Research, testing and application potential of steel fiber reinforced ultra-high performance concrete

Raziskave, preskušanje in možnosti uporabe zelo visoko zmogljivega mikroarmiranega betona z jeklenimi vlakni

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Abstract

This paper deals primarily with research and testing of ultra-high performance concrete (UHPC) made with or without the addition of steel fibers. Two stages of research are presented and discussed in detail: first - UHPC based mostly on local component materials and produced in the form of a premix with a commercial name ForteCrete150®, and second – modified UHPC, made with a partial cement substitution by limestone filler, as a more eco-friendly and sustainable solution. The obtained results indicate that there is a great potential for application of ultra-high performance concrete, especially in the form of premix that can be prepared on-site. The addition of limestone filler (and potentially other types of mineral additives) as SCM, could generally contribute to improvement of a negative agenda surrounding the cementitious composites.

Povzetek

Članek obravnava predvsem raziskave in preskušanje zelo visoko zmogljivega betona (UVZB), izdelanega z dodatkom jeklenih vlaken ali brez njega. Podrobno sta predstavljeni in obravnavani dve stopnji raziskav: prva - UHPC, ki temelji predvsem na lokalnih komponentnih materialih in se proizvaja v obliki predhodno pripravljene mešanice s komercialnim imenom ForteCrete150®, in druga - modificirani UHPC, ki je narejen z delno zamenjavo cementa s polnilom iz apnenca kot okolju prijaznejša in trajnostna rešitev. Dobljeni rezultati kažejo, da obstaja velik potencial za uporabo zelo visoko zmogljivega betona, zlasti v obliki predhodno pripravljene mešanice, ki jo je mogoče pripraviti na kraju samem. Dodajanje apnenčevega polnila (in morebitnih drugih vrst mineralnih dodatkov) kot SCM bi lahko na splošno prispevalo k izboljšanju negativne obravnave cementnih kompozitov.

Keywords: ultra-high performance concrete, steel fibers, premix, mineral additives, cement substitution, limestone filler, sustainable construction materials

Ključne besede: zelo visoko zmogljivi beton, jeklena vlakna, predhodno pripravljena mešanica, mineralni dodatki, nadomestek cementa, apnenčevo polnilo, trajnostni gradbeni materiali

1. INTRODUCTION

It is a well-known fact that in the last century concrete has become the most extensively used construction material in the world. Its basic components are cement, aggregate and water, but there is also an increasing amount of different mineral additives and chemical admixtures, which are applied in order to improve various properties of concrete. On the one hand, the concrete industry has to keep producing composite materials of superior quality and durability, and on the other hand it must utilize new technologies in order to reduce CO_2 emission and make concrete more eco-efficient. The worldwide research and application of various kinds of concrete is currently heading in many different directions, and one of its most promising types is certainly High performance concrete (HPC).

High performance concrete represents a cementitious composite with substantially improved physical-mechanical properties, durability and ductility, compared to ordinary concrete. The most noticeable of these improved parameters are the compressive strength of at least 120 MPa and flexural strength of at least 20 MPa (at the age of 28 days), but even more important is the composites' extremely prolonged durability. For instance, HPC has improved resistance to carbonation and chloride ion penetration, higher level of waterproofness, enhanced resistance to freeze and thaw in the presence of deicing salts and lower abrasion, in comparison with ordinary concrete.The same properties are even more superior in case of the so-called Ultra-high performance concrete (UHPC), which is a direct consequence of the achieved denser packing of the particles and the exceptionally compact structure.

Very often, HPC and UHPC are strengthened with steel fiber reinforcement (SFR) that increases their tensile strength and ductility. The main constituents of such composites (SFRUHPC) are usually: pure cement of highest class (CEM I 52,5), quartzite-based fine aggregates, steel fibers, water, mineral additives and chemical admixtures. The special sub-category of UHPC are ready-mixed products (premix), which can be prepared either at the concrete plant or on the construction site.

