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Physical-mechanical properties and durability of ultra-high performance concrete (UHPC)

Stefan Mitrović*[1)], Dragana Popović[1)], Miroslav Tepavčević[2)], Dimitrije Zakić[1)]

[1)] *University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia*
[2)] *DNEC, Abu Dhabi, UAE*

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ABSTRACT

This paper presents the results of the authors' laboratory testing of physical, mechanical and durability properties of Ultra-high Performance Concrete (UHPC). The short history of development and application of UHPC concrete is presented in the first part of this paper while the second part deals with the experimental investigation, presenting the results of material characterization obtained from physical-mechanical and durability tests. Based on the results shown in the paper, the mean value of compressive strength obtained at 28 days is 114 MPa, with the average density of 2270 kg/m3 in hardened state. The results showed that tested UHPC belongs to the highest class of water impermeability V-III, as well as the highest class MS0 (without visible damage) in a simulated freeze-thaw environment and de-icing salt attack test. Also, the highest class XM3 for abrasion resistance was achieved. Additional tests showed that the tested concrete fulfils the requirements for the highest exposure classes XC4 and XD4, in terms of resistance to carbonation and the penetration of chloride ions. Conclusions and recommendations for further development and possible application of UHPC are presented at the end of paper.

1 Introduction

Ultra-high Performance Concrete represents one of the most innovative and promising directions of concrete development in modern structural engineering. The reason for the fast development of concrete properties is a rapid growth of the civil engineering industry (Figure 1) [1]. In this context a substantial increase in construction of high rise buildings and long spans bridges within a short time period can be noticed[2]. This is the main reason for a significant enhancement in physical-mechanical properties and the durability of concrete. In the last 30 years, the durability of concrete structures has become a priority in well-developed countries, because 30-50% of the total budget for construction works has been spent on repairs and maintenance of existing structures [3]. A goal to minimize repair costs has led to a remarkable improvement in the durability and impermeability (resistance to harmful environmental agents) of UHPC which in turn translates to reduced maintenance costs and a longer life span of the structures.

UHPC concrete fulfils all the specific requirements of modern civil engineering and therefore has found multiple applications in modern construction in the last 30 years. A great number of technical papers and studies have been published on UHPC concrete, regarding development of its properties and areas of application. In the initial developing phase, UHPC concrete was made with high quality natural materials like cement CEM I (pure portland cement clinker), quartz sand, quartz flour, silica fume, HRWR agents (High Range Water Reducer -super plasticizer), steel fibres. The third intensive source of global CO_2 emission is the cement industry with app. 5% share (Figure 2)[4], [5]. Also, exploitation of quartz sand is endlessly ruining natural resources and it is harmful for the environment. In the last 10 years there is a trend to use cheaper and recycled materials (fly ash, ground granulated blast furnace slag, limestone powder) [6], [7], [8] as a partial cement replacement in UHPC mix designs, as well as partial replacement of quartz sand and quartz flour with waste glass [9].

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* Corresponding author:
E-mail address: smitrovic@imk.grf.bg.ac.rs

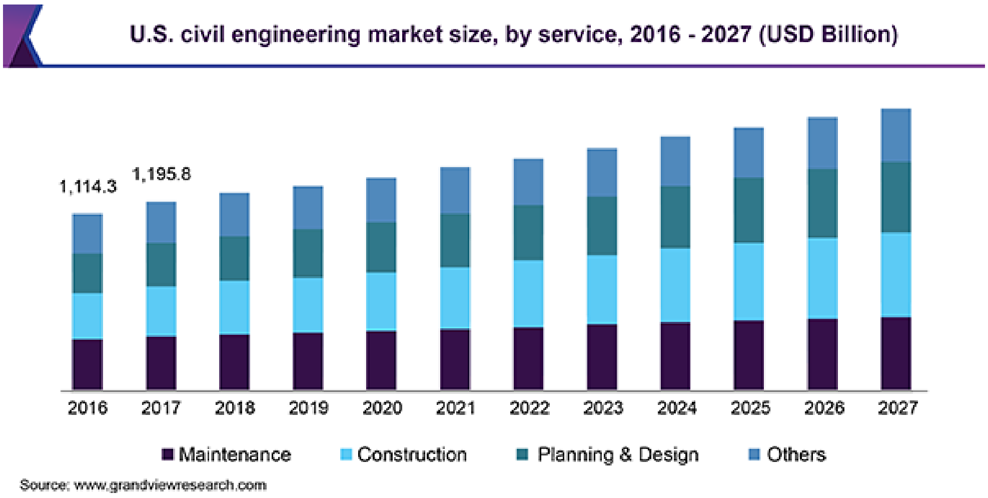

Figure 1. Civil engineering market size in the USA 2016-2027 [11]

