haegerman cone). Used Haegerman cone and spiled sample as the measuremnt test result is shown in Fig. 1. Average values of the workability of HPC mixtures prepared on September 14, 2023 are shown in Tab. 2. Illustration of the consistency test is shown in Fig. 2. The larger the diameter of the spilled sample, the less viscous the mixture is, and this will result in more sedimentation of particles during hardening of the HPC mixture.

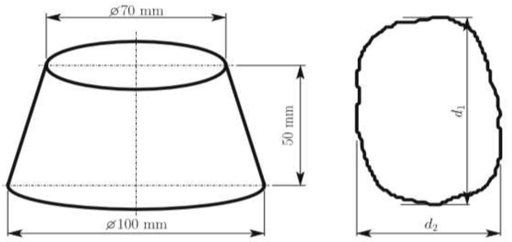

Fig. 1 *Mini-flow desk test – the Haegermann cone (left), a spilled sample as the measurement test result (right) [37]*

The fresh HPC mixture was poured into prepared molds for the production of the test specimens – see Fig. 3. The dimensions of the produced test specimens were 100 x 100 x 100 mm. The test specimens prepared in this way were stored in the laboratory under constant conditions of temperature and humidity. Samples were hardened for 28 days. After 28 days, the test samples were removed from the molds and prepared for monitoring of the steel fibres sedimentation in HPC mixtures. During the production of the test specimens, the ambient temperature and humidity values were recorded (see Tab. 3).

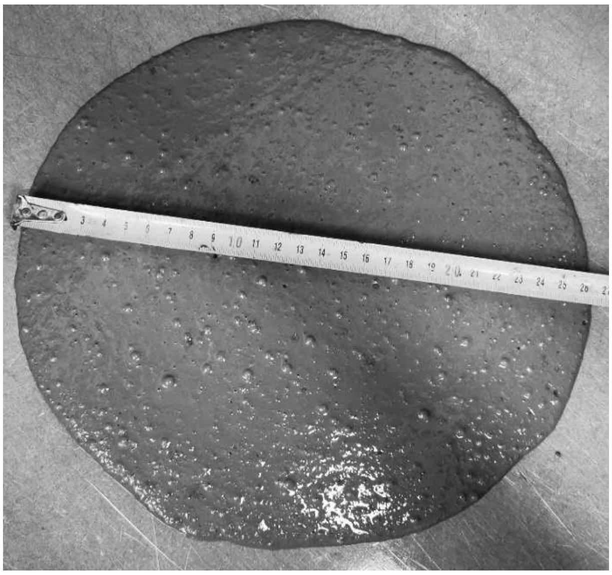

Fig. 2 *Mini-flow desk test – mixture B (date September 14, 2023)*

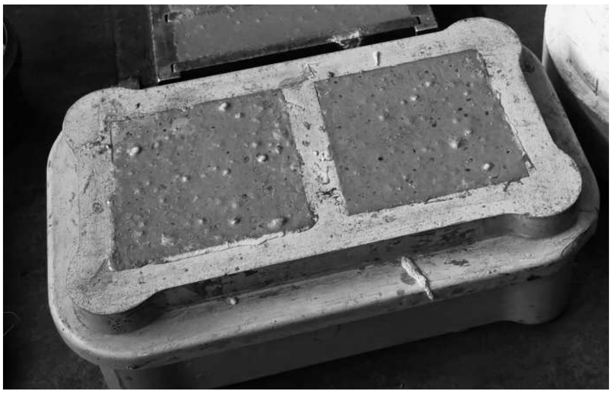

Fig. 3 *Production of the test specimens for analysis of the fibre sedimentation in HPC mixtures – mixture B (date September 14, 2023)*

Tab. 2 *Workability test results $d_1 \times d_2$ [mm]: T30s —flow test after 30s; T1min—flow test after 1 min; T5min— flow test after 5 min; T10min— flow test after 10 min, T30min— flow test after 30 min*

Mixture	T_{30s}	T_{1m}	T_{5min}	T_{10min}	T_{30min}
A	210×225	230×245	250×280	250×280	250×280
B	250×250	270×275	285×295	285×295	285×295
C	260×265	290×290	300×315	300×315	300×315
D	280×280	305×305	325×330	325×330	325×330

Tab. 3 *Date and air conditions (temperature and humidity) during production of the test specimens for analysis of the fibre sedimentation in HPC mixtures*