The main drawback in the application of UHPC, apart from its high price, is the fact that cement industry is considered as one of the biggest producers of CO_2. In addition to that, natural aggregates, such as quartzite sand represent non-renewable resources. Thus, the modern tendencies in concrete production are focused on partial replacement of cement and/or natural aggregate with recycled or waste materials. Worldwide, many researchers are discovering different types of locally available waste and recycled materials, usually with pozzolanic properties, and testing their application as supplementary cementitious materials (SCM). Some of the SCM's can be used only as cement replacement, but there are also materials which may be applied both as aggregate and cement replacement, such as: recycled glass, industrial slag or limestone filler. In this way, more eco-friendly composites, such as Green steel fiber reinforced high performance concrete (GSFRHPC) can be produced.

In terms of application potential, SFRUHPC represents a very strong candidate material for reparation or casting of concrete structures that are exposed to severe environmental conditions, such as: bridge girders and columns, dam surface and road overlays, decorative façade elements, tunnel linings, ultra thin stairs and balconies, blast resistant structures, etc.). Another quality that recommends the application of this type of material is its high early-age performance.

Having all the above stated facts in mind, this paper will primarily focus on the research process and testing results of a special cementitious composite, based primarily on local materials and produced in the form of a premix with a commercial name ForteCrete150®. This densely packed fine-grained SFRUHPC with very low water content was optimized and designed to exhibit favorable workability in the fresh state, as well as outstanding mechanical properties and ultra-high durability parameters in the hardened state.

The second part of the paper shall focus on the opportunities for modification of the UHPC mix design in order to achieve more environmental-friendly and sustainable construction material. One of the possibilities to be first considered in this research, was to replace part of the cement with some other fine granulated component material. The fact that a significant portion of cement in the UHPC (between 30% and 35%), is not activated during the hydration process, supports the idea of replacing this quantity of cement with some other material, such as limestone (LS) filler.

2. RESEARCH PROCESS AND TESTING OF ULTRA-HIGH PERFORMANCE CONCRETE PREMIX

Comprehensive research of Ultra-high performance concrete (UHPC) at the Faculty of Civil Engineering in Belgrade started in the first half of 2019, with the beginning of a collaboration between the Faculty and Spajić d.o.o., a company based in Negotin, Republic of Serbia. This company, which was already well-known for production of steel fibers, decided to develop their own utra-high performance concrete premix under the commercial name: ForteCrete150®. The basic idea was to select optimal component materials for such UHPC premix, if possible of local origin, and to perform the complete testing of the composite, both in the fresh and hardened state. After the thorough research, the optimization of the concrete mix design was carried out in order to achieve the best quality of the product.

It is a well known fact that the collaboration between research institutions and companies is essential for the economic development of every country. In this case, the scientific-based but also commercial collaboration has lead to a significant progress in research of ready mixed ultra-high performance concrete. Apart from the ForteCrete150® as a final product, this collaboration has also yielded one defended master thesis [1] as well as two papers within PhD studies. Additionally, three scientific papers have been published, two presented at international conferences [2], [3], and one published in nationally significant journals [4].

This chapter presents the development in the experimental investigation of UHPC properties. The applied mixtures are presented with a detailed explanation of composition and the quantities of individual components. Furthermore, the process of preparing the fresh concrete mix is described. Also, the testing methods and results of physical-mechanical

Table 1: Type of materials and their quantities in the mixture preparation [5]

Material	Type	Manufacturer	Density (kg/m^3)	Quantity (kg)
Cement (C)	CEM I 42.5 (52.5)	CRH/Lafarge/Lukavac	3150	Premix (20)
Sand (QS)	Quartzite sand	Rgotina	2640	Premix (20)
Silica fume (MS)	Micro-silica	Italy	2200	Premix (20)
Admixture (HRWR)	HRWR	BASF	1050	0.345
Fibers (SF)	Steel fibers	Spajić d.o.o.	7850	0/0.765/1.530
Water (W)	Potable water	Water supply	1000	1.720

Table 2: Mixture proprotions [7]

Material	C	MS	QS	SF	HRWR	W
Proportion	1.000	0.184	1.043	0.337	0.046	0.220

properties are presented. Finally, based on the literature overview and the results obtained, conclusions and perspectives for further research are provided.

2.2. Experimental program

2.2.1. Materials and mix design

For the production of UHPC specimens, the fresh concrete mixture was prepared using a ready-made mixture (premix) with cement, quartzite sand and silica fume, which were previously mixed together at the production facility. The weight of a single bag of premix was 20 kg, which was sufficient to produce 8 liters of fresh concrete mixture. The type and quantities of all component materials can be seen in Table 1 and Table 2. During the mixing of dry components, water, high-range water reducing admixture (HRWR) and brass coated steel fibers (optional) were added to the mixture [2], [4].

