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Development of UHPC mixtures from an ecological point of view

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HIGHLIGHTS

- Partial substitution of cement in UHPC with supplementary materials is studied.
- Adequate SCMs do not lead to a significant degradation of mechanical properties.
- The effect on packing density outweighs the factor of SCM’s hydraulic reactivity.
- Replacement of cement with adequate SCMs leads to better ecological properties.
- Considering material savings and enhanced durability improves the UHPC eco-balance.

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ABSTRACT

Reinforced Concrete (RC) is the predominant and most frequently used building material with a worldwide annual material flow of approximately 20–25 billion tons. Consequently, cement as the most used inorganic binding material is responsible for more than 5% of the total anthropogenic CO_2 emissions. Ultra High Performance Concrete (UHPC) is an emerging high-tech building material that – in comparison to normal strength concrete (NSC) – allows for more slenderness and increased durability when designing RC-structures. The ecological impact of UHPC is affected by the high cement content with more than double the amount needed in comparison to normal strength concrete. Substitution of cement in the mixture by less-energy-intensive hydraulic concrete additives is investigated regarding its influence on the concrete properties and its environmental impact parameters calculated for the different UHPC mixtures.

1. Research significance: Sustainability in concrete construction

In the European Union about 40% of total energy consumption is attributed to the building and construction sector. In central European countries about 70% of the total material flow is caused by the building industry [1,2]. These figures illustrate the importance of sustainability in the building sector. Therefore, besides the efforts to improve construction materials, the issue of sustainability has gained more and more attention in recent years and has become a primary focus in the construction materials industry.

The ecological targets include the minimizing of the exploitation of non-renewable resources, thereby ensuring the regeneration of renewable resources and the reduction of building waste and residues. Furthermore, the efficient use of raw materials for the production of building materials and concepts for the reuse and the recycling of building waste are necessary to keep up with future demand as laid out in the Brundtland Report of 1987, where the term “sustainability” was first defined [3].

Reinforced Concrete (RC) is well known as the most important construction material worldwide. Recent success in the formation of superplasticizers has given way to the development of the new concrete family of Ultra High Performance Concrete (UHPC), which is reaching a level in compressive strength that was earlier only possible with steel. Several guidelines dealing with the material properties and design concepts for UHPC have meanwhile been elaborated [4–6].

The world’s annual overall material flow for concrete is estimated to be approximately 20–25 Gt [7,8]. This amount of concrete would correspond to a cube with a side length of more than 2 km filled with concrete. Cement is the most used inorganic binding material. According to the literature its worldwide production in 2012 amounted to about 3.6 Gt [9], which has a significant ecological impact due to its production technology. The current rate of growth in cement production is about 3–5% per year. The cement industry is responsible for 5–8% of the total anthropogenic CO_2 emissions [10]. This high figure comes predominantly from the de-acidification of limestone, the main raw material in cement

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production and in addition from the energy compounds necessary to reach the calcination temperature of 1450 °C. Therefore a considerable potential reduction of the environmental impact of concrete lies in the partial substitution of cement by less-energy-intensive hydraulic concrete additives. This has an even greater significance in concrete materials like UHPC with a high cement content.

In the first part of the present study, UHPC mixtures with steel fibers using different supplementary cementitious materials (SCMs) are investigated in comparison with a reference UHPC mixture. The goal is to reach similar properties of fresh and hardened concrete with a lower impact on the environment. To quantify this effect, in a second step the primary energy input (PEI) and the following environmental impact indicators were considered in a quasi-life-cycle assessment (LCA) approach for UHPC:

- Global warming potential (GWP).
- Acidification potential (AP).
- Eutrophication potential (EP).

The influence of ozone in the stratosphere (ODP) and the photochemical creation process (POCP) is not taken into account. Data reflecting the energy and environmental impact indicators were taken from the literature [11–13].

