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Ultra-High Performance Concrete Mixes with Reduced Portland Cement Content

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Ultra-high performance concrete (UHPC) usually contains a very high proportion of ordinary Portland cement which requires a high amount of energy for its production. The present investigations aimed at systematically developing UHPC produced with supplementary cementitious materials to achieving strengths above 150 MPa at an age of 28 days under normal conditions or above 200 MPa with heat treatment. The cement was replaced with different amounts of ground granulated blast furnace slag and fly ash. The effect on the workability of fresh concrete and the evolution of compressive strength was investigated. A reduction in water and super plasticizer requirement was obtained with these materials. However, compressive strength decreases with the content of mineral additions. This loss could be partly compensated by increasing the fineness of the slag or fly ash. It was found that the type and dosage of superplasticizer have a significant effect on strength development. An appropriate choice of materials enabled the achievement of strengths above 200 MPa after heat treatment for concrete made with binders containing 25% Portland cement and 75% slag.

Keywords: *Binder, Fly ash, GGBS, Mineral additions, UHPC.*

1. Introduction

Contemporary UHPC is produced with a high content of Portland cement (DAfStb 2008) whose production requires considerable amounts of energy. Thus the development of new UHPC compositions with less Portland cement clinker is of economical and ecological importance. In the present investigations, ground granulated blast-furnace slag and fly ash were used as alternative cementitious materials to replace Portland cement in the reference mix M2Q. As well as comparable workability, strengths similar to the reference mix were required. New mix compositions were designed based on the knowledge of the hydration of M2Q, the reactivity of the new components and the packing density of the particles in the mix as whole.

2. Methods

The packing density of the mixes was determined according to Schwanda (Schwanda 1966).

The fresh concrete was characterized by measuring slump flow with the Haegermann cone according to EN 1015-3, but without jolting. The relative yield stress and viscosity were measured using a rotation viscometer to provide a better description of fresh concrete workability. The relative yield stress was determined using the Herschel-Bulkley Model and the relative viscosity with the Bingham Model, see (Metzger 2006).

The specimens were demoulded after 24 hours and either stored in water at 20°C until testing or heat treated for 24 hours at 90°C (age one to three days) and then stored at 20°C/65% RH. The heat treated specimens were investigated before and after heat treatment, i.e. at an age of 3 days, and then at ages of 7, 28, 56, 90 days and 2 years. The specimens stored in water at 20°C were investigated at the same ages as the heat treated specimens.

The composition of the young concrete was investigated in situ seven minutes after water addition and up to the time of setting using X-ray diffraction. A position sensitive detector was used with Cu Kα radiation. A scintillation detector was used for the analysis of powder prepared from the hardened concrete specimens, (Gerlicher et al. 2009). The silicate phases were investigated using ^{29}Si-NMR spectroscopy. This combined approach enabled the quantification of the amounts of crystalline and amorphous silicate phases.

3. Reference Concrete Composition

The M2Q (maximum grain size 0.5 mm) mix was used as the initial reference composition (Tab. 1).

The phase composition of specimens stored in water at 20°C and heat treated at 90°C determined by X-ray diffraction and NMR spectroscopy are shown in Fig. 1. In the case of the specimens stored in water, it is apparent that the amount of C-S-H increases with age because of the reaction of silica fume with portlandite. After 28 days the reaction was still incomplete, cf. Fig. 2.

Table 1. *Reference concrete composition*

Constituents		M2Q
Cement	kg/m³	876
Silica fume	kg/m³	142
Water	kg/m³	187
Superlasticizer	kg/m³	13
Quartz flour	kg/m³	218
Quartz sand	kg/m³	985

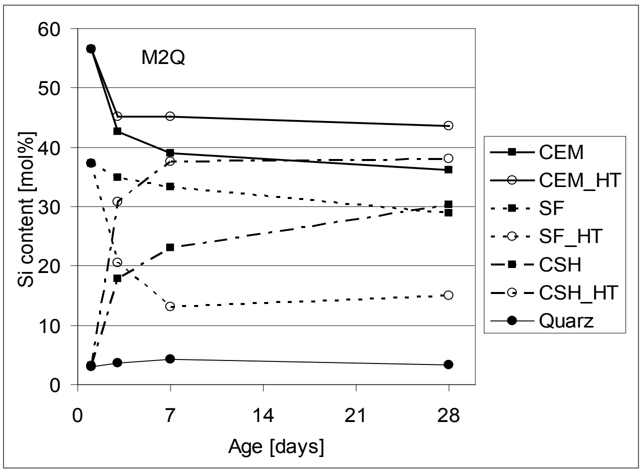

Fig. 1. *Silicate phases in M2Q determined by NMR spectroscopy. After water storage at 20°C and before and after heat treatment at 90°C (HT)*

Heat treatment accelerated the reaction of the silica fume to C-S-H which was to a large extent complete after 7 days. In contrast to the specimens stored in water, the cement did not react appreciably following heat treatment (age 3 days). At an age of 28 days about 80% of the cement was still present as unreacted clinker in the concrete.