Several types of cement, including CEM I 42.5R, CEM I 52.5N and CEM I 52.5R from the nearby suppliers such as CRH, Lafarge and Lukavac (Bosnia and Herzegovina) were tried, in order to find the optimal mix design of the premix. The main idea was to show the potential of using local raw materials to create UHPC (with or without SF). In this project, various combinations with different cement types and fiber contents were considered. A total of seven concrete mixtures were analyzed in this first stage of the investigation. All UHPC mixtures were prepared in the same way, which is schematically illustrated in Figure 1.

2.2.2. Specimens and test methods

During the research of ultra-high performance concrete, numerous tests were conducted in order to quantify the most important physical and mechanical properties of the composite. The objective was to assess whether the premix ForteCrete150® could be classified as ultra-high performance concrete. The results of these tests related to the original premix formulation, have been published in two scientific papers [2], [4], which provide detailed descriptions of the test methods performed on the UHPC samples. These tests included the following properties:

1. Bulk density - which was determined in both fresh and hardened state, using standard specimens in the form of cubes with dimensions of 10x10x10 cm and prisms with dimensions of 4x4x16 cm, in accordance with SRPS EN 12390-7 [5].
2. Compressive strength – which was determined at the ages of 1, 3 and 28 days, using standard cube specimens with dimensions of 10x10x10 cm in accordance with SRPS EN 12390-3 [6].
3. Flexural strength – which was determined at the ages of 1, 3, and 28 days, using standard prismatic specimens with dimensions of 4x4x16 cm in accordance with SRPS EN 1015-11 [7].
4. Concrete strength was also determined by using the Pull-off test in accordance with SRPS EN 1542 [8], on the specimens in the form of plates and cubes with dimensions of 15x15x5 cm and 10x10x10 cm, respectively.
5. Waterproofness of concrete – which was determined at the age of 28 days, using concrete cubes with dimensions of 10x10x10 cm, according to SRPS EN 12390-8 [9].
6. Resistance to simultanious freeze/thaw and deicing salt attack – which was determined according to SRPS CEN/TS 12390-9 [10]; the test was conducted on plate samples with the dimensions 10x10x5 cm at the age of 28 days in a chamber with controlled humidity and temperature levels.
7. Abrasion resistance – which was determined at the age of 28 days, in accordance with SRPS EN 14157

[11]; the applied samples had standard abrasion surface of 50 cm².

8. Resistance to carbonation - an accelerated test was used in order to evaluate the resistance to carbonation in accordance with fib Bulletin No. 34: Model Code for Service Life Design [12]. Prisms that had been broken after 28 days served as the test samples. The samples were placed in a chamber for 28 days at a constant temperature of 20°C and 65% humidity, where they were exposed to CO_2 at a concentration of 2%. After this period of time, the samples were broken by splitting, treated with phenolphthalein solution ($C_{20}H_{14}0_4$), left to dry for 30 minutes and evaluated.
9. Resistance to chloride ion penetration – which was performed on concrete cylinder specimens with 100 mm diameter and 100 mm length, at the age of 28 days. The test was conducted in accordance with the requirements of NT Build 492: Non-Steady State Chloride Migration Standard [13]. The penetration of the chloride ions in the form of a layer of silver color on the surface of the sample could be plainly visible after treatment with silver nitrate solution. Seven locations omitting edges of the specimens were utilized to assess the chloride penetration, and the results were used to calculate the chloride ion migration coefficient.

2.2.3. Results and discussion

As it was already mentioned, the first phase of research was focused on the original premix, without any substitutions of cement or quartzite sand. The physical and mechanical properties of concrete were determined in both fresh and hardened state for all of the seven different mixtures. In the following text, the most significant achieved results, as a function of the type of cement and steel fiber content, are presented. More detailed results can be found in the previously published scientific papers [2], [4].