2. Substitution of cement in UHPC mixtures by SCM

A main focus of this research was to develop new mixtures for UHPC with the substitution of high-energy-intensive cement by locally available supplementary cementitious materials like granulated blast furnace slag (GBS) or fly ash (FA). Due to the high cement content of about 800 kg/m^3 in its mixture proportions, UHPC has a critical impact on the environment if compared with NSC. By substituting the cement content with SCMs, attention was directed to the workability of fresh concrete and the mechanical properties of hardened concrete. To visualize the effect the properties were studied in comparison with a reference mixture using only cement as a binder. Since the highest achievable compressive strength was not within the focus of this research, no heat treatment was applied to the UHPC specimens.

2.1. Degree of substitution

The substitution of cement of >30% by weight with quartz filler material was investigated at the Royal Institute of Technology, Stockholm [14] for different types of high strength concrete. The mixtures with reduced cement content had similar workability and compressive strength. The increase in packing density by the ultra-fine filler material and the large content of unreacted cement due to the low water-binder ratio was discussed as being responsible for this behavior.

Results of another study with a similar focus were presented by Heinz [15], substituting Portland cement by using GBS at a different percentage by volume. The effect on workability and mechanical properties of the UHPC mixtures is discussed. For non-heat-treated mixtures, the best results were obtained at a substitution range between 35% and 55% by volume.

The degree of substitution of Portland cement by SCMs (fly ash, granulated blast furnace slag) in UHPC mixtures was also studied based on the concept of the particle packing density by Puntke [16]. An optimum substitution rate for GBS and FA in this respect was obtained at 31% by weight [17].

In the present study, Portland cement was substituted by GBS in fine and extra fine quality, as well as by FA. The results, gained on the basis of a substitution rate in the UHPC mix design of 45% by weight, are discussed in Section 3.

2.2. Mixture proportions

The reference mixture is a fine grain mixture, UM-5 with a maximum grain size of 0.5 mm. As binder material a CEM I 42.5 R, SR 0 (free of C$_3$A) was used. The range of the grain sizes was 0.1–0.5 mm for quartz sand, below 40 µm for quartz powder and for the finest grain, microsilica (97% SiO$_2$), 0.1–0.3 µm. The steel fibers had a length of 15 mm and a diameter of 0.20 mm. As superplasticizer a special formulation provided by SIKA-Austria was applied. The mix design of all mixtures (reference mixture, mixtures with SCMs) is presented in Table 1. The mixture proportion of the reference mix UM-5 was strongly based on the maximization of the packing density of the fine grain, thereby reducing the required amount of water. The methodology used was the set-up developed by Puntke [16], identifying the voids in a powder-filled small container by slowly adding water until the level of the powder surface drops and thus indicates the point of water saturation. The maximum packing density corresponds to the minimum required amount of water.

The w/c$_{eq}$ value in Table 1 is the equivalent water to binder ratio and has been derived on the basis of the *k*-value concept according to EN 206-1 [18]. Thereby the hydraulic activity of SCMs is taken into account via the *k*-factor ($k = 0.4$ for FA and $k = 0.8$ for GBS). In addition the volume based water/fines ratio, w/f is defined as an indirect measure for the packing density. With respect to this decisive role of the fines (particles <125 µm) [6,19], the w/f ratio was kept nearly constant in the mixture proportions (see Table 1).

2.3. Characterization of supplementary cementitious materials used

The material characterization of the SCMs was performed using specific surface analysis (Blaine value, cm^2/g), material density and grain size distribution by laser granulometry. The material properties for the SCMs used in the UHPC mixtures are shown in Table 2.

The grain size distribution of the SCMs and the cement is shown in Fig. 1. Due to their latent hydraulic properties, GBS and FA provide favorable properties for the substitution of cement. Both are locally available in Austria as by-products of the blast furnace process of steel or from caloric power stations. Therefore the environmental impact of these SCMs is accounted for in the industry where they first appear and is not taken into account for the environmental impact balance of concrete (this approach being in line with the recommendations in [20]).