The amount of C-S-H was observed to increase in the heat treated concretes by 18% between 28 days and 2 years. Because of the pozzolanic reaction of the silica fume, an increase of 67% was determined for the specimens stored in water at 20°C. Thus without heat treatment more C-S-H formed over two years resulting in a degree of hydration of the silica fume similar to that of the heat treated concrete. After two years more cement had reacted in the concrete which had not been heat treated, Fig. 2. The measurements did not reveal a reaction of the quartz components.

4. Use of Ground Granulated Blast-Furnace Slag (GGBS)

Ground granulated blast-furnace slags of different fineness were used to replace Portland cement in the reference mix M2Q at 15, 35, 55 and a maximum of 75 vol.%. The effect of superplasticizer type and dosage on the workability of the fresh concrete and the compressive strength of the hardened concrete was investigated.

At first, the cement was replaced by GGBS similar in fineness to the cement (< 40µm). Since the lower surface area of GGBS requires less wetting than cement and the reaction of GGBS is slower, slump flow increased considerably with the amount of GGBS at constant water content of the mix. Consequently, the water content was reduced to obtain workability comparable to the reference M2Q, i.e. a slump flow of approximately 25 cm. This resulted in a reduction of water/binder ratio. Increasing amounts of GGBS also led to lower compressive strengths. In the case of the concrete with 15% replacement, the 28 d compressive strength was 188 MPa, similar to the strength of the reference concrete stored in water. With heat treatment, the strengths were near the reference concrete. Heat treatment enabled strengths above 200 MPa for cement replacement up to 55%, see (Gerlicher *et al*. 2008).

The investigations on the phase composition of fresh concrete up to first setting with in situ X-ray diffraction showed, as expected, a decrease in the amount of clinker phases and the formation of ettringite and portlandite. No change in the amount of quartz flour was apparent. The amount of portlandite decreased with GGBS content, (Gerlicher *et al*. 2009). Even after prolonging the measurement to 84 hours, no portlandite was present in the mix with 75% replacement.

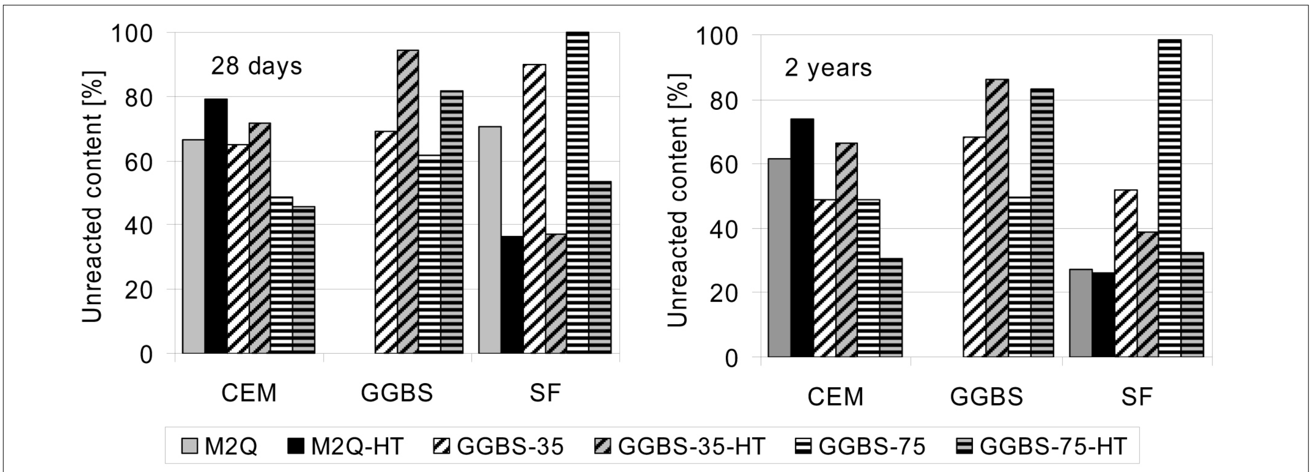

Fig. 2. *Unreacted silicate phases after storage in water at 20°C and heat treatment at 90°C (HT) at ages of 28 days (left) and 2 years (right). GGBS-35 and GGBS-75 concretes with 35 vol.% and 75 vol.% replacement of cement by GGBS, respectively. HT: heat treated concrete*

In investigations on concrete with GGBS, NMR spectroscopy revealed higher degrees of hydration of Portland cement at high GGBS contents. A reduction in the degree of hydration of silica fume due to the production of less portlandite was also observed (Fig. 2). It is apparent that heat treatment resulted in a premature standstill of the GGBS reaction.

