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Development of Ultra High Performance Concrete and Reactive Powder Concrete with Nanosilica

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Abstract. The article is dedicated to the design and production of Ultra High Performance Concrete (UHPC) and Reactive Powder Concrete (RPC) using silica fume and nanosilica. Nanosilica and fine steel fibres were used for the production of RPC. Compressive strengths of UHPC and RPC above 150 MPa have been achieved. It has been demonstrated that UHPC and RPC can be produced using standard concrete mixing system without the use of activating mixing and without a special treatment regime during maturing of the concrete. Aging of the concrete took place in a normal environment, without elevated pressure or temperature. The aging process at 20 ℃ allows the use of UHPC and RPC for the ready-mixed concrete when working on high volume construction projects. Even without thermal treatment, without the application of solidification pressure and without autoclaving, RPC reached a compressive strength of more than 180 MPa and a flexural tensile strength after 60 days greater than 22 MPa. The high tensile bending strength may be considered as the main advantage of RPC, as the RPC parameters allow, for instance, the use for pre-stressed structural elements where a high initial strength is also required.

1. Introduction

Ultra High Performance Concrete (UHPC) or Ultra High Strength Concrete (UHSC) refers to composite material with Portland cement based binder with a compressive strength of more than 150 MPa, high ductility and excellent durability. These properties are achieved by high content of cement, low water-cement ratio, using superplasticizers, additives (silica, fly-ash, blast furnace slag, metakaolin) and dispersed reinforcement. Reactive Powder Composite (RPC) is a cement binder material with compressive strengths between 200-800 MPa. It differs from UHPC by higher cement content and maximum grain sizes, which typically do not exceed 600 μm. The main principles of the RPC design include the elimination of coarse aggregate, thereby improving the homogenity of the mixture. Porosity is minimized by granulometry optimization. High strength is achieved by a very dense structure with optimal granulometry of all raw materials, thermal treatment at elevated pressure before and during setting and hardening, high proportion of siliceous extracts and dispersed reinforcement. The positive side of UHPC and RPC is the ability to produce supporting elements of very thin cross-sections, utilizing high strengths of these concrete, thereby relieving the whole construction and further positive is the high durability and associated sustainability and reduced need for repairs.

2. Specification of UHPC and RPC proposal in comparison with normal concrete

2.1. Input raw materials

Ordinary dense concrete has an air content of about 2 %, with UHPC and RPC we are trying to achieve the maximum density, thereby increasing the strength and durability. In addition to cement, we select high doses of very fine admixtures; the maximum aggregate grain size for UHPC can be up to 16 mm, but usually up to 8 mm.

The amount of cement in the UHPC is between 700 and 1100 kg·m^{-3}, which is approximately three times higher than that of ordinary concrete. High dose of cement is one of the reasons for the high price of UHPC, greater development of hydration heat and volume changes during shrinking of concrete. Portland cement CEM I or mixed CEM II strength classes 42.5 or 52.5 are used [1]. Cement should contain a smaller proportion of C_3A due to less consumption of mixing water, which also increases the fineness of grinding [2].

Due to the very low water-cement ratio (typically 14-20 %, compared to 40-50 % for ordinary concrete), UHPC contains less water than is needed for hydration of all cement grains (23-25 % by weight of cement). This way the cement grains also gain a filling function.

Superplasticizers (strongly water reducing) are necessary for the production of UHPC and RPC as the low water-cement ratio and fine impurities deteriorate, or even make the process impossible. A dose of superplasticizer in UHPC can be up to fifteen times higher than in conventional concrete [3]. Superplasticizers based on polycarboxylates proved to be the most effective.

