ACHIEVING MIXTURES OF ULTRA-HIGH PERFORMANCE CONCRETE

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ABSTRACT

Ultra-High Performance Concrete (UHPC) is a relatively new concrete. According to [11] UHPC is that concrete which features compressive strength over C100/115 class. Up to this point standards for this type of concrete were not adopted, although its characteristic strength exceeds those specified in [33]. Its main property is high compressive strength. This provides the possibility of reducing the section of elements (beams or columns) made of this type of concrete, while the load capacity remains high. The study consists in blending mixtures of UHPC made of varying proportions of materials. The authors have obtained strengths of up to 160 MPa. The materials used are: Portland cement, silica fume, quartz powder, steel fibers, superplasticiser, sand and crushed aggregate for concrete - andesite.

Keywords: proportion of materials, steel fibers, silica fume, quartz powder, superplasticiser

REZUMAT

Betonul de ultra înaltă rezistență (BUIR) este un beton relativ nou. Potrivit [11] BUIR este acel beton care prezintă o rezistență la compresiune peste clasa C100/115. Până în acest moment standardele pentru acest tip de beton nu au fost stabilite, deși rezistența sa caracteristică le depășește pe cele specificate în [33]. Proprietatea sa principală este rezistența la compresiune. Aceasta oferă posibilitatea reducerii secțiunii la elementele (grinzi sau stâlpi) realizate din acest tip de beton, în timp ce capacitatea de încărcare rămâne ridicată. Studiul constă în obținerea unor amestecuri de BUIR făcute prin modificarea proporțiilor de materiale. Autorii au obținut rezistențe de până la 160 MPa. Materialele folosite sunt: ciment Portland, silice, pudră de cuarț, fibre de oțel, superplastifiant, nisip și agregat concasat- andezit.

Cuvinte cheie: proporții de materiale, fibre de oțel, silice, pudră de cuarț, superplastifiant

1. INTRODUCTION

Due to the fact that Ultra-High Performance Concrete (UHPC) is not completely understood, there is no worldwide harmonization of the existing standards and codes for this type of concrete. If [11] calls it the concrete that exceeds the C110/115 class, according to [19] UHPC is a material with the following characteristics: a compressive strength of minimum 150 MPa and a tensile strength that is more than 5 MPa. According to [28] UHPC is a material with a compressive strength that must exceed 150 MPa. They are also taking into consideration a maximum size for aggregates and a maximum water-binder ratio (W/B).

2. EXPERIMENTAL STAGE

The study started from the need of a mix of UHPC using local materials and the least amount of cement (which is the most expensive material) and getting higher compressive strength without resorting to heat treatment.

2.1. Materials which form UHPC

Determining the composition of UHPC concrete mixes started with setting target values for compressive strength and achieving a self-compacting concrete (SCC) with rheological characteristics according to the method proposed by [25] which was adopted by the European Guidelines for Self-Compacting Concrete. In Romania the guidelines were first introduced in 2008 by [16] and [14]. The selection of the best materials available according to [1] used for the production of High Performance Concrete (HPC), is only one step in the efficient and economical production of concrete. Currently, it is generally admitted that the selection of cementitious materials (binder) and the optimization of the composition of a HPC or UHPC requires attention and experience [7]. After examining the most appropriate material selection, particular focus must be kept on the proportions in order to achieve desired properties in HPC [2].

2.1.1. Cement

Cement is a key component for all types of concrete: Normal Strength Concrete (NSC), High Performance Concrete (HPC) and Ultra-High Performance Concrete (UHPC). The type of cement used was CEM I 52.5R [6], according to [32], Portland type cement with high initial strength.

2.1.2. Mixing water

By using a low water-cement (W/C) ratio the compressive strength can be improved. In conventional concrete the water-cement ratio is usually between 0.4 and 0.6 but not less than 0.4, in order to obtain a good hydration and a workable concrete mix. In UHPC a very low W/C ratio of about 0.15 to 0.30 is used to obtain a stronger, denser material structure. By doing so, the number of capillary pores is reduced due to the small amount of water in the mixture. In the presented study the water-cement ratio was between 0.25÷0.32. The water used, was from the public water supply. According to [35] this type of water needs not be tested, it is considered suitable for use in the production of concrete.

