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Comparative Investigations on Ultra-High Performance Concrete with and without Coarse Aggregates

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SUMMARY

In the present paper UHPC was produced with crushed basalt with the particle size from 2 to 5 mm. The compressive strength has reached the same magnitude as reactive powder concrete (RPC) in which the maximal aggregate size is smaller than 1.0 mm. The use of the coarse aggregates led not only to the decrease in cementitious paste volume fraction, but also to some changes in mixing process and in mechanical properties. UHPC containing coarse aggregate was easier to be fluidised and homogenized. The mixing time can be shorter than that for RPC. The both tested UHPC exhibited a similar behaviour under compressive stresses, except somewhat different modulus of elasticity and strain at peak stress, which related to the stiffness of the used aggregates. The lower paste volume fraction and the hindrance of the stiffer basalt split resulted in a lower autogenous shrinkage of UHPC containing coarse aggregates.

Keywords: ultrahigh performance concrete, reactive powder concrete, coarse aggregate

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1 INTRODUCTION

Ultra-high performance concrete (UHPC) is one of the latest developing in concrete technology. Depending on its composition and the treating temperature its compressive strength ranges between 150 N/mm² and up to 800 N/mm² 1. Some basic principles improving the properties of concrete were suggested in 1, e. g. the optimisation of the granular skeleton, the densification of the cementitious matrix through lowing water to binder ratio and post set heat treatment, as well as the elimination of coarse aggregates. In 1 it was emphasized that the difference in thermal and mechanical properties between aggregate and cementitious matrix is one of the main reasons for the micro cracking in the interface zone, and that the length of the micro cracks is proportional with the grain size of aggregates. Therefore, the grain size of aggregate should be limited to 0.6 mm. The ultrahigh performance concrete produced in such a way is called as reactive powder concrete (RPC). However, the smaller the aggregates, the larger is the aggregate surface to be enveloped with cementitious paste. This leads to a high paste volume in reactive powder concrete to get a sufficient flowing ability for manufacture. The cement content ranges often from 700 up to 1000 kg/m³ 23, which indicates some disadvantages in concrete properties, e.g. high autogenous shrinkage.

Experiments in this paper showed that concrete with coarse aggregates can also reach the compressive strength of reactive powder concrete. The behaviour of UHPC with and without coarse aggregates during mixing process and the concrete properties in fresh and hardened state were comparatively investigated.

2 MATERIALS AND CONCRETE COMPOSITIONS

In both UHPCs the powder was composed of ordinary Portland cement CEM I 42,5 R, white silica fume and quartz powder. The fineness of this quartz powder is between the silica fume and the cement and was used as a micro filler to optimise the packing density of the powder mixture. According to the suggestions in 1 coarse aggregate was eliminated in UHPC1 (Table 1). Only quartz sand in the range of 0.3 to 0.8 mm was used as aggregate. So UHPC1 is comparable to a RPC. In UHPC2 basalt splits with particles from 2 to 5 mm were used as coarse aggregate, and the same sand in UHPC1 as fine aggregate. Superplasticizer (SP) on the basis of polycarboxylateether ensured the both UHPC a high fluid ability as self-compacting concrete.

Table 1 Proportion of self-compacting UHPC with and without coarse aggregates

Materials	UHPC1 (RPC)	UHPC2
Cement CEM I 42.5 R ©	1.0	1.0
Water to cement ratio (w/c)	0.268	0.302
Water to binder ratio (w/b)	0.206	0.232
Volumetric water to powder ratio	0.431	0.487
Quartz sand (0.3-0.8 mm)	1.532	0.811
Basalt split (2-5 mm)	0.0	1.830
Paste volume fraction	60%	50%
$f_{c,cyl.100*200}$ (N/mm², 28d/20°C)	150-160	150-165
$f_{c,cyl.100*200}$ (N/mm², 90d/20°C)	165-180	165-175

The volume fraction of the cementitious paste (water + powder) in both UHPCs is higher than that in conventional HPC and SCC, as shown in Fig. 1. This can be reasoned by the fact that the superplasticizer content in the UHPC was almost the saturation dosage. A higher superplasticizer dosage could not significantly increase the paste fluidity. In this case the concrete consistency depends mainly on the paste volume fraction and the grain size of the aggregates. In UHPC1 the aggregate surface to be enveloped with cementitious paste was so large that the paste volume fraction had to be increased up to 60% to get the sufficient fluid ability, while it was 50% in UHPC2 containing coarse aggregates (Fig. 1).