Date	Temperature [°C]	Humidity [%]	Prepared HPC mixture	Temperature of the mixture after mixing [°C]
January 9, 2023	18.3	41.6	A	22.8
			B	20.6
			C	20.3
			D	18.9
April 12, 2023	19.1	33.4	D	25.1
September 14, 2023	22.4	55.2	A	27.2
			B	25.3
			C	24.3
			D	24.1

3 Sedimentation evaluation methods proposal

The cubes (100 x 100 x 100 mm) were prepared from all HPC mixtures (A, B, C, D) for the analysis of the fibres sedimentation in these mixtures. After 28 days of the hardening, the test specimens were taken out from the molds. Then, test specimens were cut into halves in verticaly direction (from surface to the bottom of the sample). After cutting the test HPC specimens, it became clear that the samples with a higher water content showed areas without steel fibres in the middle part. This phenomenon occurred due to the slowest hardening of the concrete in the middle of the entire concrete and due to the high content of water in the mixture, when the disturbed fibres in the concrete were more easily settling by hindered sedimentation. For illustration, the border of the area without steel fibres (or with a minimum amount of fibres) for sample D produced on April 12, 2023 is shown in Fig. 4.

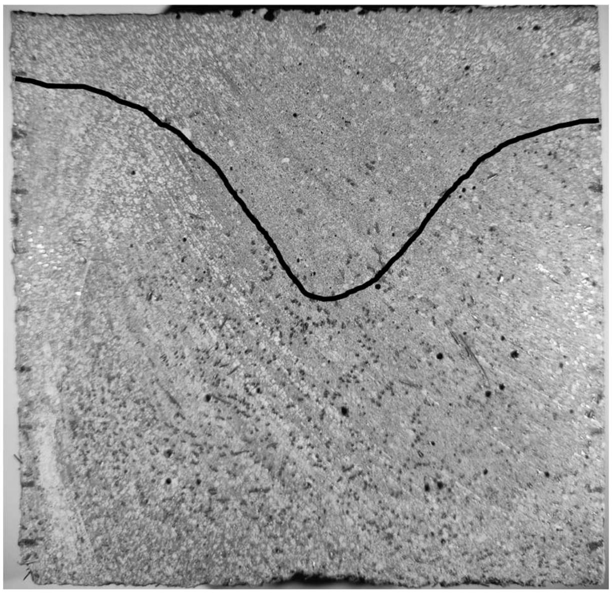

Fig. 4 *Boundary od sedimented steel fibres after 28 days of HPC hardening – mixture D (date April 12, 2023)*

On the basis of this result, two methodologies for determining the sedimentation of steel fibres in the HPC mixture were proposed. For both method, the fiber distribution was determined at a pre-defined depth below the surface using a laser confocal microscope Olympus LEXT OLS 3000. This distribution of steel fibres was monitored at a given depth along the entire cross-section of the sample (i.e. in a length of 100 mm). For the sake of objectivity, the measurement was carried out in steps of 10 mm from the surface of the test speciment, i.e. measurement were done in the depth h = 10 20, 30, 40, 50, 60, 70, 80 a 90 mm from the surface. A lens 5x was used for monitoring. It means, the width of the monitored area was approx. 4 mm. On one part of the cube, the amount and distribution of fibers in a predefined depth of the entire cross-section was determined.

The images obtained from microscopy analysis were used for the design of both methods of monitoring the sedimentation of steel fibres in HPC mixtures. Obtained images for sample D produced on April 12, 2023 is shown in Fig. 5.

From obtained images were proposed two methods for evaluation of the fibre sedimentation in HPC mixtures. The first proposed method consists in determining the number of all fibres in a given depth of the sample below the surface in the entire cross-section. In this case, the result is the average number of fibres in a given depth. The areas with the slowest hardening are taken into account here. The second method takes into account the uneven hardening of the HPC mixture in the entire volume and the associated uneven sedimentation of the fibres. The result of this second method is the determination of the so-called critical depth h_k, i.e. the maximum depth in which there are still places without fibres below the surface of the hardened sample (see Fig. 5).