2.1.3. Admixture

A side effect of a low W/C ratio is that the workability of the concrete mixture decreases. This can be compensated by using admixtures which improve the workability of the concrete mixture [34]. Since UHPC has a very low water/cement ratio (W/C) for a good workability, the best possible solution is the use of the latest admixture type of superplasticiser, namely polycarboxylatether (PCE). It is also called High Range Water Reducers (HRWR). The density of the superplasticiser is about 1.07 kg/dm^3. The admixture is added to the concrete during mixing. The suggested consumption by the producer [22] and [30] is between 1÷50g per kg of cement for normal strength concrete (NSC), in this case it was around 50g per kg. The possibility of tailoring additives for specific purposes is likely to be one of the most important sources of innovation in the future [29].

2.1.4. Silica fume

The optimum dosage of silica fume (SF), according to research by [27] is 25%. Through its presence it is possible to obtain high strength and low permeability both at early ages and at later ages. Particles finer than cement, for the most part SF, are introduced to fill the intergranular space and to achieve a denser packing [26]. The aforesaid can be visible in Fig 1. This was studied in detail and had developed algorithms which are represented in 3D by [13] and [31].

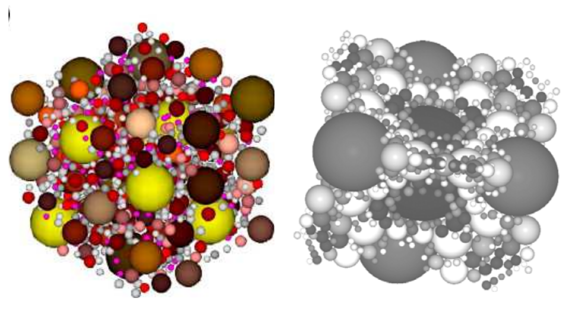

Fig. 1. Simulated 3D microstructure of UHPC based on mathematical algorithm. [13] (left) and [31] (right)

Achieving a maximum compaction from all particles (cement, SF and sand) so that each type is used to fill the gaps of larger particles (Apollonian distribution) is a must for a dense mixture. SF is a type II concrete addition, which includes pozzolanic or latent hydraulic materials such as natural pozzolan and fly ash. SF is a by-product of industrial production of silicon or ferro-silicon alloy, having in composition round particles of silicon dioxide. This spherical particles help to increase the fresh concrete workability and because the particles are more than 100 times smaller than cement, they fill the space between the concrete. By this they grow density and compactness [7]. SF is a very reactive pozzolana with a specific surface area of 18÷25 m^2/g and the recommended dosage by the producer is within the range 2÷10% by weight of cement. The density of this latently hydraulic blend of active ingredients is about 300 kg/m^3.

2.1.5. Quartz Powder

Quartz powder (see Fig. 2) is a type I filler for concrete, used to improve the grading curve and to achieve excess paste, giving concrete a very good flow. The quartz aggregate is assigned an elastic modulus of 97 GPa and a Poisson's ratio of 0.08 [5].

Fig. 2. Quartz powder

2.1.6. Steel Fibers

The main purpose for adding steel fibers to UHPC is to improve his tensile behavior. Steel fibers increase the ductility of brittle materials, but the addition of fibers to concrete enhances also its toughness and strain at peak stress [24]. Hybrid reinforcement concept (adopted by the authors in the study) was developed by [20], using a short fiber and long fiber blend. For UHPC was developed a concept based on the so called "multiscale" to a mixture of fibers of different sizes [27]. The mixture of fibers increases the tensile strength and strain capacity for a percentage of reinforcing fiber of more than 1%. The maximum fiber is limited by the need to achieve workability [8]. The fibers used were of two types: short straight fibers, trade name WHS 9/0.175/S and long fibers with wavy ends WMS 25/0.4/H/AISI [4] (see Fig. 3). The raw material from which they are made of is a corrosion-resistant high carbon wire. The surface is stainless steel with no coating, free of fat and oils. The main advantages are: they increase the compressive-, tensile- and bending strength, reduce requirements for independent reinforcement bars, reduce crack width, improve ductility, retrieve efforts of contractions and improve resistance to freeze-thaw. Among the disadvantages: it can sometimes be seen on the surface of the concrete and they rust in corrosive environments. For the short fibers the tensile strength is minimum 1450 N/mm^2 and for long fibers is minimum 2200 N/mm^2 (high tensile strength). Other features are: density 7850 kg/m^3 and a melting point around 1450÷1520 °C.