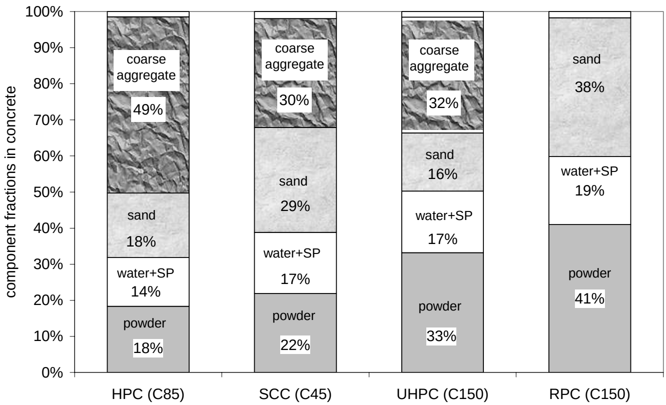

Fig. 1 Component volume fractions in HPC, SCC and UHPC

3 UHPC IN MIXING PROCESS

In the mixing process all particles of solid components are repositioned through relative movement and rotation. Smaller particles fill progressively the voids between coarser particles. Mixing water fills the remained voids between all solid particles and facilitates their movement as a lubricant. The dispersing process of the particles and the feature of the power consumption during mixing are shown in Fig. 2 (left). The time at which the power-time curve reaches the asymptote is defined as stabilisation time 4. Generally it is also the mixing time.

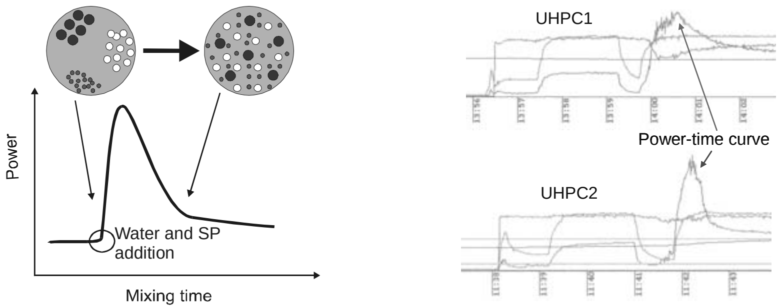

Fig. 2 Power consumption during mixing process

Fig. 2 (right) shows the power consumption of both UHPC mixtures produced in a forced mixer R08 at Maschinenfabrik Gustav Eirich GmbH & KG. The power consumption peak for UHPC2 containing coarse aggregates is high and narrow, while for UHPC1 without coarse aggregate low and wide. The stabilisation time for UHPC2 was approx 2 minutes. The total time from dry mixing to discharging was approx 3.5 minutes. For UHPC1 the stabilisation time and the total time was about 3,5 and 5.5 minutes, respectively.

The power consumption feature and the different mixing time can be attributed to the friction between solid particles. In fact, the friction depends on the particle surface feature and the thickness of the water layer enveloping the particles. The thicker the water layer, the lower the friction. In the first seconds after water addition some mixing water was enclosed in agglomerates of fine particles (cement, silica fume and quartz powder). This part of water did not contribute to fluidise the concrete. After these agglomerates had been destroyed by the dispersing effect of the superplasticizer and the friction between solid particles, the enclosed water was released and thickened the water layer around solid particles. The concrete became more and more fluid, leading to the decrease in power consumption. In UHPC1 without coarse aggregate the friction between solid particles is obviously reduced. More time is needed to destroy the agglomerates.

The reduced friction in UHPC1 leads not only to a slower fluidisation, but also to a slower homogenisation of the whole concrete mixture. After 4 minutes mixing in a laboratory forced pan mixer there were still some lumps (10-15 mm) swimming in the fluid concrete. More 3 minutes mixing was needed to destroy these lumps. In the case of UHPC2 such lumps thoroughly disappeared after 2 minutes mixing.

4 THE PROPERTIES OF FRESH ULTRA HIGH PERFORMANCE CONCRETE

Some properties of fresh UHPC were investigated with the experimental apparatus, which are usually used to determine the properties of self-compacting concrete. Details of these apparatus are described in 5.