Like the reference mix M2Q, heat treatment caused a rapid reaction of the silica fume in concrete with 35 vol.% replacement of cement by GGBS (GGBS-35). No further reaction was detectable after 7 days. Without heat treatment, the silica fume continued reacting, almost reaching the strength of the heat treated concretes after 2 years. Both cement and GGBS in heat treated concretes only reached a low degree of hydration which barely changed in the following 2 years (Fig. 2). Like the reference mix M2Q, more C-S-H was formed after two years if heat treatment was not applied. The amount of C-S-H in the heat treated concrete increased by about 11% between 28 days and 2 years. An increase of as much as 80% owing to the reaction of the silica fume was observed during the same time period for the concrete stored in water at 20°C.

Even after two years, no appreciable silica fume reaction was observed for the concrete with 75% replacement by GGBS (GGBS-75) and not subjected to heat treatment. Although heat treatment accelerated the pozzolanic reaction, only 20% of the GGBS reacted, see Fig. 2.

A fine GGBS (< 10 µm) was used in further investigations. The increased fineness affected the workability and strength of the concretes. Lower slump flow and higher compressive strengths were measured (Gerlicher *et al.* 2008).

The ability of superplasticizers based on polycarboxylate ether to liquefy the mixes was investigated. It was found that superplasticizer dosage and type have a significant effect on strength development. It was possible to reduce the dosage considerably from 4.2 (SP1) to 1.5 wt.% (SP2) with respect to cement weight. The low dosage had a decisive effect on the strength development of the concretes. With a suitable choice of materials, it was therefore possible to achieve strengths over 200 MPa after heat treatment with only 25% cement and 75% GGBS similar in fineness to the cement (Fig. 3).

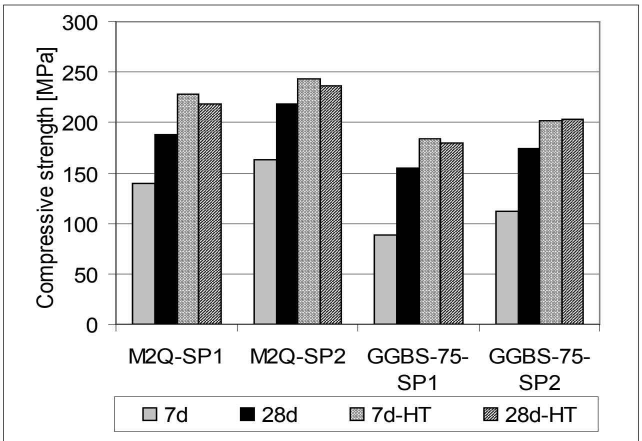

Fig. 3. *Comparison of the effectiveness of superplasticizers SP1 and SP2 for concrete adjusted to the same workability and with the same water content with respect to the binder, i.e. sum of cement and GGBS. HT: heat treated concretes*

5. Use of Fly Ash

The effect of fly ash as a pozzolanic binder component on the workability of the fresh concrete and the compressive strength of the hardened concrete was investigated. The differently reactive constituents of the reference mix were partly or completely replaced by fly ashes of different fineness.

It was shown in (Heinz *et al.* 2009) that the replacement of cement by fly ash reduces the requirement on water and superplasticizer of the mix. However, compressive strength is lower at higher replacement levels. This loss of strength can be partly compensated by increasing the fineness of the fly ash. If fly ash is substituted for quartz flour, the fineness of the fly ash determines the workability of the fresh concrete. Independent of fly ash fineness, the strength of the reference mix with quartz flour was achieved.

Based on the results obtained on the substitution of individual mix components in (Heinz *et al.* 2009), different levels of combined replacement were considered by taking packing density and the chemical reactivity of the components into account. The two mixes M1F and M2F in Tab. 2 were designed (Gerlicher *et al.* 2009a).

Table 2. *Composition of Mixes M2Q, M1F, M2F*

Composition		M2Q	M1F	M2F
Cement	kg/m³	876	747	572
Fly ash	kg/m³	0	244	487
Silica fume	kg/m³	142	121	144
Water	kg/m³	187	187	187
Superplast.	kg/m³	13	13	13
Quartz flour	kg/m³	218	0	0
Quartz sand	kg/m³	985	1039	871

In the following, two 4-component systems comprising cement, fly ash of medium fineness, silica fume and quartz are considered. The systems are characterized by a reduced proportion of the energy-intensive materials cement and quartz flour.