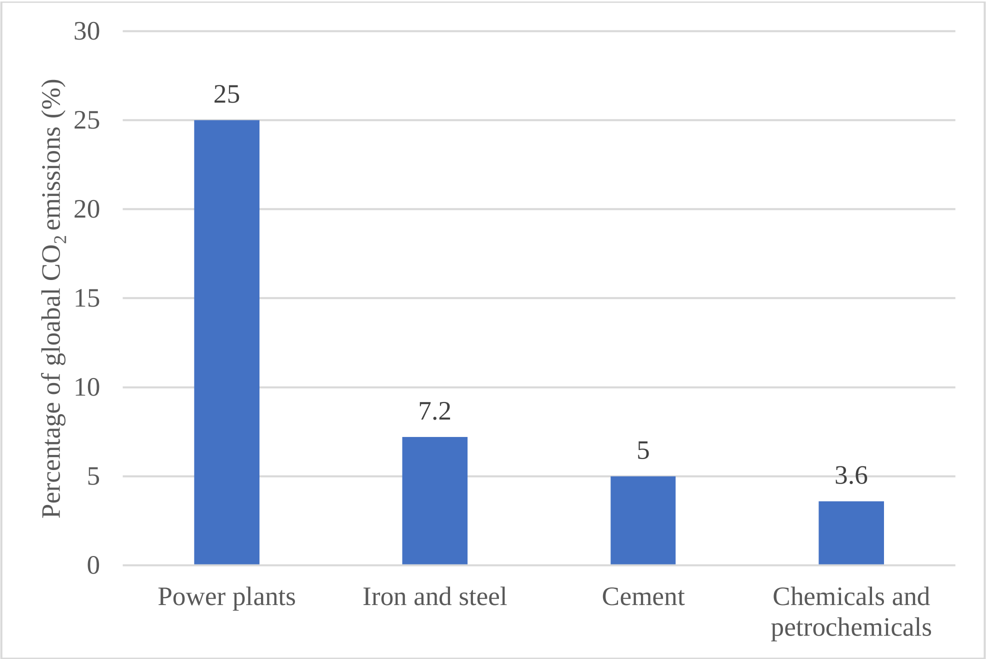

Figure 2. Trend of CO_2 emissions by worldwide industry [5]

2 Ultra-high performance concrete in general

2.1 Definition of Ultra-high Performance Concrete (UHPC)

The most commonly used definition of UHPC is new generation cementitious composite with improved physical-mechanical characteristics, durability and ductility compared to normal concrete and High Performance Concrete (HPC) [10].Current codes, standards and guides already consider parameters for specification of UHPC.

The most important of these parameters are: compressive strength of at least 120 MPa at 28 days, tensile strength of at least 20 MPa at 28 days and high durability and ductility with a very low water/cement ratio.

In several of the recently published papers the authors investigated UHPC concrete with fibres as a combination of three concrete technologies: self-compacting concrete (SCC), fibre reinforced concrete (FRC) and high-performance concrete (HPC) (Figure 3)[11],[12], [13].

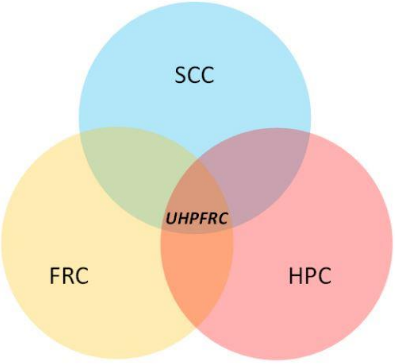

Figure 3. Definition of UHPFRC concrete (UHPC concrete with fibres)[12]

2.2 Properties of Ultra-high Performance Concrete (UHPC)

UHPC is a relatively new material, used for 30 years in construction, and in experimental programme for 40 years. The most important properties of UHPC are:

- UHPC is typically made with large amounts of Portland Cement CEM I (from 700 to 1000 kg/m^3) and with a very low w/c ratio [6], [8], [9], [10], [11], [13], [14], [15];
- This concrete has a high compressive strength (over 120 MPa at 28 days), as well as tensile strength (over 20 MPa at 28 days) [6], [8], [9], [10], [11], [13], [14], [15];
- UHPC is usually mixed like a self-compacting concrete (SCC), which means superior fresh state properties in terms of consistency and workability;
- Improved durability, mainly resistance to carbonation and chloride ion penetration which provide longer service life of structures; also, UHPC has a high-level resistance to water penetration, freeze and salt attack, as well as abrasion resistance;
- Using steel fibres in the mixture helps in strengthening of the cement matrix which exhibits significantly better mechanical characteristics, and also higher ductility capacity of structural elements in seismic area;
- Using UHPC gives the opportunity for reduction in cross sections of structural elements and total costs.

All of the above stated are positive properties of UHPC which were a motivation for further development and application of this construction material. However, UHPC also has some negative characteristics, such as:

- High amount of cement in the mixture with low w/c ratio gives poor rheological properties (shrinkage and creep). Furthermore, a large proportion of cement cannot be completely hydrated with relatively low w/c ratio. This is not eco-friendly and not cost-effective[7];
- Lack of standards and codes for design and numerical modelling of UHPC structures. At the moment, some countries, like France, have guidelines for the design of mixtures and properties of UHPC in a fresh and hardened state [16] and standards for design of concrete structures from non-reinforced, reinforced and prestressed UHPC with or without steel fibres [17];
- Production of UHPC includes increased costs of mixtures, workforce and construction. Qualified workforce and special equipment are required for construction of UHPC structures.

2.3 Application of Ultra-high Performance Concrete (UHPC)

UHPC is rapidly taking an important place in modern engineering. For the last 30 years, UHPC has been used in various applications in civil engineering from buildings to bridges. UHPC can be successfully used for production of precast bridge girders, bridge deck slabs, seismic columns, wind turbine masts, tunnels, piles etc. Besides, UHPC can be used for repair and reconstruction of existing structures after accidents and damages, or the expired life cycle of the structures.

The most important application of UHPC is in bridge construction. Over 40 bridge structures have been completed using UHPC, most of them in the USA, Canada and China[18]. The first application of UHPC in North America was in 1997, for construction of the “Sherbrooke Pedestrian Bridge“(Figure 4) in Quebec, Canada [10]with a clear span of 60 m. The first UHPC bridge in the USA was a highway bridge “Mars Hill Bridge” (Figure 5) with a total span of 33.5 m [19], [20].The span record-holder is a pedestrian bridge “The Peace” made in 2002 in Seoul, South Korea with the main arch span of 120 m [10]. The pilot project for bridge construction in China was a railway bridge “Luan Bai Dried” built in 2006 [21]. In this context, UHPC has been used to ensure connection performance in bridge joints [18].

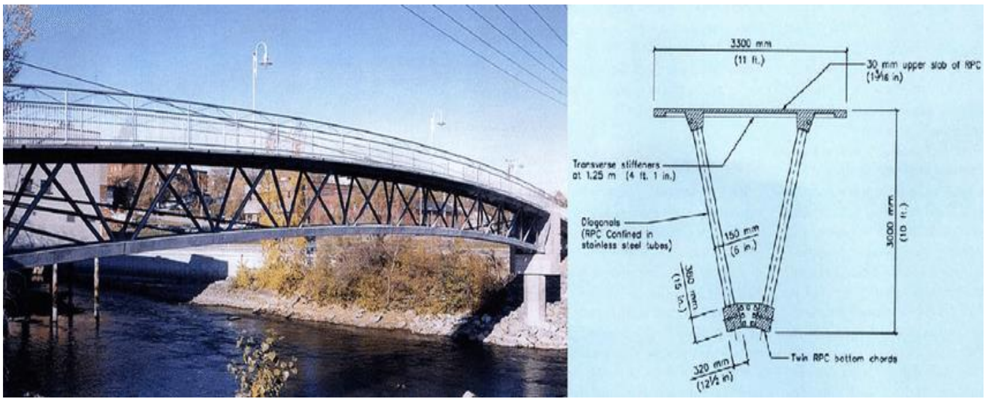

Figure 4. Sherbrooke Pedestrian Bridge, Quebec, Canada (1997) [22]

Figure 5. Mars Hill Bridge, Iowa, USA (2006) [20]

UHPC has also gained interest in the field of building components, such as roof components, cladding, sun shades, lattice façade elements and others. The MuCEM (Figure 6) is the first building in which UHPC was used in different context - as façade elements and cladding [10]. The first application of UHPC in Spain was in 2003 for the composite structural elements of the Reina Sofia Museum in Madrid (Figure 7). Commercial UHPC known as Ductal was imported from France to manufacture the composite columns [10].

