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HIGH STRENGTH CONCRETES BASED ON THE CHOICE OF THE BEST PARTICLE SIZE DISTRIBUTION IN AGGREGATE*

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Abstract. *The requirements of the modern (high-end) construction industry demand the development of new types of concrete of high, and especially very high strength and with significantly improved properties in terms of durability. They provide new possibilities in the field of concrete technology of high strength and performance. When designing the composition of high-strength concrete (HSC), a special attention should be paid to the particle size distribution of aggregates, which should be chosen so as to achieve an "optimal" packing of the aggregate grains. The maximum grain size has been reduced to 2 mm. The Funk-Dinger formula was used to calculate the particle size distribution, which also takes into account fine particles of mineral powder additives. CEM I 52.5R, pure quartz sand, quartz filler, silica fume, powerful superplasticizer and low water/binder ratio were chosen for making HSC. In total, five different concrete mixtures were made. The paper presents the results of testing important properties of hardened concrete at ages from 1 day to 90 days and statistical processing of the obtained test results.*

Key words: *high strength concretes, aggregate particle size distribution, compressive strength, tensile strength*

1. INTRODUCTION

The review of the literature reveals different possible classifications of concrete, regarding the compressive strength, in terms of ranges which define concretes according to this property. Table 1 provides the classification of concrete based on the value of the

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compressive strength which is to a large degree in agreement with the classifications stated by other authors [1].

Procedures employed when selecting the material for making HCS, as well as for calculating the mix composition of HCS differ from the procedures employed for normal strength concretes. In the case of normal strength concretes, the procedures are even defined by ASTM and BS standards while this is not the case for HSC. In the literature, there are recommendations for the choice of materials and specific principles have been established, although, there are also some contrasting opinions. In general, authors agree about the following: It is necessary to

- select the particle size distribution of aggregate which provides the highest possible compactness of concrete when using fillers
- use the highest class cement, or energetically modified cement
- use silica fume and other suitable mineral admixtures
- make concrete with as low w/c factor as possible
- use high range water reducer (HRWR)
- use steel microfibers

Table 1 Classification of concrete based on the compressive strength value

Concrete type	Compressive strength [MPa]
Normal strength concretes	20 - 50
High strength concretes (HSC)	50 - 100
Ultra-High Performance Concrete (UHPC)	100 - 150
Reactive Powder Concrete (RPC)	> 150

As for the HSC mix design, a special attention should be paid to the particle size distribution of aggregate, which must be selected so as to achieve the optimal packing of aggregate grains. A well-chosen particle size distribution should provide a higher packing of grains in a given volume, i.e. the void between the grains should be minimal. After a number of modifications in the approach to the calculation of an "ideal" particle size distribution which would provide the packing of aggregate grains, including fine particles, Funk and Dinger [2] produced the following mathematical expression (1):

$$CPFT = \frac{d^n - d_s^n}{d_{max}^n - d_s^n} \cdot 100\ \% \tag{1}$$

where:

d – is the sieve opening in mm,
d_s – is the finest sieve opening in u mm (finest filler particle),
d_{max} – is the highest nominal value of aggregate grain in mm,
n – is the distribution modulus 0.2 to 0.4,
CPFT – **C**umulative **P**ercent **F**iner **T**han *d*

Chu & all researched mechanical properties and microstructure of UHPC while consistently implementing the principles listed in the previous text [3]. The result of their experimental research were concretes which had the flexural strength from 22 MPa to 24 MPa and compressive strength from 126 MPa to 155 MPa at the age of 28 days.

It is recommended to use CEM I of the 52,5 R strength class for making UHPC. Requirements of the contemporary (high-end) construction industry demand the development of new kinds of binding materials with improved properties, specially designed for concretes of high, and particularly of very high strength, with considerably improved characteristics in terms of durability. They provide a new potential in the field of high strength concrete technology and performance. One of such innovative binders is the Energetically Modified Cement - EMC. The Energetically Modified Cement is produced by intensive grinding – mechanical activation of pure Portland cement (CEM I) together with various kinds of mineral admixtures. This technology was developed at the Department of Civil engineering at the Luleå University of Technology, Sweden [4]. Additional intensive grinding achieves a number of goals: activity of cement, puzzolanic activity of fly ash and chemical reactivity of ground granulated slag are all increased. EMC cements have grinding fineness of 5500 to 6000 cm^2/g by Blaine. The use of EMC cement can provide an increase of concrete strength of up to 100% at the same age in comparison with the high strength concretes made with “ordinary” PC.