From Table 2 it could be seen that both UHPCs satisfied the demands on self-compacting concrete. Compared with conventional SCC no principle difference has been observed. Due to the very low w/b-ratio and the very high fineness of silica fume and quartz powder the viscosity of the UHPC is obviously higher than that of conventional SCC. The air content is therefore somewhat higher than in conventional SCC.

Table 2 Properties of fresh self-compacting UHPC

	Without coarse aggregate	With coarse aggregate
Slump flow (mm)	790	765
t_{500} (sec.)	4.0	7.0
V-funnel test (sec.)	8.6	15.6
L-box-test (H_1/H_2)	0.9	0.92
U-box-test (Δh)	0	0
Air content	4.0-5.5%	2.5-3.5%

5 MECHANICAL PROPERTIES OF HARDENED CONCRETE

The grain size of the aggregate has no significant affect on the achievable compressive strength. The both non-fibre reinforced self-compacting UHPC presented here have the cylinder strength in the range of 150-165 N/mm² after 28d water curing at about 20°C and approx 190 N/mm² after heat treatment at 90°C, respectively. In 9 UHPC containing coarse aggregates with a maximal grain size of 8 mm showed a comparable strength. Upper limits of grain size of coarse aggregate used for UHPC should be studied in future work.

The stress-strain curve of the both non-fibre reinforced UHPC subjected to compressive stress showed almost a same characteristics. Due to the perfect interface zone between aggregate and cementitious matrix the stress-strain curve keeps almost linear up to the stress level of about 80% peak stress. Compared with high strength concrete UHPCs exhibit higher brittleness. At peak stress they failed explosively. A descending branch could not be observed. The only obvious difference is the strain at peak stress. It is about 3.400 µm/m for UHPC2 and 4.400 µm/m for UHPC1, respectively. This can be related to the higher stiffness of UHPC2.

In principle the elastic modulus of UHPC is higher than that of conventional concrete with a same type of aggregates. Its magnitude depends on the type of aggregate and the paste volume fraction. For instance, UHPC without coarse aggregate contains normally quartz sand smaller than 1 mm. Its modulus of elasticity is about 48.000 N/mm^2, lower than UHPC containing basalt split (ca. 58.000 N/mm^2). The UHPC composed of bauxit split can even reach the value over 70.000 N/mm^2 6.

The relationship between modulus of elasticity and compressive strength is similar as that supposed in CEB-FIP Model Code 1990 11, regardless of the grain size. However, due to the high paste volume the modulus of elasticity of UHPC is about 12% lower than that predicted with the equation in CEB-FIP Model Code 1990 (Fig. 3).

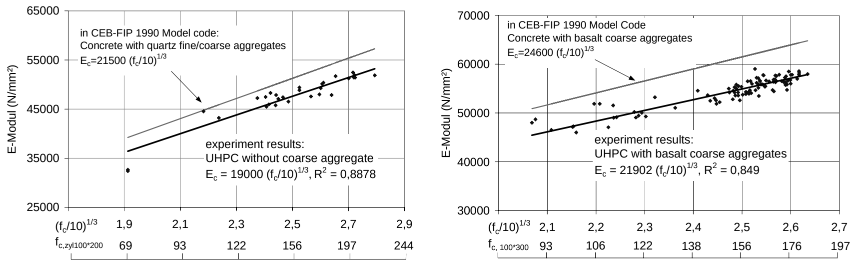

Fig. 3 Relationship between modulus of elasticity and compressive strength of UHPC

6 THE AUTOGENOUS SHRINKAGE OF ULTRA HIGH PERFORMANCE CONCRETE

The autogenous shrinkage is the macroscopic volume reduction of unloaded cementitious materials when cement hydrates after initial setting. It is the combination of chemical shrinkage and volumetric contraction caused by self-desiccation under sealed isothermal conditions 7. The autogenous shrinkage of the both investigated UHPC were tested on specimens of 150×150×700 mm³. The total deformation vs. time curves are shown in Fig. 4, in which the total deformation is the sum of autogenous shrinkage and thermal dilation caused by temperature rise during cement hydration. The autogenous shrinkage was calculated by subtracting the thermal dilation from the measured total deformation. Theoretically autogenous shrinkage occurs when concrete begin to set. However, the thermal dilation coefficient of concrete at very early age is not a certain value. It is much higher than that of hardened concrete and decreases rapidly with concrete age. The experiments in 88 indicated that, it begins to become constant approximately at the time of the highest temperature in concrete. So the autogenous shrinkages of the both UHPC in this paper were considered after the highest temperature and denoted in Fig. 5.