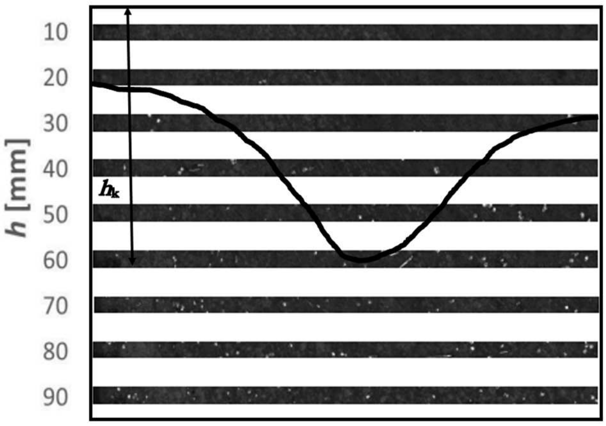

Fig. 5 *Images of the fibres obtained by laser confocal microscope Olympus LEXT OLS 3000, lens 5x – mixture D (date April 12, 2023). Include boundary od sedimented steel fibres*

4 Results

The result of the first proposed method is the determination of the number of fibres in a given depth of the sample below the surface in the entire cross-section. This method was used to determine the mean value of the number of fibres depending on the depth below the surface for 4 HPC mixtures with different proportions of water content. The measurement was performed for 3 test specimens prepared from mixtures A, B, C and 4 test specimens prepared from mixture D. Dependence of number of the steel fibres in HPC mixture on the depth below the surface for all test specimen sis shown in Fig. 6-9. The mean value of the number of fibres depending on the depth below the surface for HPC mixtures, together with the upper and lower limits, is shown in Fig. 6-9.

The Fig. 6-9 show a considerable dispersion of the measured values of the number of fibers at a defined depth below the surface. These diferrencies are due to the different ambient temperatures during the production of the test specimens. These different temperatures also had an effect on the different temperatures of the prepared HPC mixtures immediately after mixing (see Tab. 3). Due to this reason, the upper and lower limits of the dispersion of the measured values were determined – see Fig. 6-9.

From the results, the size of the mean value of the number of fibres at a given depth below the surface was evaluated for water content in the HPC mixture (Fig. 10). It is clear from the evaluation that for the sample with the smallest water content (sample A – water content 160 kg/m³), the dependence of the fibres number on the depth below the surface is almost constant. In contrast, in the sample with the highest water content (sample D – water content 210 kg/m³), there was an exponential increase in the inhomogeneity of the fibres in the HPC mixture.

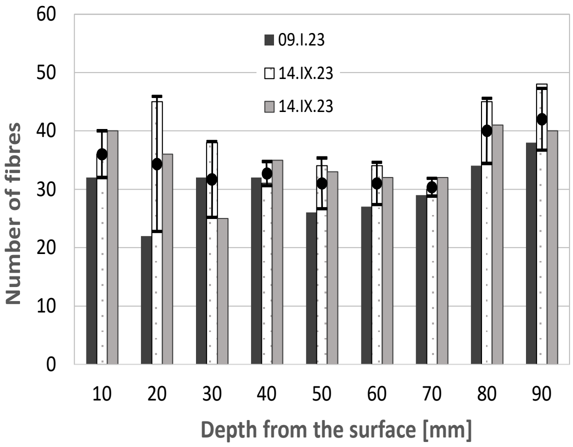

Fig. 6 *Dependence of number of the fibres on the depth below the surface – mixture A. The legend indicates the date of concreting*

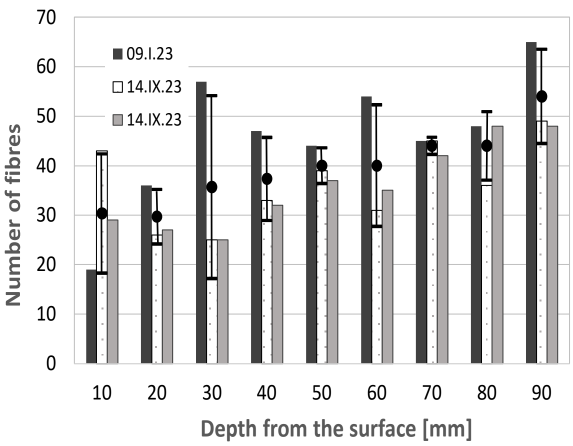

Fig. 7 *Dependence of number of the fibres on the depth below the surface – mixture B. The legend indicates the date of concreting*