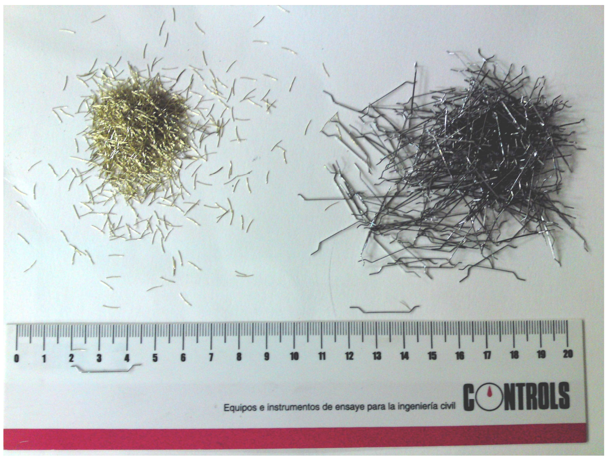

Fig. 3. Long and short steel fibers

The fibers used were added into the mix as an addition. The reinforcement ratio studied was 1% by volume for mix 13 and 2% for mix

14. The dosage of steel fibers (kg/m^3) was calculated with the equation from [3]

2.1.7. Aggregates

Aggregates used were river sand with a range between 0/4 mm and andesite [36] with a range between 4/8 mm. The sand had a density of about 1300 kg/m^3 with a determined humidity of 5%. A visual examination of the 4/8 mm aggregates reveals that it is only one type of rock, igneous rock - andesite basaltic compact, gray color with irregular scrap shavings, homogeneous aspect in terms of compactness color and mineralogical composition. The structure is porphyritic with no alteration zones and contains no minerals leading to a rapid deterioration over time. The mineralogical composition is: feldspar macle plagioclase ~5%, pyroxene ~6%, rarely quartz. The pilotaxitic pasta consists of microliths of plagioclase feldspar and pyroxene ~89% [15]. The grading curve fits the favorable mix total grain size area for maximum aggregate size of 8mm [10].

2.2. The results of the research into the fresh concrete

To achieve the proposed objective 9 mixes have been made without fibers and to a number of another 5 mixes added hybrid fibers (short 1/3 and long 2/3) were added. The mixes with best characteristics (fresh and hardened) are presented in Table 1.

Table 1. *Mix proportions by weight of cement*

Constituents of UHPC	Mixes			
	no fibers		with fibers	
	R 10	R 11	R 13	R 14
Cement	1	1	1	1
Water	0.27	0.25	0.27	0.25
Super-plasticiser	0.04	0.04	0.05	0.05
Silica fume	0.27	0.25	0.27	0.25
Quartz powder	0.70	0.65	0.70	0.65
Fibers	0.0	0.0	0.13	0.22
Sand	0.54	0.50	0.54	0.50
Andesite	0.92	0.85	0.92	0.85

According to the results that refer to mixes chosen and represented in Table 2, the characteristics required by Self-Compacting Concrete (SCC) are not achieved [9], but they are sufficient for fluid concrete (very workable) and easy to put into work, see Fig. 4. The concrete achieved is used to cast structural elements for the experimental study of the PhD thesis of two of the authors.

Fig. 4. Image taken during the casting of structural elements

The differences between the experimentally determined and the calculated density do not exceed the range of 40 kg to 1 m^3 of concrete.

Table 2. *Fresh UHPC properties*

Features of UHPC	Mixes			
	no fibers		with fibers	
	R 10	R 11	R 13	R 14
W/C	0.27	0.25	0.27	0.25
W/B	0.22	0.20	0.22	0.20
Slump [mm]	260	250	215	205
Slump-Flow [mm]	460	440	390	360
Calculated density [kg/m^3]	2444	2494	2523	2607
Experimental density [kg/m^3]	2412	2450	2492	2582

A representative Slump-Flow test, conducted for mix 14, is shown in Fig. 5.