Alternative approaches for the allocation of the environmental impact generated by the industrial processes to main products and by-products or waste differ between primary and secondary process, the latter one representing the required specific treatment of waste or by-products for further use [21,22]. Different allocation methods, e.g. based on the mass ratio between product and

Table 1
Constituents of the different UHPC mixtures.

Components	UM-5	UM-5-FA	UM-5-GBSf	UM-5-GBSef
	(kg/m^3)			
Cement CEM I 42.5 R	729	401	401	401
Microsilica ($k = 1.0$)	124	124	124	124
FA ($k = 0.4$)	–	328	–	–
GBSf ($k = 0.8$)	–	–	328	–
GBSef ($k = 0.8$)	–	–	–	328
Quartz powder	397	397	397	397
Quartz sand	833	833	833	833
Total water (incl. SP)	200	200	200	200
Superplasticizer (SP)	30	30	30	30
Fibers (Stratec 0.2/15)	155	155	155	155
w/c$_{eq}$	0.234	0.305	0.254	0.254
w/f	0.47	0.44	0.45	0.45

Table 2
Material properties of cement and SCMs.

	CEM I	FA	GBSf	GBSef
Density (g/cm^3)	3.24	2.51	2.74	2.90
Blaine value (cm^2/g)	4387	4410	4790	5620
D_{50}:MMD (mass-median-diameter) (μm)	11.05	14.29	14.71	8.47

Cement: CEM I 42.5 R, SR 0.
FA: fly ash.
GBSf: granulated blast furnace slag fine.
GBSef: granulated blast furnace slag extra fine.

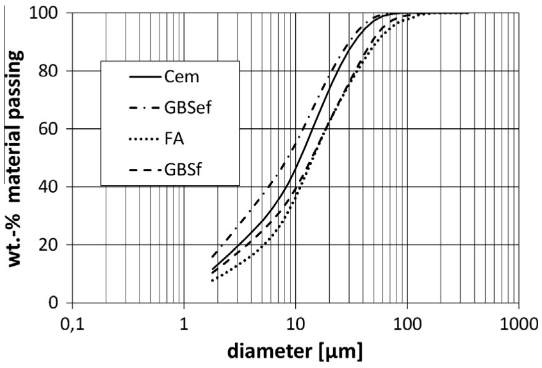

Fig. 1. Grain size distribution by laser granulometry.

by-product or related to the currently added economic value, can lead to different and sometimes even higher environmental burdens of the by-product than the replaced material; however, none of the procedures are incontestable [21]. Moreover other advantages like resource savings should then be taken into account in the total balance.

3. Material properties of UHPC with supplementary cementitious materials

3.1. Fresh concrete properties of UHPC mix design with reduced cement content

Taking into consideration the manufacturing technique, sufficient time should be allowed before the UHPC stiffening process starts. For the mixtures under investigation it was found that the workability was appropriate approximately 20 min from the addition of water, thus enabling the casting process from placing the concrete until release of entrapped air within this time slot. To provide a basis for judging the workability and identifying the optimum viscosity of the UHPC mix, the slump-flow test for mortars was performed on the basis of the European Guidelines for Self-Compacting Concrete [23]. However, with respect to the quick stiffening process, the slump flow test was modified in terms of measuring the spread of the fresh concrete already after 2 min (see results in Fig. 2). Thereby a diameter of 270 mm turned out to be the lower limit of the slump flow to enable proper handling of the UHPC mix. The temperature of the mixture plays an important role and should not exceed 30 °C during the mixing process.

3.2. Hardened concrete properties

Curing and storing conditions of specimens were in accordance with the Austrian standard ONR 23303 [24] (remove from mold after 24 h, then up to the 7th day storage under water in curing tank, afterwards further curing in air under laboratory conditions up to the 28th day). The compression tests were performed on 100 mm cubes made of fiber reinforced UHPC on the 28th day after preparation. As shown in Fig. 3, the compressive strength of the reference mixture UM-5 was 166.1 MPa. A similar result with only 2.6 MPa below was obtained for the mixture UM-5-GBSef, fiber reinforced UHPC with the substitution of 45% by weight of the cement by extra fine GBSef. The other two substitution mixtures reached values of 139.4 MPa (UM-5-GBSf) and 124.7 MPa (UM-5-FA) respectively, which is 83% and 75% of the compressive strength of the reference mixture.