The density of the fresh concrete was in the range between 2282 and 2529 kg/m³. The lower value of this range corresponds to 0% of fibers, while the upper value relates to a fiber content of 2% (by volume). In the hardened state, slightly lower values were obtained, ranging from 2270 to 2490 kg/m³. This density is lower or equal to ordinary concrete without and with

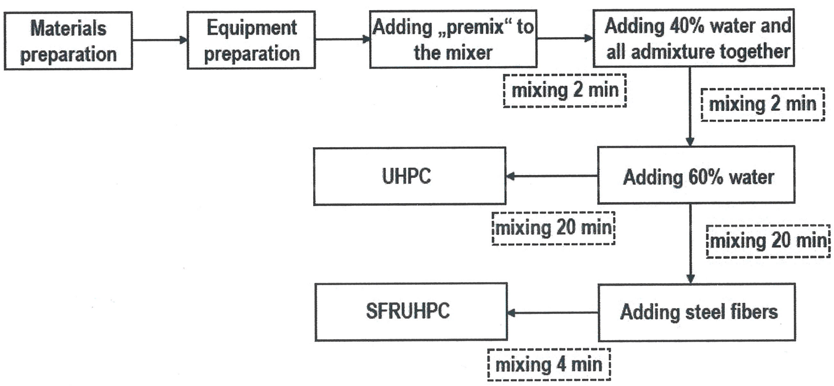

Figure 1: Mixing procedure for UHPC mixtures with and without steel fibers [2].

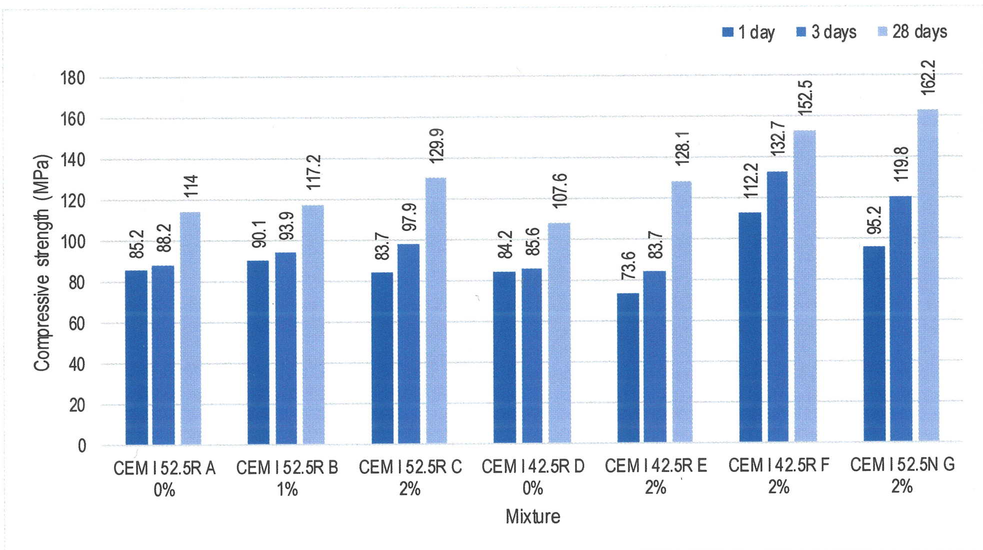

Figure 2: Test results of compressive strength for different ages and mixtures [2]

reinforcement bars (2400 and 2500 kg/m^3, respectively). As a consequence, a lower self-weight of structures made with UHPC may be expected, compared to typical concrete structures. This results in reduced design forces and allows smaller dimensions of structural elements.

The results of the compressive and flexural strength tests are shown on Figures 2 and 3. The maximum value of compressive strength was 162.2 MPa, while the maximum value of flexural strength was 24.5 MPa with a 2% fiber content, at the age of 28 days. It was noticed that fibers have a positive influence on obtained strength values. At the same time, the type of cement and the workability of the concrete mixture also had significant influence on the strength levels. The obtained results indicate that tested UHPC mixtures showed higher compressive and flexural strength values (3-4 times) compared to ordinary PC concrete.

Figure 4 presents the results of the Pull-off test for mixtures with different fiber contents. Similar to the compressive and flexural strength tests, it can be noted that fiber addition had a positive influence, which was expected because fibers tend to stiffen the cementitious matrix. Additionally, it can be observed that increasing the fiber content from 1% to 2% doesn't lead to an increase in pull-off force.

As far as the waterproofness is concerned, the mean value of water penetration was measured at 6.3 mm. It can be concluded that the tested UHPC belongs to the highest class V-3 (very low water permeability) as per SRPS U.M1.206 [14].