An important component of UHPC and RPC are silica fume. According to various authors [1], [4] and [5], the optimal rate of silica fume in UHPC is between 20-35 %, but it is very dependent on the water-cement ratio, where the lower silica fume content decreases with lower water content. Round grains result in better workability, but mainly fill the gap between cement particles and contribute to a more dense structure. Silica fume reacts with free lime, in small amounts contained in dry cement, but mainly with calcium hydroxide resulting from hydration of cement during CSH gel production. The 18 % amount of silica from the cement weight is sufficient to react with all $Ca(OH)_2$. Not all grains of the cement get hydrated, so less silica fume is enough, however to fill the gap between the cement grains the optimal dose of silica is up to 30 %. In conventional concrete, the silica fume also has a stabilizing function – they reduce water separation. With higher proportions of silica, however, there's an increase in water consumption, resulting in the need to increase the dose of superplasticizers in the UHPC. Silica fume also plays an important role in the transit zone. The transition zone (the area between aggregate and cement paste) in conventional concrete is one of the weakest places because it contains pores and crystals of $Ca(OH)_2$ and ettringite. The layer thickness is 10-50 μm. Thanks to the low water-cement ratio in the production of UHPC and the pozzolan reaction between calcium hydroxide and mineral impurities, the CSH gel is formed and the transit zone then becomes almost as dense as the matrix itself.

The use of nanoparticles in UHPC seems also perspective. These are, for example, nano-silicon dioxide (nano-SiO_2), calcium nano-carbonate (nano-$CaCO_3$), nano-aluminum oxide (nano-Al_2O_3), nano-titanium dioxide (nano-TiO_2) and nano-iron oxide (nano-Fe_2O_3). Their features include a large surface area. Nanoparticles contribute to cement hydration due to their high reactivity, they can act as nano-reinforcement and as filler when they compact the microstructure and the transit zone, thereby decreasing porosity.

Nanosilica has a higher purity, a higher amount of non-crystalline silica, higher pozzolanic activity than silica. Nanosilica increases the amount of hydration products, thus decreasing the amount of portlandite. By adding nanosilica, consistency and water-consumption deteriorate, improving strength, especially at an early stage. The optimal amount to maintain acceptable spill values and at the same time the highest strengths was 3 % of the cement.

Aggregates and fillers. In ordinary concrete, the transition zone is the weakest point of the matrix, with UHPC it is the aggregate. It is therefore necessary to choose hard aggregates such as gabbro, granite, diabase or basalt. The largest grain size is 16 mm, but for strengths above 150 MPa, it is recommended to reduce the size. Larger fractions aggravate the homogenization of the mixture, on the other hand, it is one of the cheapest components of UHPC, therefore from and economic and ecological point of view there's an attempt to use it as much as possible. For example, quartz flour or other residues from aggregate grinding are used as fine fractions in UHPC.

UHPC containing a diffused reinforcement – fibres – is referred to as Ultra High Performance Fibre Reinforced Concrete UHPFRC. UHPC is a brittle material, so there short fibres are added to the mix to improve tensile strength, toughness, hardness and impact resistance. The reinforcement prevents the initiation and propagation of cracks, because it transmits tension through the fibre-to-concrete interface [6]. The most commonly used fibres are steel or carbon due to their high strength. Their content in the UHPC is between 0.5 and 3 % (by volume). High fibre content leads to worse UHPC workability and high cost because 1 % of the volume can be more expensive than the concrete itself. For RPC, a steel fibre dose of 1.5-3 % (volume) is recommended.

2.2. Homogenization

During mixing of the concrete components, the mixture must be homogenized and the air pores eliminated as much as possible. Special procedures have been tried to achieve this, such as vacuum mixing or application of pressure before and during solidification. However, it is desirable to limit these processes because, in addition to the need for special technological equipment, they increase labour and cost compared to conventional strength concrete.

The dosing of components does not differ from conventional concrete; first there are binders, fillers, followed by water with superplasticizing additives (possibly with other additives) and finally dispersed reinforcement. Due to the high content of fines, the required mixing time may be increased.

2.3. Strength

The minimum compressive strength varies according to different authors, but on average the UHPC should reach at least 150 MPa. Tensile strength for UHPC and RPC are between 8 and 15 MPa, and a tensile bending strength of between 30 and 60 MPa. Strengths are affected by composition, storage and care. Long-term strengths according to experiments [7] have shown that 3.5 years of strength were 40 % higher than in 28 days.