The optimized mixes M1F and M2F exhibited the same workability properties as the initial mix M2Q. However, the mix M2F rapidly stiffened after initial good workability (Fig. 4). Strength decreases with increasing fly ash content and simultaneous cement reduction (Fig. 5). The compressive strength of the heat treated concretes was well over 200 MPa.

Owing to the high cost and scarcity of silica fume, the replacement of this material is of economic interest. The partial and complete replacement by processed fly ash (< 10 µm) had been investigated (Heinz *et al.* 2009). As well as differing chemically from silica fume, this material is finer possessing a higher specific surface.

Starting from the reference mix M2Q, 25, 50 and 100 vol.% of the silica fume was replaced by processed fly ash in mixes SA25, SA50 and SA100, respectively. The resulting enhanced water requirement of the fly ash concretes had a pronounced effect on fresh concrete consistency.

Despite smaller particle surface areas for wetting, the lower packing density of the particles worsened workability. To be able start mixing the concrete with complete replacement at all, it was necessary to raise the superplasticizer dosage by 39%. This concrete was then, however, high viscous.

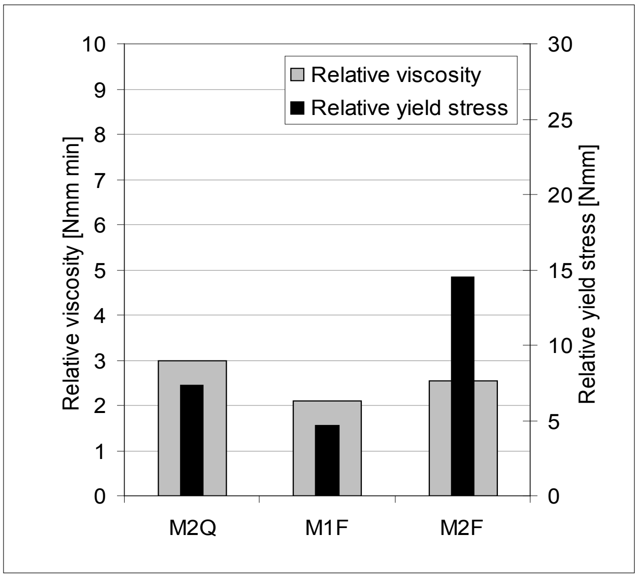

Fig. 4. *Relative yield stress and viscosity of the mix M2Q and the optimized mixes M1F and M2F*

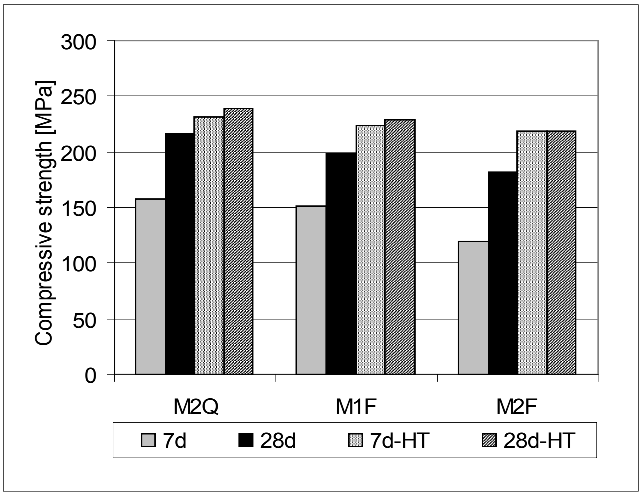

Fig. 5. *Compressive strength of M2Q and the optimized mixes M1F and M2F. HT: heat treated concrete*

Owing to the slow hydration reaction of fly ash, the strength development of the concretes stored in water at 20°C became slower with decreasing silica fume content. Thus the 28 day strength decreased with the fly ash content of the mix. In the case of the heat treated concretes, the strength of the reference mix can be reached for replacement up to 50 %. The strength of the concrete completely without silica fume (SA100) was lower, but still well above 200 MPa. It should be taken into account that mix SA100 was produced with a higher superplasticizer dosage which delays strength development, see Fig. 6.