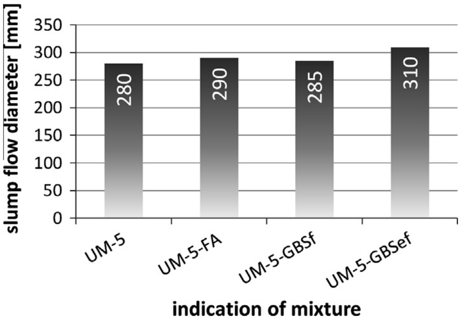

Fig. 2. Results of slump flow test after 2 min.

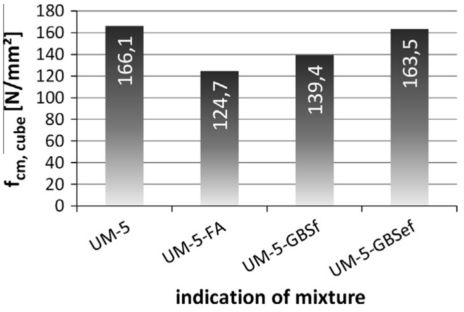

Fig. 3. Compressive strength.

Table 3
Puntke test results – packing density.

UHPC mix	n_w (%)	n_f (%)
UM-5	39.7	60.3
UM-5-FA	39.2	60.8
UM-5-GBSf	39.1	60.9
UM-5-GBSef	38.9	61.1

The best results in terms of workability (see Fig. 2) as well as compressive strength (see Fig. 3) were obtained from the substitution of cement by GBSef with a Blaine value close to 6000 cm^2/g. For the evaluation of the packing density of the different mix proportions Puntke tests [16] were performed. The results of these tests (representing average values of 3 tests each) are listed in Table 3. The packing density of the fine grain (n_f) corresponds to the amount of water (n_w) required to fill the voids ($n_f = 1 - n_w$). The packing densities of the mixtures with SCMs are slightly above the value of the reference mixture, the highest one with 61.1% for GBSef.

4. Comparison of the ecological properties of different UHPC mixtures

Based on the promising mechanical properties, the developed UHPC mixtures using SCMs were evaluated in terms of environmental impact indicators. In radar charts, usually used to indicate environmental impact categories of construction materials [25], the results of the influence of the substitution of cement in UHPC and the position of UHPC in relation to the concept of "green concrete" according to [26] are shown.

4.1. Comparison of UHPC with NSC

The main topic of this section is the comparison between the relevant UHPC mixtures and NSC on the basis of their ecological properties. These were calculated from the primary energy input parameter and environmental impact indicators for the constituents of the different mixtures. The respective data have been derived from sources [13,27]. The procedure applied is a simplified LCA approach according to EN ISO 14040 [28], focusing on the materials required for 1 m^3 compacted concrete. For the sake of better comparability to NSC, for the UHPC mixtures the influence of potential steel fibers was not considered. The environmental impact parameters taken into account are listed in Table 4, including the scaling factors to be applied when interpreting the graphs in Figs. 4 and 5.

Fig. 4 shows the effect of the environmental impact indicators in the mix design of 1 m^3 compacted UHPC. The ecological data of the individual ingredients were assessed and weighted according to their percentage in each mixture. The results were generated for the three mixtures discussed, using the scaling factors listed in Table 4 for illustration reasons (see Figs. 4 and 5).

In comparison to normal strength concrete C30/37, the data show a substantial increase for UHPC in all parameters. Comparing the two UHPC mixtures UM-5 and UM-5-GBSef, a significant reduction in the parameters thanks to the substitution of cement can be seen as the result: in detail a reduction of about 32% of PEI non-renewable, 24% of PEI renewable, 42% of GWP and 20% of AP is achieved. The results in Fig. 4 thus demonstrate clearly the effect in the UHPC mix design towards mixtures of less ecological impact when substituting cement with SCMs. In addition, in order to provide a realistic evaluation and make use of the full ecological potential of UHPC, the possible reduction in the amount of material used to reach the same load bearing capacity and the increase of the durability has to be taken into account.