3. Experimental part

3.1. Goal of experimental work

Given the current concrete technology, High Strength Concrete HSC with strengths of about 110 MPa is commonly used. However, there is also an area of so-called Ultra High Strength Concrete UHPC, which is characterized by strengths of about 160 MPa, and so-called reactive powder composites RPC with compressive strengths up to about 300 MPa. Until now, UHPC and RPC have not been commonly used in the industry for the construction of monolithic structures. UHPC and RPC are most commonly prepared under laboratory conditions, using a special treatment and homogenization. The realization of the preparation of large volumes of UHPC and RPC for the application on a construction site for the ready-mixed concrete is not very widespread precisely due to the challenging homogenization of the components of this special concrete, e.g. the use of activating mixers. In addition, special care is also frequently required in the course of aging of UHPC and RPC. The conducted experimental work has set out the goal of preparing UHPC and RPC using conventional mixers as they are used for the production of ready-mixed concrete. Also, the maturing conditions were set identically as in the case of treating the concrete after it was stored on the site, i.e. without the use of heat-curing modes.

Another objective of the experiment was to monitor the economic aspect of input materials for the production of UHPC and RPC. The price of these concrete types compared to ordinary concrete is increased by the high dose of cement and microfillers, and in the case of RPC, also the addition of dispersed reinforcement. For the production of UHPC and RPC, high-quality raw materials with well-defined properties and minimal variability of these properties need to be used, which represents a further increase in costs compared to ordinary concrete. The aim of the UHPC and RPC recipe design was, in addition to achieving the high strength required, also using common raw materials so that the UHPC and RPC prices were not too high in the comparison with ordinary concrete.

3.2. Raw materials

3.2.1. Cement. CEM I 52.5 R cement was used. Medium grain is 10 μm, the remaining 20 μm on the mesh screen is 22.2 %. Specific weight is 3140 kg·m^{-3}, specific surface is 501 m^2·kg^{-1}, Na_2O equivalent is 0.65 %.

3.2.2. Silica fume. Silica RW-Füller, RW silicium GmbH. It contains (96.0±1,5) % SiO_2 and not more than 0.9 % SiC, 0.9 % K_2O and 0.12 % Na_2O. The loss on annealing is 1.2 %, pH 7.5. The specific surface area when using the BET method is 18-22 m^2·g^{-1}. 95 % of the particles have a size of less than 10 μm and 70 % less than 1 μm.

3.2.3. Nanosilica. Nanosilica is from SkySpring Nanomaterials, Inc., Houston, Texas. Specific weight is 2160 kg·m^{-3}, apparent density is only 100 kg·m^{-3}, surface area 160 m^2·g^{-1} and content SiO_2 98.7 %. The size of spherical particles is between 10 and 20 nm, but the grains are clustered into agglomerates having a medium particle size of 8.3 μm (measured in aqueous suspension).

3.2.4. Ground limestone. Ground Devonian limestone with a higher proportion of dolomite, specific surface area is 432 m^2·kg^{-1}, apparent density 2160 kg·m^{-3} and specific weight 2540 kg·m^{-3}.

3.2.5. Aggregate. UHPC samples contained 2 or 3 aggregate fractions of: 0-4, 4-8 and 8-16 mm. Mined siliceous sand was used for the 0-4 mm fractions. Basalt coarse crushed aggregates of fractions 4-8 mm and 8-16 mm were washed and dried to remove undesirable dust particles. In the RPC mixtures the aggregate was silica sand, the maximum grain was 0.135 mm.

3.2.6. Superplasticizing additive. Sika® ViscoCrete®-2700 superplasticizer based on ether-polycarboxylate. The bulk density at 20 °C is 1080 kg·m^{-3} and alkali ratio (Na_2O equivalent) is less than 1.0 %.

3.2.7. Water. The mixing water was used from the water supply line.

3.2.8. Fiber reinforcement. The straight thin steel fibers from KrampeHarex were used in the RPC, diameter of 0.2 mm and a length of 6 mm. The tensile strength of steel fibers is 2100 MPa ± 15 %.

3.3. Design and production of UHPC

The water-cement ratio (ratio of water to binder) was calculated in accordance with EN 13263 [8], when calculating the amount of silica fume to a maximum of 11 % of the cement quantity (70 kg for UHPC 1 and 82.5 kg for UHPC 2). The XC or XF environment according to standard EN 206 [9] was not specified, the k-value of silica fume was 2.0. The water-cement ratio for UHPC 1 was 0.18, with UHPC 2 at 0.16. The proportion of silica to cement is in both cases 0.15 and the superplasticizer dose is 2.5 % of the cement. The composition of UHPC is given in Table 1.