The investigation of the UHPC resistance to frost and deicing salt attack was carried out according to SRPS CEN/TS 12390-9 [10]. The test was carried out on plate samples with dimensions of 10x10x5cm at the age of 28

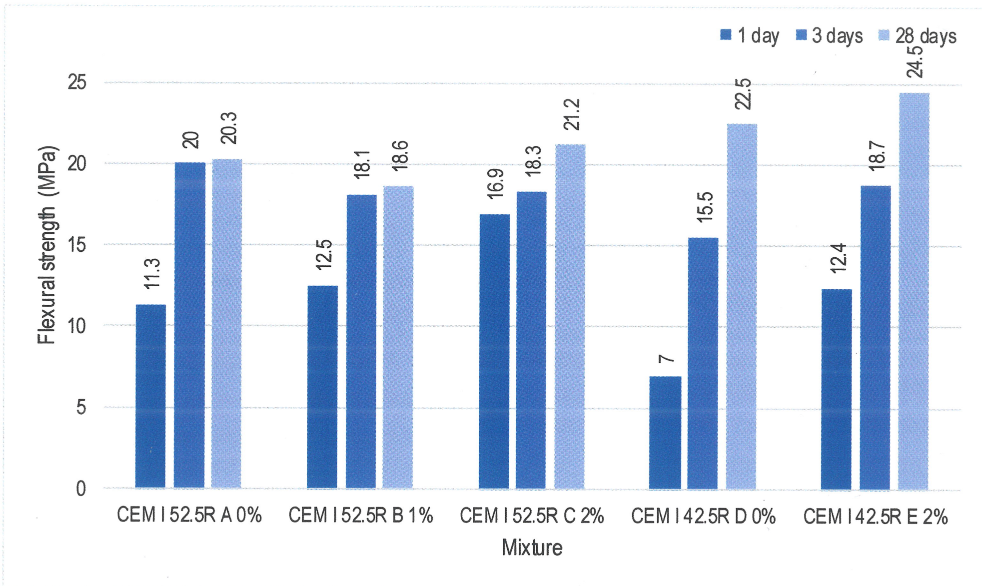

Figure 3: Test results in flexural strength for different ages and mixture [2].

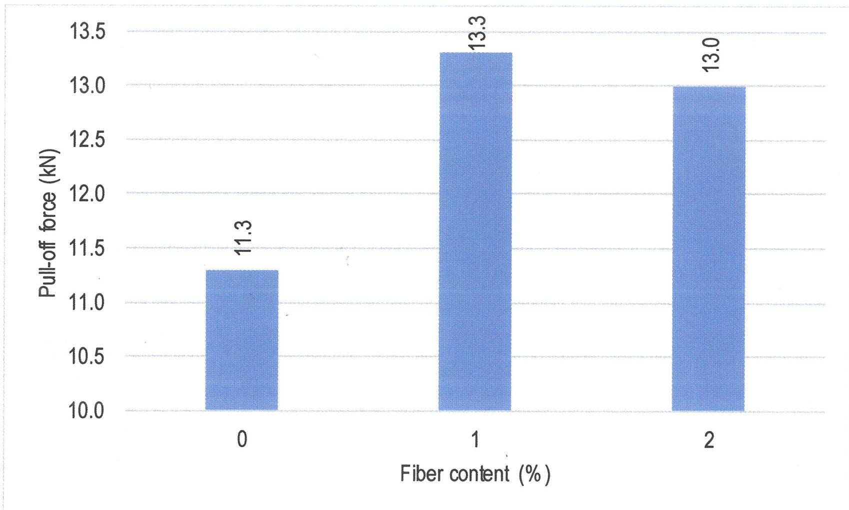

Figure 4: Pull-off test results for different fiber content [2]

days in a chamber with regulated temperature and humidity conditions. No damages after 25 cycles were observed on the surface of the samples, as it can be seen on Figure 5. It can be concluded that the tested UHPC belongs to the highest class MS-2 (zero damage) according to SRPS U.M1.206 [14].

The investigation of the abrasion resistance of UHPC was performed by using a test according to SRPS EN 14157 [11]. The used samples were 28 days old and square in shape, with the abrasion surface of 50 cm^2. Based on the test results, the average value of abrasion wear HB was lower than 14 $cm^3/50cm^2$, meaning that the tested UHPC belongs to the highest class H-3 according to SRPS: U.M1.206 [21].