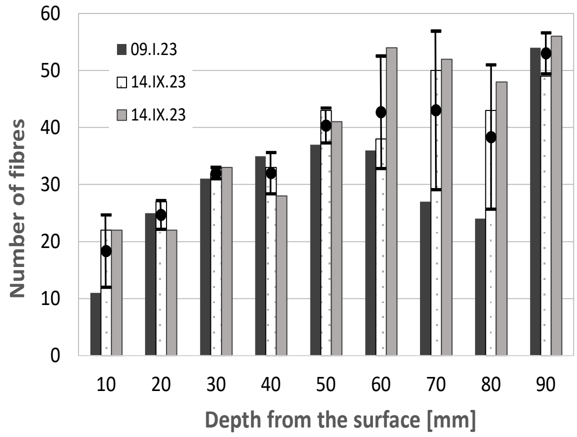

Fig. 8 *Dependence of number of the fibres on the depth below the surface – mixture C. The legend indicates the date of concreting*

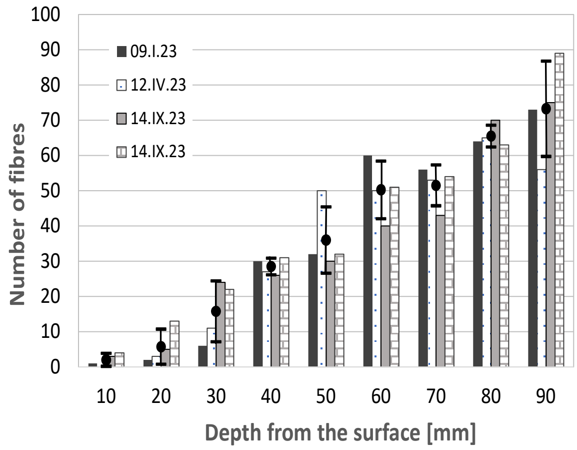

Fig. 9 *Dependence of number of the fibres on the depth below the surface – mixture D. The legend indicates the date of concreting*

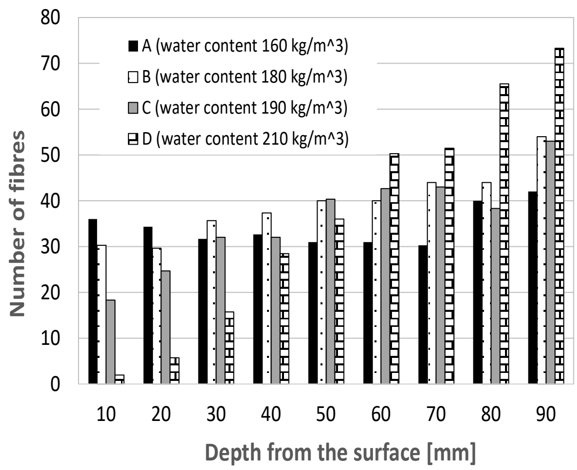

Fig. 10 *Dependence of mean value of the number of fibres on the depth below the surface for all prepared mixtures*

From Figure 10, it is clear that with the increase in the proportion of water content in concrete mixtures, there is an increase in the inhomogeneity of the dispersion of fibres in HPC mixtures. In connection with this phenomenon, the so-called critical depth h_k, i.e. the maximum depth in which there are still places without fibres below the surface of the hardened sample (see Fig. 5), was subsequently introduced for the evaluation of fibre sedimentation. The value of the critical length was determined from the images of sedimented fibres in pre-defined depth obtained by laser confocal microscopy. The dependence of the critical depth h_k on the water content is shown in Fig. 11. The obtained values of the critical depth h_k for all test specimens prepared with same water content was equal. The results mentioned in Fig. 11 corresponds to the results obtained by first method (see Fig. 10), i.e. value of the critical depth exponencially increase with content of water in HPC mixture.