Table 1. UHPC composition.

Material	UHPC 1 Quantity [kg m^{-3}]	UHPC 2 Quantity[kg m^{-3}]
CEM I 42.5 R	700	750
Silica fume	105	112
Siliceous sand 0-4 mm	655	725
Aggregate 4-8 mm basalt	265	675
Aggregate 8-16 mm basalt	660	-
Water	155	150
Superplasticizer	17.5	18.75

Mixing: Dispersing into a forced mixer was carried out as follows: firstly, dry ingredients (aggregates, cement, silica fume) were mixed, and then gradually during the mixing the water with superplasticizer additive was added.

After mixing, a Slump test was performed and UHPC was then placed in 150x150x150 mm metal cubes. Compaction was carried out on a vibrating table. The samples were taken out of the forms after 1 day and stored in an aqueous environment until the compression tests were performed after 7 and 90 days [10].

3.4. Design and production of RPC

Two RPC formulas were proposed, the first containing nanosilica (RPC 1), in the second mixture this nanosilica was replaced with ordinary silica fume (RPC 2). The composition is in Table 2 [10].

Table 2. RPC composition.

Material	RPC 1 Quantity [kg m^{-3}]	RPC 2 Quantity [kg m^{-3}]
CEM I 42.5 R	1000	1000
Silica fume	150	180
Nanosilica	30	-
Ground limestone	150	150
Siliceous sand 0-4 mm	1100	1100
Water	290	315
Superplasticizer	17.5	18.75
Steel fibres	110	110

The water-cement ratio was w = 0.23, for the RPC 2 mixture it was increased to 0.25 in order to achieve a higher consistency.

The ratio of sand to cement was 1.1, the amount of steel fibres being 4 % of the volume of the mixture. The proportion of superplasticizing additive is 2.5 % by weight of cement.

Mixing: The nanosilica was first mixed with a total dose of water, superplasticizer and a smaller amount of silica sand for 10 minutes, and this suspension was then used as a dose of mixing water. The steel fibres were poured into the mixer at the end.

4. Tests carried out and results

The consistency of fresh UHPC was determined by the Slump test according to EN 12350-2 [11]. The consistency of fresh RPC was determined by a spill of mortar on the flow table test according to EN 1015-3 [12]. The volume weight was tested according to EN 12350-6 [13] and 12390-7 [14]. The results of those tests are shown in Table 3 [10].

Table 3. Consistency and Volume weight of UHPC and RPC.

Mixture	Slump [mm]	Spill [mm]	Volume weight Fresh concrete [kg.m^{-3}]	Volume weight Hardened concrete [kg.m^{-3}]
UHPC 1	240	-	2550	2530
UHPC 2	240	-	2500	2480
RPC 1	-	190	2620	2610
RPC 2	-	180	2590	2570

The compressive strength was tested according to EN 12390-3 [15]. The values of compressive strength on UHPC and RPC samples are shown in Table 4 [10]. Flexural strength was determined according to EN 1015-11 [16]. Flexural strength values are given in Table 5 [10].

Table 4. Compressive strength of UHPC and RPC.

Mixture	Compressive strength [MPa]			
	7 days	28 days	60 days	90 days
UHPC 1	117.3	148.2	155.6	163.1
UHPC 2	114.2	144.3	154.1	160.1
RPC 1	113.3	156.9	191.9	202.1
RPC 2	104.4	152.2	185.6	190.8

Table 5. Flexural strength of RPC.

Mixture	Flexural strength [MPa]		
	7 days	28 days	60 days
RPC 1	17.2	22.3	24.4
RPC 2	16.9	19.2	22.8

5. Discussion of results

Within the experimental work, UHPC and RPC recipes were designed and produced. Bulk density in fresh and hardened condition, fresh concrete consistency, compressive strength of concrete and tensile strength of concrete after bending have been determined.

The Slump was 240 mm for both UHPC recipes. Due to the high content of fines and the relatively high dose of superplasticizing additive, however, the concrete was very sticky.

The spill of RPC 1 was 190 mm, RPC 2 was then 10 mm smaller, although larger amount of mixing water was used. The content of the wires contributed to a stiffer consistency, as compared to the UHPC the mixture was less sticky. RPC often achieve fluid consistency, so it would also be appropriate to modify the design of the mixture, or to try another type of superplasticizing additive [10].