After the accelerated carbonation test, no decrease in the alkalinity of the concrete was observed, i.e. the depth of carbonation was measured to be 0.00 mm (Figure 6). The tested concrete belongs to the highest class of carbonation resistance, which corresponds to the exposure class XC4, as defined by the standard SRPS EN 206 [15]. The mean value of the chloride migration coefficient was $8.454*10^{-14}$ m^2/s. The surface of concrete sample after treatment with silver nitrate solution is shown on Figure 7. The mean value of the chloride migration coefficient was calculated to be $8.454*10^{-14}$ m^2/s. According to this result, the resistance of the tested UHPC was 8-10 times higher than the ordinary concrete, which classifies this UHPC in the group „very good", i.e. in the highest exposure class XD4, as defined by SRPS EN 206 [15].

3. UHPC WITH THE ADDITION OF LIMESTONE FILLER

The second stage of the investigation of UHPC was aimed towards creating a new, more environmentally friendly mixture. From the previous chapter and the overview given in [3] it can be concluded that this type of concrete contains a very high amount of cement, usually ranging between 800-1000 kg/m3. This value of consumed cement is one of the obvious obstacles for further development and wider application of UHPC. The cement industry is typically renowned for its negative influence on the environment. So, it is necessary to find a solution to preserve great mechanical and durability characteristics of UHPC and in the same time to reduce the usage of cement. As it was already mentioned, one of the possibilities is to replace part of the cement with some other fine granulated component material. Considering the fact that in UHPC between 30% and 35% of cement does not get activated during the hydration process, it is obvious that it would be a good idea to replace it with some other component [16]. Since the inactivated cement acts like the filler in UHPC mixtures, the decision was made to replace a part of cement with limestone (LS) filler.

LS filler is a fine mineral material that has been used in concrete production for many years. It is a component that is produced by crushing and grinding of the natural stone - limestone. LS is widely applied in Serbia, as well as across the world, so it was easy to implement its utilization in these UHPC mixtures. During the years, different researches have concluded that LS brings many benefits when added to normal concrete and UHPC mixtures [17, 18]. It can provide better packing density, if particles are finer than cement particles, but also it can improve the process of cement hydration [17, 18]. The workability and flowability of fresh concrete are also better when LS filler is applied. This improvement becomes important when the fibers are added to mixture, because the addition of fibers disturbs the properties of fresh concrete mixture.

From the referent literature overview, the following conclusions were made:

- LS filler should have finer granulation than cement or at least the same one,
- The optimal amount of cement to be replaced by LS filler should be between 20 and 30%; higher quantities may also be used, but should not exceed 50% of the total mass of cement.

With these conclusions, several new mixtures of UHPC with LS filler as SCM were investigated at the Faculty of Civil Engineering in Belgrade. The basic mixture (reference) was the one described in the previous chapter (see Table 1), which was made with Lukavac cement.

Figure 5: Surface of concrete sample after 25 cycles of freeze-thaw and salt attack [7]

Figure 6: Sample surface after treatment with phenolpthalein solution [7]

Figure 7: Sample surface after treatment with silver nitrate solution [7].

Table 3: Basic and four new mixtures [2]

Mixture	BM	F-20	F-30	C-20	C-30
Cement (C)	1	0.8	0.7	0.8	0.7
Fine filler (F)	0	0.2	0.3	0	0
Coarse filler (C)	0	0	0	0.2	0.3

3.1. Experimental program

As it was already stated, the reference mixture was the one made with Lukavac cement. Four new mixtures, made with addition of LS filler were prepared by replacing a certain amount of cement in the basic mixture (BM). The two types of LS filler were used: one with the main particle size of 2.5 μm (F-fine) and the other with 11 μm (C-coarse). For each type of filler, two mixtures with LS as a cement replacement were prepared: with 20% and 30% of cement replacement (by mass). In Table 3, an overview of the investigated UHPC mixtures is presented; the numeric values are given as a percent of the cement mass in BM.