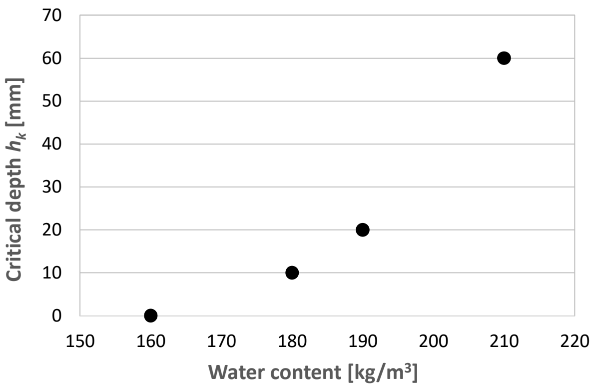

Fig. 11 *Dependence of the vritical depth h_k on water content*

5 Conclusions

The aim of this work is to propose a methodology for evaluating inhomogeneity due to the sedimentation of fibres in High-Performnce Concrete (HPC) mixtures. Four concrete mixtures with same component proportion was chosen for experiments. Water was the only one component, that was changing in mixture recipes. Steel fibres with a ratio of diameter/length = 0.3/20 were used as reinforcement. The fibre volume in mixture was 1.5 %.

A methodology was proposed for the evaluation of fiber sedimentation in HPC mixtures. The proposed methodology is based on the monitoring of fibres number at predefined depths below the surface of the hardened concrete structure.

Two methods of evaluating fibre sedimentation in HPC mixtures were proposed. One method determines the total number of fibres at a predefined depth below the surface across the entire width of the test specimen. The second method evaluates the so-called critical depth h_k, i.e. the maximum depth in which there are still places without fibres below surface of the hardened sample. Both methods confirmed that there is a limiting water content in the HPC mixture at which there is an abrupt increase in the inhomogeneous distribution of the fibres in the hardened concrete. For a quick evaluation of the fibres sedimentation of in HPC mixtures, it is therefore possible to use the method of determining the critical depth, i.e. the depth when the sedimentation of the fibres occurred.

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References

[1] KMITA, A. (2000). A new generation of concrete in civil engineering. In: *Journal of Materials Processing Technology*, Vol. 106, No. 1-3, pp. 80 – 86. Elsevier B.V. ISSN 0924-0136

[2] Ductal [online]. Holcim Techology Ltd. (cited November, 19, 2023). Available from: https://www.ductal.com/en

[3] MAZZACANE, P., RICCIOTTI, R. and TEPLY, F. (2009). LA Passerelle des Anges. In: *Workshop on Ultra High-Performance Fibre-Reinforced Concrete (UHPFRC)* [online]. pp. 1 – 11. AFGC and fib. (cited March 14, 2020). Available: http://www.planete-tp.com/IMG/pdf/2UHPFRC-20091117-18_Marseille_cle07c191.pdf

[4] Lávka pro pěší a cyklisty v Táboře-Černých mostech [online]. KŠ Prefa. ©2020. (cited November 19, 2023). Available from: https://ksprefa.cz/portfolio/lavka-pro-pesi-a-cyklisty-v-prostoru-cernych-mostu-v-tabore/

[5] Štvanická lávka [online]. Kloknerův ústav ČVUT v Praze ©2020. (cited November 19, 2023) Avalaible from: https://www.klok.cvut.cz/stvanicka-lavka/#pll_switcher

[6] AFGC (2013). *Ultra High-Performance Fibre-Reinforced Concretes, Recommandations.* Paris, France: Association Francaise de Génie Civil (AFGC).

[7] YOKOTA, H., ROKUGO, K., SAKATA, N. (2007). *Recommendations for Design and Construction of High Performance Fiber Reinforced Cement Composites with Multiple Fine Cracks (HPFRCC).* In: Concrete Engineering Series 82. 113 p. Japan Society of Civil Engineers.

[8] KOLÍSKO, J., BOUŠKA, P., ČÍTEK, D., HUŇKA, P., RYDVAL, M. and VOKÁČ, M.

(2015). Metodika 1 - Metodika pro návrh UHPC a pro materiálové zkoušky. Czech Technical University, Klokner Institute. 32 p.

[9] fib special activity group, New Model Code, et al. (2013). *fib Model Code for Concrete Structures 2010*. Ernst & Sohn, Wiley. doi:10.1002/9783433604090

[10] RYVOLOVÁ, M., SVOBODOVÁ, L., BAKALOVA, T., VOLESKÝ, L (2021). Influence of Basic Environment of Geopolymer Composites on Degradation Rates of E and AR Type Glass Fibers. In: *Manufacturing Technology*, Vol. 21, No. 2, pp. 246-253. J. E. Purkyne University in Ústí nad Labem, Czech Republic. ISSN: 1213-2489