In their experimental research Artega & all investigated the effects of energetically modified cement on achieving high concrete strengths [5]. They concluded that the replacement of CEM I with 30% to 35% EMC provides concretes with 50% higher strengths than the reference concrete.

The indispensable ingredient of UHPC is the silica fumes. In addition to the so-called micro silica fume, whose specific surface area ranges between 15 m^2/g and 35 m^2/g, for making of UHPC also is used the nano silica fume with the specific surface area from 100 m^2/g to as much as 400 m^2/g. Nano silica fume “completes” the particle size distribution curve in the area of finest particles and provides a great contribution to early strengths of UHPC concrete. Authors who investigate high strength concretes agree that replacing a part of cement with silica fumes contributes to the increase of strength, including those at the earliest age. In the paper [6] the authors published the results which indicate that the replacement of 10% of cement with silica fumes produces concretes which have up to 40% higher strength than the reference concrete.

The following two principles which are observed when designing the composition of UHPC are mutually related, and it is the use of a very low water-binder ratio and the obligatory use of powerful superplasticizers (HRWR) of the latest generation. The water/binder ratio value is usually about 0.25 or even less. For this reason, in HSC and UHPC it is common to use a higher percentage of superplasticizer (around 3%, and even more) than in the normal strength concretes (0.6% to 1.2%) in order to achieve the desired workability which facilitates their practical application. Zhang & all studied the effects of the water-to-binder ratio on the properties of UHPC [7]. The presented results indicate that the reduction of the water/binder ratio from 0.22 to 0.16 (in 0.02 increments) contributes to the increase of the UHPC strength for 50%, and even slightly higher.

In classical concretes, fibers, including steel ones, are used in order to increase the ductility of concrete and of certain increase of tensile strength, which nevertheless remains low. It is considered that the addition of fibers in normal strength concretes has almost no effect on the increase of compressive strength. In the case of UHPC the addition of steel microfibers having length (l) up to a maximum of 25 mm, but usually between 13 mm and 16 mm provides a great contribution to the increase of strength. The fiber diameter (D) is usually 0.20 to 0.30 mm. Aspect ratio l/D is most commonly between 60 and 70. Fang & all in the paper [8] investigated the effects of the percentage of addition of steel microfibers and their geometrical characteristics on the properties of UHPC. The addition of steel microfiber in the amount of 1%, 2% and 3% facilitates the increase of the compressive strength for 10% to 15%, and of the uniaxial tension resistance of up to 300%.

On the basis of the stated principles, the authors of this paper carried out an experimental investigation (which to a great extent can be considered initial) for the purpose of obtaining UHPC which could be implemented in practice. All the principles laid out in the introduction were observed and the results obtained in the experiment are presented hereinafter.

2. Experimental Research

Results of the experimental research presented in this paper are obtained in the Laboratory for Building Materials of the Faculty of Civil Engineering and Architecture of the University of Niš. The experimental research program is conceived so as to verify all previously mentioned principles for making of UHPC which can have practical application. It is planned to vary the type and amount of cement, as well types and amounts of mineral powder admixtures, in combination with low values of the water/binder ratio and different thermo-hygrometric conditions of concrete curing, especially at an early age of concrete. This paper presents only the results obtained so far on the reference concrete, concretes with the addition of silica fume and concretes with the addition of micro-reinforcing steel fibers at the age of up to 28 days. All other results are to be published on future occasions when they become available.

2.1. Materials used in the experiment

2.1.1. Cement

Cement CEM I of the 52.5 R class manufactured by “Moravacem” Novi Popovac was used for making concrete. The cement in question meets all the quality conditions prescribed by the standard SRPS EN 197-1 and they can be considered generally known. The chemical composition of cement is presented in table 2.