The process of mixture preparation was the same as the one showed in Figure 1, for the case when fibers were not added. The only difference was that all components were measured manually, and their mixing in the dry stage lasted for 5 minutes, instead of 2 minutes as for the premix. Three basic properties of UHPC were determined: density, compressive strength and consistency (flowability). Concrete density in the hardened state was determined on cubes with dimensions 10x10x10 cm, as well as the compressive strength in the same way as it was described in Chapter 2. The flow test was performed in accordance with SRPS EN 12350-5 [19].

3.2. Results and discussion

For all mixtures, the density was measured in both fresh and hardened state. The mean value of density for all mixtures in the fresh state amounted to 2235 kg/m^3 and 2220 kg/m^3 in the hardened state. Those values match the values obtained in the first stage of investigation (see Chapter 2).

The obtained results of the flow test showed that the starting premises were correct. Namely, almost all mixtures with the LS filler had better workability than the BM (except F-20). When comparing different mixtures made with LS, it can be concluded that the replacement of cement by 30% of fine LS filler had the most influence on the flow test results. In the case of 20% of cement replacement, the coarse (C) filler showed notably better result than the fine (F) filler. The complete results of the flow test are shown in Table 4, where the mean value of fresh concrete flow diameter (d) is given.

The results of compressive strength test are shown on the graph, which is given in Figure 8. The mean strength at 3 days had the highest value for BM specimens, but also

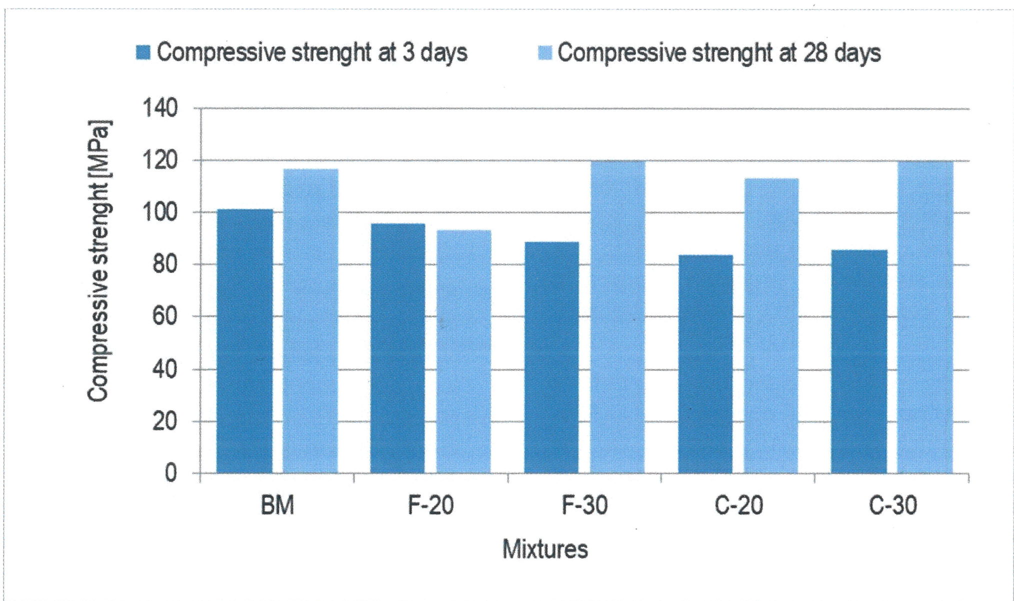

Figure 8: Test results of compressive strength for different ages and mixtures [3].

Table 4: Results of the flow test [2]

Mixture	BM	F-20	F-30	C-20	C-30
d (cm)	63.5	56.5	71	68.5	66.5

the mixtures with C filler had lower strength that the ones with F filler, tested at the same age. The situation is quite different when the strength results are discussed considering the specimens tested at 28 days. In this case, the reference mixture (BM) and the mixtures with 30% of cement replacement reached strength values of approximately 120 MPa. So, for the highest amount of cement replacement the filler fineness did not have any significant influence. In the case of 20% of cement replacement, both mixtures (F-20 and C-20) had lower strength that the BM. Also, it can be concluded that all the mixtures with LS addition had higher strength increase, except for the mixture F-20. However, it is necessary to point out that, during the testing of F-20 specimens at the age of 28 days, the equipment malfunctioned, so the obtained results are not credible.