[11] MAJKO, J., VAŠKO, M., HANDRIK, M., SÁGA, M. (2023). Challenges in Tensile Testing of Thermoplastic Composites Reinforced with Chopped Carbon Fibre Produced by Fused Filament Fabrication Method. In: *Manufacturing Technology*, Vol. 23, No. 2, pp. 216-224. J. E. Purkyne University in Ústí nad Labem, Czech Republic. ISSN: 1213-2489

[12] MOSTOFINEJAD, D., BAHMANI, H., AFSHAR, J. (2023). Prediction of Mechanical Properties of High-Performance Concrete (HPC) Reinforced with Steel Fibers. In: *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, Vol. 47, pp. 1971-1993. Shiraz University. ISSN 2228-6160

[13] MA, Y. Q. (2013). Experimental Study on Mechanical Properties of Steel Fiber Reinforced High Performance Concrete. In: *Advanced Materials Research*, Vol. 859, pp. 56-59. Scientific.Net. ISSN: 1022-6680

[14] ABDULHAMEED U. A. (2019). Statistical Evaluation of Compressive Strength in High Performance Concrete (HPC) with Steel Fiber Addition. In: *Sustainable Structures and Materials*, Vol. 2, No .1, pp. 14-31. ISSN: 2616-4779

[15] SHEHAB EL-DIN, H. K., MOHAMED, H. A., KHATER, M., AHMED, S. (2016). Effect of Steel Fibers on Behavior of Ultra High-Performance Concrete. In: *International Interactive Symposium on Ultra-High-Performance Concrete*. 10 p. doi: https://doi.org/10.21838/uhpc.2016.11

[16] LAU, A., ANSON, M. (2006). Effect of high temperatures on high performance steel fibre reinforced concrete. In: *Cement and Concrete Research*, Vol. 36, No. 9, pp. 1698-1707. Elsevier Ltd. ISSN: 0008-8846

[17] XU, L., WU, F., CHI, Y., CHENG, P., ZENG, Y., CHEN, Q. (2019). Effects of coarse aggregate and steel fibre contents on mechanical properties of high-performance concrete. In: *Construction and Building Materials*, Vol. 206, pp. 97-110. Elsevier Ltd. ISSN: 0950-0618

[18] ZHANG, W., ZHENG, M., ZHU, L., REN, Y., LV, Y. (2022). Investigation of steel fiber reinforced high-performance concrete with full aeolian sand: Mix design, characteristics and microstructure. In: *Construction and Building Materials*, Vol. 342, Part B, 12 p. Elsevier Ltd. ISSN: 1879-0526 (online)

[19] ALI, B., KURDA, R., AHMED, H., ALYOUSEF, R. (2022). Effect of recycled tyre steel fiber on flexural toughness, residual strength, and chloride permeability of high-performance concrete (HPC). In: *Journal of Sustainable Cement-Based Materials*, Vol. 12, No. 2, pp. 141-157. Taylord & Francis Group. ISSN: 2165-0373

[20] KALIFA, P., CHÉNÉ, G., GALLÉ, C. (2001). High-temperature behaviour of HPC with polypropylene fibres: From spalling to microstructure. In: *Cement and Concrete Research*, Vol. 31, No. 10, pp. 1487-1499. Elsevier Ltd. ISSN: 0008-8846

[21] GUERRINI, G. L., CATTANEO, S., DHIR, R. K., NEWLANDS, M.D., WHYTE, A. (2015). Residual Properties of Hybrid Polypropylene-Steel Fibre Reinforced HPC Exposed to High Temperatures. In: *Application of Codes, Design and Regulations*: Proceedings of the International Conference held at the University of Dundee, Scotland, UK on 5–7 July 2005

[22] XIAO, J., FALKNER, H. (2006). On residual strength of high-performance concrete with and without polypropylene fibres at elevated temperatures. In: *Fire Safety Journal*, Vol. 41, No. 2, pp. 115-121. Elsevier Ltd. ISSN: 0379-7112

[23] SMARZEWSKI, P. (2019). Influence of basalt-polypropylene fibres on fracture properties of high-performance concrete. In: *Compossite Structures*, Vol. 209, pp. 23-33. Elsevier Ltd. ISSN: 1879-1085

[24] ALOMAYRI, T.S., ALI, B. (2023). Investigating the load-deflection behaviour and drying shrinkage resistance of HPC reinforced using different cellulose fibres. In: *Journal of Building Engineering*, Vol. 73, 15 p. Elsevier Ltd. ISSN: 2352-7102 (online)