Volume weight in the fresh state of the UHPC1 mixture was 2550 kg·m^{-3}, for UHPC2 2500 kg·m^{-3}, in solid state it was lower, according to expectations - 2530 and 2480 kg·m^{-3}

Compressive strengths of UHPC were tested after 7 and 90 days. Although UHPC1 contained also a larger aggregate fraction (8-16 mm), the compressive strength was slightly higher.

The compressive strength of 150 MPa was exceeded, which is usually referred to as the threshold for the classification of Ultra High Strength Concrete.

Due to the fact that the UHPC 1 recipe contained 50 kg·m^{-3} more cement than the UHPC 2 recipe and achieved sufficient strength, it would be possible to reduce the cement content, which would contribute to better workability and cost savings while maintaining the required high strength.

Two RPC recipes were designed and produced. The difference between them consisted in the use of nanosilica (RPC 1) and a slightly increased water dose (RPC 2).

A better RPC compaction would be contributed by the softer consistency, which was determined as a spill of mortar at the shaking table; the spill value was 190 mm for RPC 1 and 180 mm for RPC 2. Consistency, however, was very sticky („honey like“) and would complicate use in both prefabrication and in situ casting. The solution could be to adjust the amount of superplasticizing additive, change its type, add water (water-cement ratio was very low) or replace part of the cement with another active ingredient. Increasing the water dose would, however, result in a decrease in strength, so the solution could consist in adjusting the dose of the superplasticizing additive or the change of the type of superplasticizing additive. In order to achieve the optimum consistency of RPC, different combinations of cement, silica dust, superplasticizing additives and limestone-free water, silica sand and steel wires will be tested in subsequent experimental work.

RPC compressive strengths were tested after 7, 28 and 60 days. Even without heat treatment, pressure application or autoclaving, RPC 1 and RPC 2 recipes achieved a compressive strength greater than 180 MPa. The bending tensile strength was 24.4 MPa for RPC 1 after 60 days, with the value of 22.8 MPa for RPC 2. The high tensile bending strength can be considered as the main advantage of RPC, which allows RPC parameters to be used, for example, for pre-stressed structural elements where a high initial strength is also required.

6. Conclusion

UHPC and RPC require careful selection of quality raw materials and their stable properties. When designing, grain aggregate curves have to be followed to achieve dense structure and to choose a superplasticizing additive compatible with the type of cement used, to achieve the desired workability. For optimal homogenization, it is usually necessary to prolong the mixing time.

The biggest disadvantage of UHPC and RPC is economic difficulty. The higher price is mainly due to the high content of cement and silica fume. The use of UHPC and RPC in building structures must be seen in the long term due to its excellent durability. The use of UHPC significantly reduces the need for maintenance of structures and often expensive repairs, especially for transportation infrastructure. In terms of mechanical properties, UHPC and RPC have the potential, in addition to special constructions (such as prestressed structures) especially when building high-rise buildings and bridges. It allows to realize thin cross-sections of the structural elements, which reduces the weight of the whole structure and therefore the loading into the foundations, thus increasing the usable surface. When producing subtle constructions, fuel is saved on aggregate transport, because there’s a smaller need for it. The total consumption of cement depends on the particular building, theoretically it may be less when using UHPC, because smaller UHPC volume is needed than conventional concrete, which has a positive effect on the CO_2 emissions from the cement production. UHPC and RPC exhibit high initial strengths, allowing earlier stripping of formwork and acceleration of construction work.

The major contribution of the study is to demonstrate that UHPC and RPC can be produced using conventional raw materials and using conventional homogenization equipment and without special treatment regimes during the maturing of concrete. No special precautions have been taken with regard to concrete treatment; UHPC and RPC matured under normal laboratory conditions without heat curing. The maturing process at 20 °C allows the use of UHPC and RPC for ready-mixed concrete intended for high volume construction projects. The achieved results are beneficial for expanding UHPC and RPC for the ready-mixed concrete, allowing further application of these concrete types to monolithic structures. The positive environmental aspect of UHPC and RPC is also beneficial, as the application of these High Strength Concrete types with high utility properties may be used to build long-lasting structures with a smaller cross-section and thus save the volume of input raw materials.

7. References

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