Table 2 Chemical composition of cement, silica fume and aggregate

Chemical composition	CEM I 52.5 R	Sikafume XR/TU	Quartz aggregate
		Quantity %	
SiO_2	20.61	94.0	min. 99.00
Al_2O_3	5.45	-	max. 0.40
Fe_2O_3	3.36	-	max. 0.10
CaO	63.42	-	-
MnO	3.84	-	-
SO_3	0.80	-	-
Na_2O	0.2	-	-
K_2O	1.00	-	-
$Na_2O_{eq.}$	0.86	-	-
Loss of ignition	1.00	3.0	max. 0.20
Moisture content	-	1.0	-

2.1.2. Silica fume

Silica fume Sikafume XR/TU was used as a mineral admixture for increasing the early strengths of concrete. The specific surface area of concrete was cca. 22 m^2/g. The chemical composition of silica fume is provided in table 2.

2.1.3. Aggregate

Quartz sand produced by "Jugo Kaolin" at the Divci screening plant was used for making concrete. Three aggregate fractions were made: 0/0.5 mm, 0.4/0.8 mm and 1.4/4 mm, from which, all the subfractions of the full set of sieves were screened starting from < 0.063 mm to 2 mm. Rock flour obtained by grinding quartz from the screening plant Rgotina, also by "Jugo Kaolin" was used to provide the presence of the finest particles. This created the potential to compose the particle size distribution according to the Funk-Dinger formula with the modulus $n = 0.365$. The particle size distribution is shown in figure 1, while the chemical composition is presented in table 2.

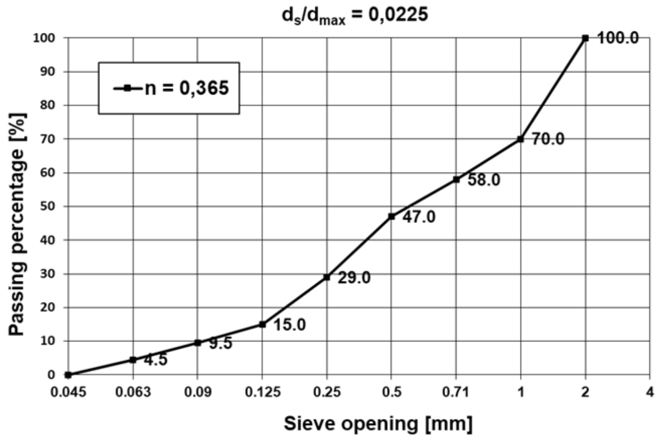

Fig. 1 Particle size composition of aggregate for concrete making

2.1.4. Steel micro fibers

In the experiment were used true steel micro fibers of circular cross-section from the cold drawn wire labeled as SA/M 0.22 x 13 mm manufactured by "Spajić" d.o.o. Negotin. Factor ratio is 59. The strength of the fibers at uniaxial tension is ≥ 2100 N/mm^2.

2.1.5. Superplasticizer

Superplasticizer of the last generation MC -PowerFlow 3100 produced by MC Bauchemie was used for the purpose of lowering the water/binder ratio and achieving the workability which facilitates the practical use of concrete. This high performance superplasticizer is based on the latest polycarboxylate terpolymer technology, and, among other things, it is designed exactly for making UHPC.

2.2. Composition, making method and curing regime of concrete mixtures

In this phase of experimental research, six concrete mixtures were made: reference (E), concrete mixtures with 10% (SF10) and 20% (SF20) of cement replaced by silica fume, concrete mixtures with 1%, 2% and 3% of addition of steel microfibers labeled as SMF1, SMF2 and SMF3 respectively. Compositions of concrete mixtures are presented in table 3.

For each type of concrete, 4 series of prisms having dimensions 40 x 40 x 160 mm were made so that the required number of specimens would be available for testing the density of the hardened concrete, as well as flexural and compressive strength at the ages of 1, 7, 28 and 90 days. Therefore, the total number of specimens is 72. Spreading on the shaking table was from 200 mm to 220 mm and it was maintained constant by varying the amount of superplasticizer.