[25] SMARZEWSKI, P. (2020). Flexural toughness evaluation of basalt fibre reinforced HPC beams with and without initial notch. In: *Composite Structures*, Vol. 235, 12 p. Elsevier Ltd. ISSN: 1879-1085

[26] RAHIMI, M., HISSEINE, O.A., TAGNIT-HAMOU, A. (2022). Effectiveness of treated flax fibers in improving the early age behavior of high-performance concrete. In: *Journal of Building Engineering*. Vol. 45, 9 p. Elsevier Ltd. ISSN: 2352-7102 (online)

[27] ALOMAYRI, T., ALI., B., RAZA, S.S., EL HACHEM, C., AHMED, H., AZAB, M. (2023). Effect of binder strengthening using micro-silica on mechanical and absorption characteristics of HPC reinforced with reclaimed jute fibres. In: *Case Studies in Construction Materials*, Vol. 18, 13 p. Elsevier Ltd. ISSN: 2214-5095 (online)

[28] ALI, M., ELSAYED, M., TAYEH, B. A., MAGLAD, A. M., EL-AZIM, A.A. (2023). Effect of hybrid steel, polypropylene, polyvinyl alcohol, and jute fibers on the properties of ultra-high performance fiber reinforced concrete exposed to elevated temperature. In: *Structural Concrete. Journal of the fib.* September 2023. Fib CEB-FIB. ISSN: 1464-4177.

[29] CZAJKOWSKA, A., INGALDI, M. (2022). Influence of Steel Fibers Content on Selected Mechanical Properties - Experimental Tests. In: *Manufacturing Technology*, Vol. 22, No. 3, pp. 267-278. J. E. Purkyne University in Ústí nad Labem, Czech Republic. ISSN: 1213-2489

[30] WANG, D., JU, Y., SHEN, H., XU, L. (2019). Mechanical properties of high-performance concrete reinforced with basalt fiber and polypropylene fiber. In: *Construction and Building Materials*, Vol. 197, pp. 464-473. Elsevier Ltd. ISSN: 0950-0618

[31] YANG, J., CHEN, B., SU, J., XU, G., ZHANG, D., ZHOU, J. (2022). Effects of fibers on the mechanical properties of UHPC: A review. In: *Journal of Traffic and Transportation Engineering (English Edition)*, Vol. 9, No. 3, pp. 363-387. Periodical Offices of Chang'an University. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. ISSN: 2095-7564

[32] SHARMA, R., JANG, J.G., BANSAL, P:P. (2022). A comprehensive review on effects of mineral admixtures and fibers on engineering properties of ultra-high-performance concrete. In: *Journal of Building Engineering*, Vol. 45, 20 p. Elsevier Ltd. ISSN: 2352-7102 (online)

[33] RYDVAL, M., HUŇKA, P., KOLÍSKO, J. (2015). Production and properties of functionally graded UHPFRC beams. In: *Advanced Materials Research*, Vol. 1106, pp. 156–159, doi: 10.4028/www.scientific.net/AMR.1106.156

[34] KABELE, P., SAJDLOVÁ, T., RYDVAL, M., KOLÍSKO, J. (2015) Modeling of High-Strength FRC Structural Elements with Spatially Non-Uniform Fiber Volume Fraction. In: *Journal of Advanced Concrete Technology*, Vol. 13, pp. 311-324. doi: 10.3151/jact.13.311

[35] KABELE, P., SAJDLOVÁ, T., RYDVAL, M. (2016). DIC analysis of shear failure in functionally graded cementitious composite beams. [Online]. (cited November 19, 2023). Available: http://isit.si/das2016

[36] RYDVAL, M., KOLÍSKO, J. (2015). Ohybová únosnost desek ztraceného bednění vyrobených z UHPFRC a vliv distribuce ocelových vláken. [Online] Bet. TKS. No. 2/2015, pp. 34–37, Apr. 2015. Available: http://www.betontks.cz/sites/default/files/BETON_2-15.pdf

[37] DOSTÁL, M., MORAVEC, J., JIROUT, T., RYDVAL, M., HURTIG, K, JIROUTOVÁ, D. (2023). Model fluids substituting fresh UHPC mixtures flow behaviour. In: *Archive of Applied Mechanics*, Vol. 93, No. 7, 14 p. Spring Nature. ISSN: 0939-1533