Table 4
Energy and environmental impact indicators.

Environmental impact indicators	Unit	Scaling factor
Primary energy input – renewable, PEI_{re}	(MJ/m^3)	10^2
Primary energy input – non-renewable, PEI_{non-re}	(MJ/m^3)	10^4
Global warming potential, GWP	($kgCO_2$-eq/m^3)	10^3
Acidification potential, AP	($kgSO_2$-eq/m^3)	1
Eutrophication potential, EP	($kgPO_4$-eq/m^3)	1

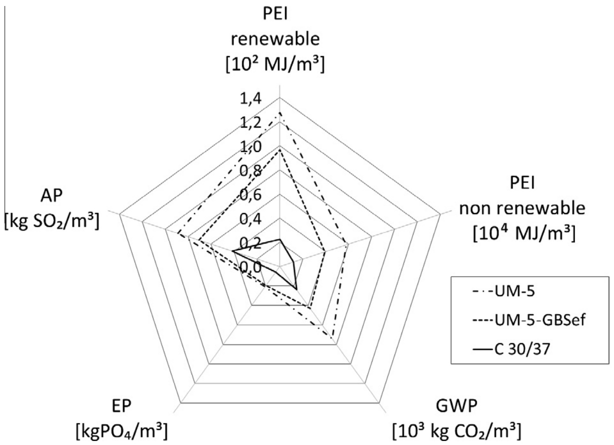

Fig. 4. Comparison of ecological indicators in UHPC mix design.

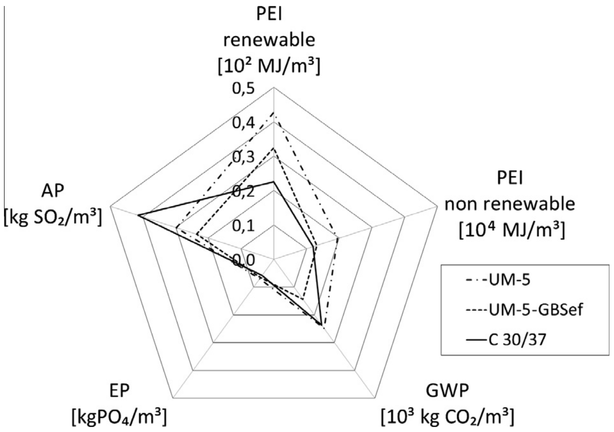

Fig. 5. Comparison of environmental impact parameters between 1 m^3 of C30/37, UHPC reference mixture UM-5 and UHPC with GBS extra fine (considering a reduction of the cross-section and increased durability of UHPC).

4.2. Comparison of building members made of UHPC with NSC

Due to its extraordinary compressive strength and the increased tensile strength (approximately 3 times higher than for NSC) UHPC allows for a reduction of the cross section compared to standard RC members, see e.g. the study presented in [1]. The reduction potential depends on the kind and the geometry of a building member, the relevant load scenarios and the decisive failure modes. While compression members allow for significantly increased slenderness when using UHPC, the reduction is rather limited when considering members subject mainly to bending. In the latter case the amount and the properties of the reinforcing steel and the inner lever arm, to some extent influenced by the compressive strength of the concrete, are decisive for the achievable slenderness. By adequately reducing the width of web sections and increasing the inner lever arm according to the shifting of the center of the compression zone, in the case of flexural members the cross sectional reduction potential may range from less than 10% to about 20%.

On the other hand, building columns are slender compression members where buckling is the predominant failure mode and cast-in reinforcement bars overtake usually substantial parts of the compression force. In this case, when assuming standard reinforcement degrees between 2% and 4%, reductions of the cross section by 30–50% can be achieved. Concerning rather compact members under compression without risk of buckling failure, the possible material savings are even larger and nearly proportional to the enhancement of the concrete strength.