Table 3 Concrete mixtures composition

Material	E	SF10	SF20	SMF1	SMF2	SMF3
	Quantity for 1 m^3					
Cement CEM I 52.5 R	735	662	589	735	735	735
Silica fume	-	73	146	-	-	-
Aggregate 0.09/2 mm	1330	1330	1330	1330	1330	1330
Quartz filler < 0.09 mm	140	140	140	140	140	140
Water	184	184	184	184	184	184
Superplasticizer	22.0	25.7	30.6	22,0	22.0	29.5
Steel microfibres	-	-	-	81.7	163.4	245.1
Water/binder ratio*	0.25	0.25	0.25	0.25	0.25	0.25

* *without superplasticizer*

Concrete mixing procedure was considerably modified, and it lasted longer than the standard procedure for the normal concrete. Firstly, sand and filler fractions were dry mixed for 3 minutes, then cement (and silica fume) were added, and it was all mixed for another 3 minutes. Finally, the superplasticizer previously mixed with water was added, after which the mixing continued for 4 minutes to allow the superplasticizer to exhibit its effects. Steel fibers were added only after 10 minutes of mixing when concrete already achieved the desired consistency. After adding fibers, the mixing continued for another 3 minutes. Concrete was placed into the steel moulds in two layers. Vibrating lasted 120 sec. with 3000 vibrations per minute, and amplitude of 0.75 mm.

For the first 24 h, specimens were cured in the moulds in the air having the relative humidity > 90% and temperature 20 ± 3 ºC. From then on, up to the day of testing, all specimens were cured in the water having temperature 20 ± 2 ºC.

3. EXPERIMENTAL RESEARCH RESULTS

In this initial phase of the research, the specimens were tested for: density of hardened concrete, flexural strength (Fig. 2 and 3) and compressive strength (Fig. 4). The tests were performed at the age of 1, 7 and 28 days. The specimens planned for the testing at 90 day did not reach this age at the moment of writing of this paper. The test results are presented in table 4.

It should be mentioned that the parts of the prism-shaped specimens remain connected after failure owing to the presence of steel microfibers – the so-called ductile failure. Figure 3 aims to show the uniform distribution of steel microfibers in the concrete mass and their proper orientation achieved during pouring in the moulds.

Fig. 2 Test setup for flexural strength testing

Fig. 3 Appearance of the concrete with steel microfibers at the failure point after testing the flexural strength

Fig. 4 Disposition during testing the compressive strength (left) and the appearance of the sample exposed to compression until failure (right)

Table 4 Test results of density, flexural and compressive strengths

Concrete label	E	SF10	SF20	SMF1	SMF2	SMF3
	Flexural strength [MPa]**					
1 day	10.3	9.7	10.0	11.4	17.5	22.8
7 days	15.3	16.1	16.8	17.5	24.2	26.7
28 days	18.0	19.2	20.3	22.4	26.7	28.9
Density at 28 days* kg/m^3	2411	2415	2420	2454	2474	2576
	Compressive strength [MPa]**					
1 days	63.6	63.7	64.9	80.2	88.8	95.5
7 days	98.2	103.8	109.5	113.7	124.6	127.7
28 days	106.4	114.1	120,4	129.3	137.0	143.5

* water saturated surface dry concrete

** results in the table represent the mean value of three individual results

Considering the values of the achieved strengths, both flexural and compressive, the choice of the specimen dimension was fully justified. The available capacity of hydraulic presses used for testing of mechanical strength of concretes at the faculties and institutes in Serbia is most often 3000 kN, so they could not be used to test the cube shaped specimens, having sides of 150 mm.

4. Test Results Discussion

The discussion of the test results is based on the comparison of the achieved strengths of individual concretes with the strengths of the reference concrete. The values of flexural and compressive strengths at all ages are adopted as the unit values, while the strengths of other concretes are expressed as a change in respect to the unit value. The test results comparison is provided in table 5.