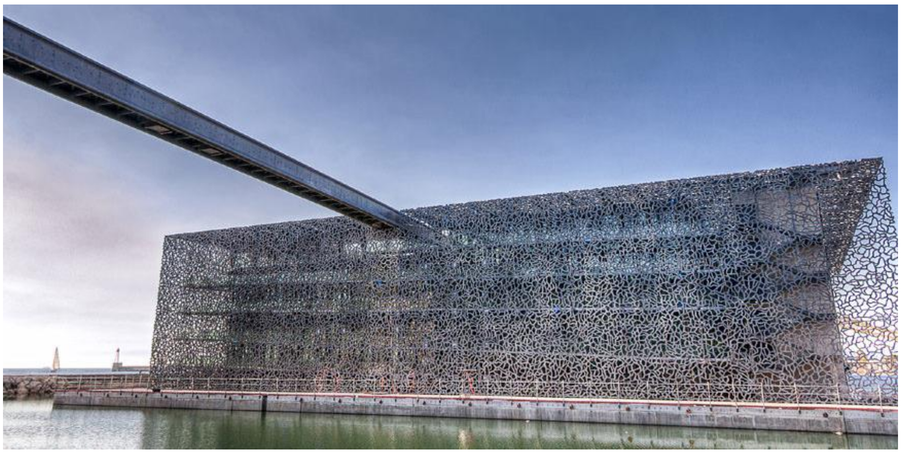

Figure 6. MuCEM museum, Marseille, France (2013) [23]

Figure 7. Reina Sofia Museum in Madrid, Spain (2013) [24]

3 Experimental programme

3.1 Scope of the experimental programme

Laboratory testing included methods to determine the basic physical-mechanical properties (density and compressive strength), water tightness, resistance to freeze-thaw and de-icing salt attack, test of abrasion resistance and additional durability parameters (resistance of the samples to carbonation and penetration of chloride ions).

Examination of UHPC was performed on cubes with dimensions of 10x10x10 cm (compressive strength test) and 7.07x7.07x7.07 cm (abrasion resistance test), as well as on prisms with dimensions of 4x4x16 cm(carbonation test), plates 10x10x5 cm (water impermeability test and freeze-thaw and de-icing salt attack test)and cylinders with a diameter/height of 100/100 mm (chloride ion penetration test).The samples were tested at the age of 1.3 and 28 days according to [25] and [26]. Number of samples is 3 for each of considered test.

3.2 Mixture design

Only one mixture with cement CEM I 52,5R (C), microsilica (MS),coarse quartz aggregate 300-500µm (CQ), fine quartz aggregate 150-300µm (FQ), High Range Water Reducer (HRWR) admixture and water (W) was considered. List of used materials with type, producer and specific density is presented in Table 1. Table 2 shows mixture proportions in relation to the cement amount, whose quantity was 850 kg/m^3 in this research. Mixture was designed according to recommendations from literature and standards for UHPC. The mix was further improved through software model for packing system optimization similar to Andersen & Andersen model. Rapid mixer with volume of 10 litres was used for mixing. Procedure of mixing is explained in Figure 8. Concrete specimens were subjected to wet curing regime, for 24 h under water-soaked cloth.

3.3 Results of the experimental programme

3.3.1 Basic physical-mechanical properties

The basic physical-mechanical characteristics of the tested materials (density, compressive strength) were obtained using the standard methods by testing cubes and prisms with dimensions of 10x10x10 cm and 4x4x16 cm, respectively. At the time of testing, the specimens were 24 hours, 3 days and 28 days old. The test results are shown in Table 3 and Table 4. The compressive strength was tested according to SRPS EN 12390-3:2014[27] and density according to SRPS EN 12390-7:2009 [28].