4. CONCLUSIONS

Based on previous literature review and experimental results, the following conclusions can be made:

1. The general conclusion is that tested UHPC has significantly increased physical-mechanical properties and improved durability when compared to the ordinary concrete for usual applications. Increased strength (both compressive and flexural) gives the opportunity for reduction of structural element dimensions and avoidance of classic reinforcement bars (steel fibers might be required if necessary). In addition, improved durability gives us the opportunity to use UHPC in structures which are exposed to severe deterioration mechanisms (i.e. harmful environmental agents), with a prospect of a much longer service life.
2. This type of concrete is suitable for structures in highly aggressive environments which will be in contact with water, like dams, river and marine bridges (piles and columns in water), etc. Also, the tested UHPC is suitable for structures exposed to severe weather conditions (like concrete slabs of bridges).
3. Main disadvantage of UHPC is the requirement for a large quantity of pure portland cement CEM I (800-1000 kg/m^3) which is especially harmful for the environment (app. 7% of global CO_2 emissions comes from the cement industry and also CEM I is a very expensive component in the mixture). Such a large amount of cement in the concrete mix makes its rheological characteristics (shrinkage and creep) worse in comparison to ordinary concrete.
4. The previous research analysis showed that the optimal amount of cement which can be replaced by LS filler is 20-30%, with a maximum of 50%. With greater reductions, the amount of cement paste is insufficient and cannot fill the space between QS particles.
5. The flow test results, obtained from own experimental program, showed that both mixtures made with 30% of cement replacement with LS had similar workability, despite the fact that the two applied types of LS fillers (F and C) had different fineness. The values of measured flow diameter obtained in the test were app. 10% higher in these two mixtures compared with the referent mixture made without LS. These results can be explained by the fact that LS filler particles are spherical in shape, and in a certain way "grease" the fresh concrete mixture giving it somewhat greater fluidity.
6. Early age compressive strength of concrete samples tested during this study were higher for the referent mixture compared to all mixtures made with LS. In concrete mixtures made with LS, the highest 3-day compressive strength was obtained in the mixture with 20% of finer LS filler. The increase in strength over time is more pronounced in mixtures made with LS filler compared to the reference. Both mixtures with 30% of LS filler had similar 28-day compressive strengths, which were somewhat higher compared to the referent one. The effect of filler fineness was not noticeable.
7. When compared to the UHPC premix as a reference, the composite made with addition of LS filler as a SCM had in general better workability, but lower strength values (less then 120 MPa). Without any doubt, such a composite represents a more eco-efficient and sustainable solution, but the decrease in strength puts it into the category of HPC, instead of UHPC.
8. Although there are other similar products on the international market, all participants in the project have acknowledged the importance of application of local component materials for production of UHPC premix. Before long, this concept was verified, especially during the Covid-19 pandemic, when the global market was confronted with huge problems regarding supply of raw materials, as well as production and transportation of goods. In these circumstances, it is essential to have local industry ready for such challenges.
9. The application potential of SFRUHPC and other types of HPC is already wide-ranging and its future

looks very promising. In the last three or four decades, HPC has been successfully used in various special engineering applications. To name just a few important ones: precast bridge girders, bridge deck slabs, seismic columns, wind turbine towers, tunnel linings, piles, ultra-thin structural elements, architectural cladding, etc. Furthermore, this type of concrete can be used for strengthening, repair and reconstruction of existing structures after accidents, damages or expired life cycle period.

10. Application of UHPC demands increased production costs, highly qualified personnel, better quality control, careful curing and special equipment (for instance, high-speed shear mixers). On the other hand, this type of composite brings longer life span, higher design flexibility, rapid construction, as well as improved resistance and robustness of concrete structures.
11. Future research in this field should include tests like DTA-TGA, XRD, ITZ, SEM analysis and additional evaluation of physical-mechanical and rheological properties of the UHPC (such as modulus of elasticity, ductility, hydration rate, creep and shrinkage, etc.).
12. Opportunities for further development of UHPC lay in the premix design optimization, where some amount of CEM I could be partially replaced by mineral additives like various types of industrial slag, ground recycled glass, mine tailings, solidified wastewater treatment sludge, fly ash and others. In addition, it is also possible to replace some amount of quartzite sand with recycled waste glass. These are the ways for development of UHPC in the future, with potentially better properties, lower construction price and less harmful environmental effects.

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