Table 5 Comparison of the flexural and compressive strength testing

Concrete label	E	SF10	SF20	SMF1	SMF2	SMF3
	Flexural strength [MPa]					
1 day	1	0.94	0.97	1.11	1.70	2.21
7 days	1	1.05	1.05	1.14	1.58	1.75
28 days	1	1.07	1.13	1.24	1.48	1.61
	Compressive strength [MPa]					
1 day	1	1.00	1.02	1.26	1.40	1.50
7 days	1	1.06	1.12	1.16	1.27	1.30
28 days	1	1.07	1.13	1.22	1.29	1.35

It can be established that the reference concrete has respectable values of flexural and compressive strength at all ages. The replacement of a part of cement with silica fume in the amount of 10% and 20% contributes to the further increase of flexural and compressive strengths. The increase of the flexural strength, and also the compressive strength at the age of 28 days amounts to 7% in the case of replacing 10% of cement, i.e. to 13% in the case of replacing 20% of cement with silica fume. Silica fume, due to its exceptional fineness and high content of amorphous silicon dioxide, is highly reactive and efficient puzzolanic material. In addition to the puzzolanic reaction, an extremely small size of silica fume particle size also helps increase the density of the binding paste by filling in the voids between the cement grains, which enhances the packing of particles and distribution of pore sizes, and which is particularly important, the quality of the transit zone, figure 5 [9].

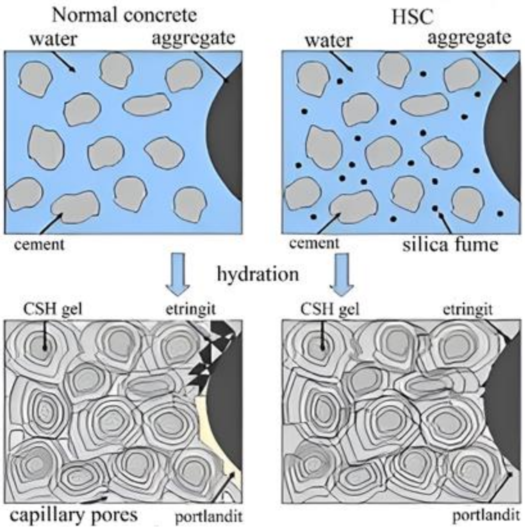

Fig. 5 Role of silica fume in fresh and hardened concrete

For the reasons of its exceptional fineness, silica fume increases the required amount of water for making concrete, see table 3. For this reason, the use of the chemical admixture (additive) such as superplasticizer is necessary, as it is high range water reducer (HRWR). It should be mentioned that the replacement of cement in the amount 20% with silica fume is very high, and that it was done only for the purpose of providing base research in the initial phase of the experiment. It is common to replace the cement up to 10%, very rarely up to 15%.

The effect of addition of steel microfibers in terms of increasing strength of fine grain concretes is more than justified, and it is much more efficient than the addition of silica fume. The increase of flexural and compressive strength is much more prominent at young age of concrete (1 day or 7 days) but this contribution remains considerable at a later date, too. Also, the effect of the increase of strengths is higher if the percentage of addition of fibers is higher, table 5. The addition of 1% of steel microfibers at the age of 28 days causes the increase of the compressive strength for cca. 20%, the addition of 2% fibers for cca. 30%, and the addition of 3% of fibers increases the compressive strength for around 35%. This was also the highest measure compressive strength, amounting to 143.5 MPa. The addition of 3% of steel microfibers can also be considered extreme, and on this occasion the first problems with mixing of fresh concrete occur, that is, one should use the appropriate high energy mixer.

5. Conclusion

Based on the obtained results of the experimental research a number of conclusions can be drawn, which can be used as a good basis for the future experimental work. In brief, the following conclusions can be made:

- By observing the fundamental and widely accepted principles, (mentioned in the introduction) UHPC can be successfully made
- With a proper choice of material for making concrete, using only CEM I in a fairly simple way, the compressive strength of 100 MPa and higher can be achieved
- Replacement of a part of cement using silica fume contributes to the further increase of flexural and compressive strengths
- Addition of steel microfibers provides a particularly high contribution to the strengths of concrete, whose increase can be up to 35% at the age of 28 days in relation to the reference concrete (addition of 3% of fibers)

The use of certain industrial byproducts which would have the role of fillers, different forms of curing, particularly in the initial period are in the plan of the future experimental research. Also, a considerable expansion in terms of types of test is planned, primarily concerning the resistance of such concretes to the adverse environmental effects.