The experimented UHPC exhibited quickly developing and very high autogenous shrinkages. This can be resulted from the accelerated self-desiccation due to the very low water to cement ratio and the very fine capillary pores, the intensified volume contraction caused by puzzolanic reaction at high silica fume content, as well as the high paste volume in UHPC.

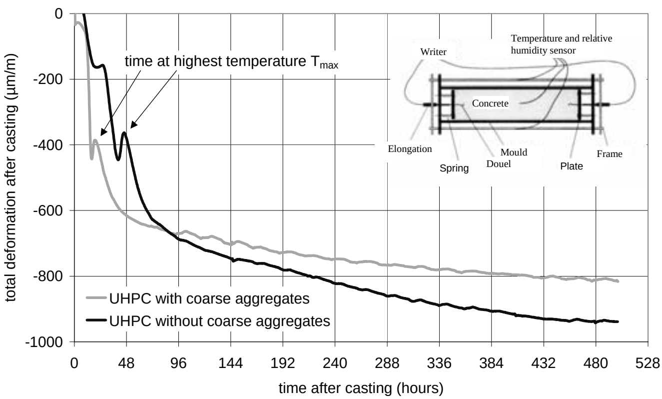

Fig. 4 Total deformation of UHPC with and without coarse aggregates

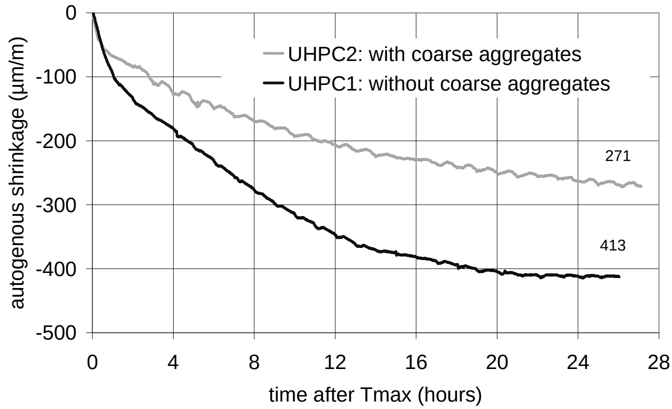

Fig. 5 Autogenous shrinkage of UHPC with and without coarse aggregate

A comparison of the two UHPC shows that three weeks after casting the autogenous shrinkage of the UHPC2 containing basalt split as coarse aggregate is about 40% lower than that without coarse aggregate. Except for the slightly higher w/c and the lower cementitious paste volume, which are advantageous for the reduction of autogenous shrinkage, the higher modulus of elasticity of UHPC2 can also make a certain contribution to decrease the autogenous shrinkage.

The high autogenous shrinkage and its quickly developing indicate a high risk of micro cracking at early ages, if a construction element made of UHPC is restrained. From this point of view, the restrained UHPC without coarse aggregate is more sensitive to cracking than UHPC containing coarse aggregate.

7 CONCLUSIONS

In this paper some comparative investigations on two UHPC were carried out. The UHPC containing coarse aggregates differs from the classic UHPC without coarse aggregate (RPC) mainly in the concrete proportion, mixing time, and in the autogenous shrinkage. The cementitious paste volume fraction in UHPC containing basalt split (2-5 mm) as coarse aggregate is about 20% lower than that in RPC possessing similar compressive strength and fluid ability. The cement content in UHPC can be then lower than 550 kg/m³, while in RPC it ranges often between 700 kg/m³ and 1000 kg/m³. During mixing the UHPC containing coarse aggregate is easier to be fluidised and homogenized. A shorter mixing time can be expected.

Both UHPC showed a high and quickly developing autogenous shrinkage. In UHPC containing coarse aggregates the lower cementitious paste volume and the stiffer basalt split result in a noticeable decrease in autogenous shrinkage. The autogenous shrinkage of UHPC containing coarse aggregates is about 60% of RPC experimented in this paper.

The both non-fibre reinforced UHPC in hardened state showed no distinct difference in mechanical properties under compressive stress, except the higher modulus of elasticity and lower strains at peak stress for UHPC containing basalt split, which can be attributed to the higher stiffness of the basalt split used.

8 ACKNOWLEDGEMENTS

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