In order to take the optimization of the cross section into account, in the present study a reduction of one third, i.e. 33% was considered as representative. In that context, it should be borne in mind that also the requirements on fire resistance could lead to a higher reduction. For the comparison with NSC, a reference concrete C30/37 is chosen.

Another important aspect is the increased durability and lifetime of UHPC members. Regarding experimental investigations on durability parameters like chloride ion penetration, carbonation, abrasion and freeze–thaw resistance, a substantial increase of the durability can be deduced. Based on experimental investigations at Kassel University [29], compared to standard NSC, the carbonation process under outdoor conditions is 3–6 times slower in UHPC. Several other studies report similar beneficial durability properties of UHPC [30–32]. In general a very low level of migration of chloride ions into the UHPC can be observed. According to [33] the chloride diffusion is retarded (based on rapid chloride migration tests) with a time factor of larger than 4 compared to ordinary concrete.

In order to consider the increased lifetime of UHPC compared to NSC structures, in the present study a factor of 2 is applied (Fig. 5). The chosen ratio corresponds to [30] where the authors expect, based on a variety of performed durability tests, that UHPC outperforms NSC by at least twice as much in service life. While the durability tests reported in the above mentioned studies [29–32] would justify even higher durability factors (at least a ratio of 3–4 can be argued), current codes on the other hand do not require a corresponding extension of the design life of buildings and structures so that it would be difficult to argue the actual benefit when applying such high factors.

Taking into account both cross-sectional reduction and enlarged lifetime in the mentioned way, the generated radar chart in Fig. 5 shows that the ecological impact is significantly reduced and thus UHPC building members may finally cause less environmental burden than NSC. Additional subsidiary factors like reduced cross sections of foundations or savings in floor space due to the use of, e.g., slender columns [1] are thereby not taken into account.

In addition the consideration of reinforcing steel and/or steel fibers is another important aspect when evaluating the ecological impact of building members. RC-structures usually contain at least a minimum amount of steel reinforcement bars while UHPC due to its brittleness is preferably equipped with a certain amount of steel fibers. Based on tensile tests with Ultra High Performance Fiber Reinforced Concrete (UHPFRC), a steel fiber amount of at least 2% by volume may lead to a strain-hardening tensile behavior of the UHPFRC rather than strain-softening [34]. However, in many cases for structural applications a fiber amount of 0.5–1% by volume may already be sufficient to avoid brittle failure. In addition UHPFRC members will usually also contain a reduced amount of steel reinforcement bars. The incorporation of both fibers and steel rebars will increase the environmental impact factors substantially due to the energy-consuming production process and may thus become one of the most dominant factors when considering all UHPFRC ingredients [35]. However, considering the environmental impact of the steel ingredients makes only sense with reference to real building members with a given reinforcement layout and is therefore not taken into account in the present study.

5. Conclusions

The present study investigates the substitution of cement in UHPC by less energy-intensive latent hydraulic concrete additives, focusing on its effect on the mechanical properties and the environmental impact categories. The production-related CO_2 emissions of such alternative additives are not considered in this context, as they are by-products of industrial processes, in which their environmental impact is accounted for. The outcome of the investigations can be summarized as follows:

1. The substitution of cement by appropriate less energy intensive cementitious materials is possible up to about 45% by weight without significant degradation of mechanical properties and workability parameters.
2. The results indicate that achieving an adequate packing density when using ultra-fine materials like extra-fine granulated blast furnace slag (GBSef) is even more decisive for the UHPC properties than the hydraulic reactivity of such materials.
3. Comparing the environmental impact categories of UHPC with that of NSC, the substitution of cement by SCMs is only a first step towards improving the sustainability of UHPC from the ecological point of view. However, when considering building members and also taking into account the reduction of material consumption and the increased durability and lifetime, the overall picture improves substantially.
4. Further optimization of the partial substitution of the cement and the use of alternative fiber materials are required to increase the acceptance and competitiveness of UHPFRC from the environmental point of view.

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