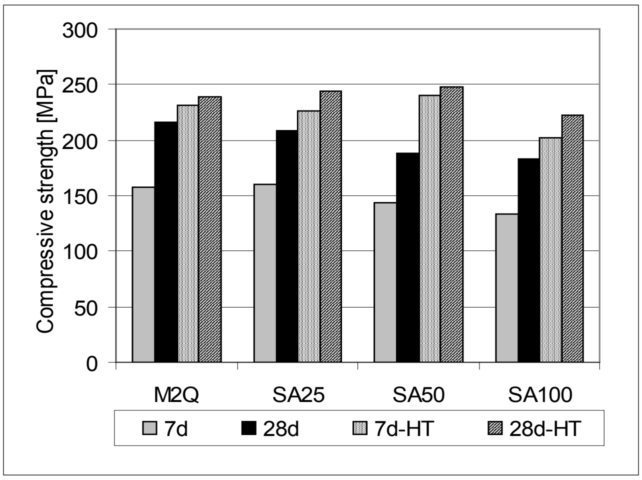

Fig. 6. *Compressive strength in dependence of proportion of silica fume replaced by sifted fly ash, HT: Heat treated concrete*

6. Conclusions

Owing to the energy intensive production of Portland cement clinker and its high content in state-of-the art ultra-high performance concrete (UHPC), the present research focuses on the reduction of the Portland cement content of UHPC while maintaining good workability and 28 day compressive strengths above 200 MPa after heat treatment at 90°C for 24 hours. Investigations on the effect of binder composition on workability, the hydration process and strength development showed that this could be achieved by the use of ground granulated blast-furnace slag (GGBS) und fly ash as a binder component.

The replacement of Portland cement by GGBS or fly ash is shown to reduce the requirement of the mix on water and superplasticizer. However, compressive strength also decreases with replacement level. This can be largely compensated by increasing the fineness of the GGBS and fly ash.

Although the reduction in Portland cement content in concretes made with GGBS enhanced the degree of hydration of the cement, the degree of hydration of the silica fume was lowered because less Portlandite was available for the pozzolanic reaction. Apparently, the reaction of the GGBS came to a standstill after heat treatment.

Investigations with different types of superplasticizer showed that superplasticizer dosage and type have a significant effect on strength development. With a suitable choice of materials strengths above 200 MPa were achieved with only 25% Portland cement and 75% GGBS after heat treatment.

Good fresh concrete workability and high strengths were obtained for separate replacement of cement or quartz flour by fly ashes of different quality. A combined replacement of cement and quartz flour also proved favourable for fresh and hardened concrete properties.

Exchanging silica fume for processed fly ash led to coarsening of the mix as a whole and, as expected, deterioration of workability. The production of concrete with complete replacement of the silica fume by fly ash was only possible with an increased superplasticizer dosage. It is possible to reach the strength of the reference mix for replacement levels up to 50%. Even the strength of concrete without silica fume was still above 200 MPa.

Acknowledgment

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References

DAfStb-Sachstandsbericht 2008. „Ultrahochfester Beton" Heft 561, Deutscher Ausschuss für Stahlbeton, Beuth-Verlag, Berlin.

Gerlicher, T., Heinz, D., and Urbonas L. 2008. Effect of Finely Ground Blast Furnace Slag on the Properties of Fresh and Hardened UHPC. In: Proceedings of the Second International Symposium on UHPC, Universität Kassel, pp. 367–374.

Gerlicher, T., Hilbig, H., and Heinz, D. 2009. Einfluss des Hüttensandmehleinsatzes auf den Hydratationsverlauf von ultrahochfestem Beton. In: Proceedings of the 17th Internationale Conference on Building Materials (ibausil), Weimar, pp. 02-0596 – 02-0598.

Gerlicher, T., Leonhardt, S., Heinz, D., and Urbonas, L. 2009. Einfluss des Steinkohlen-flugascheeinsatzes auf die Frisch- und Festbetoneigenschaften von ultrahochfestem Beton, In: Proceedings of the 17th Internationale Conference on Building Materials (ibausil), Weimar , pp. 01–1091 – 01–1098.

Heinz, D., and Gerlicher, T. 2009. Eigenschaften Ultrahochfester Betone mit zementklinkerarmen Bindemittelsystemen. Im Rahmen des DFG SPP 1182 Nachhaltiges Bauen mit Ultrahochfestem Beton (UHPC) / Technische Universität München.. – Zwischenbericht.

Mezger, T.-G. 2006. Das Rheologie Handbuch, 2. Auflage, Vincentz Network, Hannover.

Schwanda, F. 1966. Das rechnerische Verfahren zur Bestimmung des Hohlraumes und Zementleimanspruches von Zuschlägen und seine Bedeutung für den Spannbetonbau. In: Zement und Beton, V. 37, pp. 8–17.

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