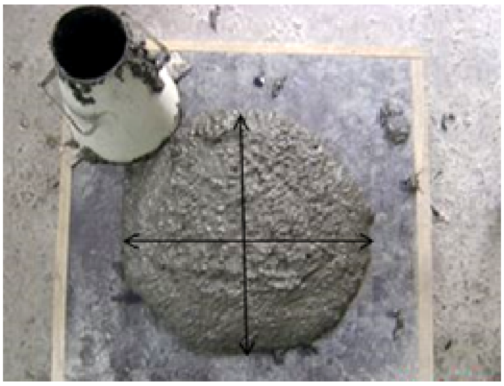

Fig. 5. Slump-flow for mix R14

2.3. The results of the research regarding hardened concrete

2.3.1. Results for compressive strength

Through mix 14 the strength target was reached. The influence of fibers in the concrete mix is relevant. Mixtures with fibers, increases resistance against the mixes without reinforcement from 138.6 MPa (R11) to 160.4 MPa (R14) and 91.7 MPa (R10) to 145.7 MPa (R13). The size of the sample is important. Higher compressive strength has been obtained with smaller samples. Therefore [21] states that samples with base size of less than 100 mm should be considered by European Standards, as UHPC aggregates are composed mainly of small-sized grains. The experimental data was obtained on cubic specimens with an edge of 150mm, 100mm, 71mm and 50mm. The eloquent data is presented in the Table 3.

Table 3. *Mean value of compressive strength of concrete for 50mm cubes*

fcm [MPa]	Age [days]	Mixes			
		no fibers		with fibers	
		R10	R11	R13	R14
fcm1	1	65.1	86.9	86.6	90.1
fcm7	7	88.7	110.9	115.4	120.1
fcm28	28	91.7	138.6	145.7	160.4

In the specialized literature according to [12] and [18] the equivalence relation can be used to develop the results obtained with different cube sizes for all classes of concrete strength see Table 4. Due to the fact that the concrete is composed of different structural members, it can be assumed that as the volume of the sample subjected to stress is greater, the greater the probability that it contains an element having a small resistance is [23]. Followed by a study [7] acquires a relationship of equivalence, relationship presented in the same table.

Table 4. *Equivalence of the average compressive strength for cubes of different sizes made for the experimental results of the research*

Source	Mathematical relationship
fib Bulletin 42 (2008)	fc,cube200 = 0.95*fc,cube150 = =0.92*fc,cube100
Ionescu I. [17], (2007) HPC	fc,cube150 = 0.97*fc, cube100
Corbu O. (2011) UHPC-RPC	fc,cube150 = 0.920*fc, cube100 = =0.844*fc, cube71 = =0.827*fc,cube50
Popa, Corbu (2013)UHPC	fc,cube150 = 0.971*fc, cube100 = =0.899*fc, cube71 = =0.822*fc,cube50

2.3.2. Results for tensile strength

In principle tensile strength is within the range 1/10 to 1/20 of the compressive strength, the results showed an average ratio of 1/12, see Table 5.

Table 5. *Mean value of flexural tensile strength of concrete for 100x100x300mm prism*

fctm,fl [MPa]	Age [days]	Mixes			
		no fibers		with fibers	
		R10	R11	R13	R14
fctm,fl28	28	6.9	8.8	14.9	15.5

3. CONCLUSIONS

Research has led to the achievement of UHPC which presents high workability in fresh state and high initial strength in hardened state. The compressive strength of 160 MPa is achieved due to the introduction of steel fibers in the concrete composition.

The special properties of the mix R14 are obtained with a moderate dosage of Portland cement and an excessively small W/B ratio. This is possible by using the new generation of superplasticisers on the maximum dosage recommended by the manufacturer, using reagents with high reactivity pozzolan (SF) and the incorporating steel fibers.

The increase of the compressive strength of the mixtures with steel fibers towards the mixtures without reinforcement, is fcm28 (R13) = 1.589*fcm28 (R10) and for fcm28 (R14) = 1.157*fcm28 (R11).

The increase of the tensile strength of the mixtures with steel fibers towards the mixtures without reinforcement, is fct28 (R13) = 2.159*fctm,fl28 (R10) fctm,fl28 and for (R14) = 1.761*fctm,fl28 (R11).

Achieving reinforcement with steel fibers, it reduces the risk of cracking at plastic shrinkage and at drying. Steel Fibers improves durability by limiting crack.

Designing a mixture of a HPC and UHPC is crucial because it will determine its structural performance level. There is no standardized mixture, because each application requires a characteristic mix.

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