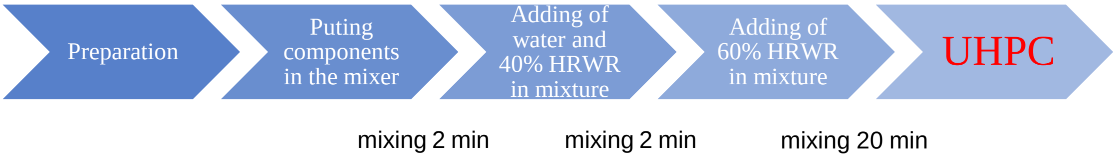

Figure 8. Mixing procedure

Table 1. List of used materials

Material	Type	Specific density (kg/m^3)
Cement	CEM I 52,5R	~ 3150
Sand	Quartz sand	2640
Silica fume	Micro-silica	2200
Admixture	HRWR	1050
Water	Potable water	1000

Table 2. Mixture proportions

Material	C	MS	CQ	FQ	HRWR	W
Proportion	1.000	0.184	1.043	0.337	0.046	0.220

Table 3.Test results of compressive strength

Sample number	Compressive strength (MPa) –age 24 hours	Compressive strength (MPa) –age 3days	Compressive strength (MPa) –age 28days
1	82.4	91.2	-
2	83.2	87.7	115.9
3	90.0	85.7	112.1
Average	**85.2**	**88.2**	**114.0**

Table 4.Test results of concrete density

State	Average density (kg/m^3)
Fresh	**2281.9**
Hardened (after 24h)	**2270.2**

3.3.2 Results of water impermeability test

The test of water penetration under pressure was carried out according to SRPS EN 12390-8:2010 [29]. Examination of water penetration was performed on plate specimens with dimensions of 10x10x5cm at the age of 28 days. The test results are shown in Table 5.

3.3.3 Results of freeze-thaw and de-icing salt attack test

The investigation of the UHPC resistance to frost and de-icing salt attack was carried out according to the standard SRPS U.M1.055:1984[30]. The investigation was carried out on plate samples that measured 10 x10 x5cm at the age of 28 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 9.

Table 5. Test results of water penetration

Sample	**V1**		**V2**		**V3**	
Side	Left	Right	Left	Right	Left	Right
Depth [mm]	5.5	5.0	4.4	4.3	8.9	9.5
Average depth [mm]	**6.3**					

Figure 9. Surface of concrete sample after 25 cycles of freeze-thaw and salt attack

3.3.4 Results of abrasion resistance test

The investigation of the abrasion resistance of UHPC was performed by using a test according to SRPS: B.B8.015:1984 [31]. The used samples were 28 days old and square in shape, with the abrasion surface of 50 cm^2. The test results are shown in Table 6.

Table 6. Results of abrasion resistance test

Sample number	**Volume mass**	**Loss mass m [g]**	**Abrasion wear H_B[cm^3/50 cm^2]**
1	2.29	24.00	**10.60**
2	2.34	24.90	**10.60**
3	2.33	23.20	**9.70**

3.3.5 Additional durability parameters

3.3.5.1 Resistance to carbonation

The investigation of the resistance to carbonation was completed using an accelerated test according to 8. fib Bulletin No.34: Model Code for Service Life Design, fib (2006) [32]. The samples used for this test were prisms, broken at the age of 28 days. The samples were put into a chamber in which they were exposed to CO_2 with a concentration of 2% for the next 28 days at the constant temperature of 20°Cand humidity of 65%. After this period of time, the samples were split apart and tested using phenolphthalein solution C20H1404 and left to dry for 30 mins. After the aforementioned time, the treated sample surfaces were entirely pink, which indicates the following: there is no decrease in the alkalinity of the concrete, specifically the depth of carbonation was measured at 0.00 mm. As a conclusion, the rate of carbonation after the accelerated test has been found negligible

Figure 10. Appearance of the sample surface after treatment with phenolphthalein solution test

3.3.5.2 Resistance to chloride ion penetration

The investigation of the resistance of chloride ion penetration was performed using concrete cylinder specimens with diameter100mm and 100mm long, at the age of 28days. The test was carried out according to the standard NT Build 492: Non-Steady State Chloride Migration, Nordic Council of Ministers (1999) [33]. After the treatment with silver nitrate solution, the penetration of the chloride ions in the form of a layer of silver colour on the surface of the sample could clearly be seen on the treated surface. The chloride penetration was measured at seven points, excluding edges, where the values obtained were used to determine the chloride ion migration coefficient. The test results are shown in Table 7.