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References

1. American Concrete Institute® - ACI 363R-10: Report on High-Strength Concrete. Reported by ACI Committee 363, First Printing March 2010.
2. James E. Funk, Dennis R. Dinger: Predictive Process Control of Crowded Particulate Suspensions Applied to Ceramic Manufacturing. Kluwer Academic Publishers, Boston, MA, pp. 786, 1994.
3. H. Chu, L. Gao, J. Qin, J. Jiang, D. Wang: Mechanical properties and microstructure of ultra-high-performance concrete with high elastic modulus. Construction and Building Materials, https://doi.org/10.1016/j.conbuildmat.2022.127385.
4. V. Ronin, L. Elfgren: Energetically Modified Cement (EMC) – Performance Mechanism. Center for High Performance Concrete, Luleå University of Technology, March 01, 2003, Sweden
5. J. C. Arteaga-Arcos, O. A. Chimal-Valencia, H. T. Yee-Madeira, S. D. de la Torre: The usage of ultra-fine cement as an admixture to increase the compressive strength of Portland cement mortars. Construction and Building Materials, https://doi.org/10.1016/j.conbuildmat.2013.01.017
6. J. C. Lim, T. Ozbakkaloglu: Influence of silica fume on stress–strain behavior of FRP-confined HSC. Construction and Building Materials, https://doi.org/10.1016/j.conbuildmat.2014.03.044
7. C. Zhang, Z. Wu, C. Luo, X. Hu, K. Li, C. Shi, N. Banthia: Size effect of ultra-high-performance concrete under compression: effects of steel fiber characteristics and water-to-binder ratio. Construction and Building Materials, https://doi.org/10.1016/j.conbuildmat.2022.127170
8. H. Fang, M. Gu, S. Zhang, H. Jiang, Z. Fang, J. Hu.: Effects of Steel Fiber and Specimen Geometric Dimensions on the Mechanical Properties of Ultra-High-Performance Concrete. Materials, 2022, 15, 3027. https://doi.org/10.3390/ma15093027
9. M. Muravljov, D. Jevtić: Građevinski materijali II, Akademska misao, ISBN 978-86-7466-527-5, Beograd, 2014.

BETONI VISOKIH ČVRSTOĆA BAZIRANI NA IZBORU NAJBOLJEG GRANULOMETRIJSKOG SASTAVA AGREGATA

Zahtevi savremene (vrhunske) građevinske industrije zahtevaju razvoj novih vrsta betona visoke, a naročito veoma visoke čvrstoće i sa značajno poboljšanim svojstvima u pogledu trajnosti. Oni pružaju nove mogućnosti u oblasti tehnologije betona visokih čvrstoća i performansi. Prilikom dizajniranja sastava betona visokih čvrstoća (HSC) posebnu pažnju treba posvetiti granulometrijskom sastavu agregata koji treba izabrati tako da se postigne „optimalno“ pakovanje zrna agregata. Veličina maksimalnog zrna je smanjena na 2 mm. Za izračunavanje granulometrijskog sastava koršćena je Funk – Dingerova formula, koja u obzir uzima i fine čestice mineralnih praškastih dodataka. Za spravljanje HSC izabrani su CEM I 52.5R, čist kvarcni pesak, kvarcni filer, silica fume, powerfull superplasticizer i low water/binder ratio. Ukupno je napravljeno pet različitih betonskih mešavina. U radu su prikazani rezultati ispitivanja važnih svojstava očvrslog betona pri starostima od 1 dana do 90 dana i statistička obrada dobijenih rezultata isptivanja.

Ključne reči: *betoni visokih čvrstoća, granulometrijski sastav agregata, čvrstoća pri pritisku, čvrstoća pri zatezanju*