4 Discussion of results and conclusions

Ultra-high Performance Concrete represents a new generation of construction material which has been developed rapidly in the last twenty to thirty years. A substantial number of papers covering this composite material has been published recently in scientific and expert journals. Based on the results of the laboratory tests conducted, the following conclusions can be made:

Table 7. Results of chloride ion penetration resistance test

Sample number	**Voltage [V]**	**L_1[mm]**			**I_{30}**	**t_p**	**t_k**	**t[h]**	**x_{av}[mm]**	**D_{nssm}[m^2/s]**
1	60	51.0			1.8	18.6	19.1	120	2.6	**$10.002*10^{-14}$**
2	60	51.5			1.7	18.6	19.1	120	1.8	**$6.888*10^{-14}$**

Figure 11. Appearance of the sample surface after treatment with silver nitrate solution

- First, the concrete density is lower than in normal concrete without and with reinforcement bars (2400 and 2500 kg/m^3 respectively, for normal concrete). The effect of this is a lower dead weight of structures made with UHPC compared to typical concrete structures. This results in reduced design forces and allows smaller dimensions of structural elements. Testing of modulus of elasticity was not in the scope of this investigation, but according to relevant literature this property should be higher than 40 GPa. [34];
- Based on results shown in Table 2, the mean value of compressive strengths obtained at 1 day is 85.2 MPa, at 3 days 88.2 MPa and at 28 days 114.0 MPa lower than 120 MPa (recommended value from standards), but it should be noted that is preliminary testing of premix. This means that the compressive strength of UHPC is significantly larger (3-4times) than normal concrete. Again, this allows smaller dimensions of structural elements made of UHPC;
- The mean value of water penetration was measured at 6.3 mm and it can be concluded that the tested UHPC belongs to the highest class V-III (very low water permeability) as per SRPS EN 12390-8:2010 [29]. This 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.;
- After the freeze and de-icing salt test, no damages were observed on the surface of the samples, which means that the UHPC belongs to the highest class MS0 (zero damage) according to SRPS U.M1.055:1984 [30].Based on this, the UHPC is suitable for structures exposed to severe weather conditions (like concrete slabs of bridges);
- Based on the results shown in Table 5, the average value of abrasion wear H_B was less than14 $cm^3/50cm^2$, meaning that the UHPC belongs to the highest class XM3 according to SRPS: B.B8.015:1984 [31].
- 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. 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 206:2017 [35];
- The mean value of the chloride migration coefficient was $8.454 \cdot 10^{-14}$ m^2/s. According to this result, the resistance of the tested concrete is 8-10 times higher than ordinary concrete, which classifies the UHPC in the group “very good”, i.e. in the highest exposure class XD4 as defined by SRPS EN 206:2017 [35].

Based on all the above stated results, the general conclusion is that UHPC has significantly increased physical-mechanical properties and improved durability when compared to the normal 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 fibres 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.

Main disadvantage of UHPC is the requirement for a large quantity of pure portland cement CEM I (700-1000 kg/m^3) which is especially harmful for the environment (app. 5% of global emissions of CO_2 comes from the cement industry and also CEM I is very expensive component in the mixture). Such a large amount of cement in the concrete mix makes its rheological characteristics (shrinkage and creep) worse.

Opportunities for further development of UHPC lay in the mix design optimization, where some amount of CEM I will be replaced by mineral additions like fly ash, rice husk ash, blast furnace slag, silica fume and others. In addition, it is possible to replace some amount of quartz sand and filler with recycled waste glass. This is the way for development of UHPC in the future with better properties, lower construction price and less harmful environmental effects.

Further development is also possible related to the standards and codes for design of UHPC structures, which will promote UHPC as a contemporary structural material and increase its application potential in civil engineering.

In further studies and research work planned for near future, investigation on the durability of UHPC concrete with steel fibres will be considered as well as experimental investigation of mixture with partial cement replacement and use of recycled waste glass instead of fine quartz and quartz sand. Other tests like DTA-TGA, XRD, ITZ, SEM analysis and further physical-mechanical properties of the UHPC (modulus of elasticity and hydration rate) will be considered in future research as well.

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