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Sustainability aspects of different UHPC mixtures

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ABSTRACT

Reinforced Concrete is the predominant and most frequently used building material with a worldwide annual material flow of approximately 20 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 Fibre Reinforced Concrete (UHPFRC) is an emerging high-tech building material that - in comparison to normal strength concrete - allows for more slenderness and increased durability when designing RC-structures. The ecological impact of UHPC is driven by the high cement content with more than double the amount needed in comparison to normal strength concrete (NSC). Substitution of cement in the mixture by less-energy-intensive hydraulic concrete additives is investigated on its influence to the concrete properties and its environmental impact parameters calculated for the different UHPC mixtures.

Keywords. UHPC, sustainability, supplementary cementitious materials, granulated blast furnace slag, environmental impact

1 RESEARCH SIGNIFICANCE: SUSTAINABILITY IN CONCRETE CONSTRUCTION

In the European Union about 40% of total energy consumption is used by the building and construction sector. In central European countries about 70% of the total material flow is caused by the building industry (Racky, 2003; Aßbrock, 2011). These two numbers illustrate the importance of sustainability in the building sector. Therefore, besides the effort in improving the construction materials the issue of sustainability has gained more and more attention in recent years and has become a primary focus in the architecture and construction materials industry.

The ecological targets include the minimization of exploitation of non-renewable resources, ensuring 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 reuse and recycle 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 (UNWCED, 1987).

Reinforced Concrete (RC) is well known as the most important construction material worldwide. Recent success in the formation of superplastizisers gave 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 (AFGC, 2002; JSCE, 2006; DAfStb, 2008).

The world`s annual overall material flow for concrete is estimated to be approximately 20 Gt (billion tons) (Sakai, 2013). This amount of concrete would correspond to a cube with a side length of nearly 10 km filled with concrete. Cement is the most used inorganic binding material. According to literature its worldwide annual production amounts to about 2.5 Gt (Weizsäcker, 2010), which has a significant ecological impact due to its production technology. The current rate of growth in the cement production is about 5% per year. Emerging countries like China and India have growth rates of up to 13%. The cement industry is responsible for 5% to 8% of the total anthropogenic CO_2 emissions (Weizsäcker, 2010). This high figure comes predominantly from the de-acidification of limestone, the main raw material in cement production and in addition from the energy compounds to reach the calcination temperature of 1.450°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 effect has an even greater significance in concrete materials like UHPC, with a high cement content in its mixture proportions.

In the first part of the present study, UHPC mixtures with steel fibres using different supplementary cementitious materials (SCM's) are studied in comparison with a reference UHPFRC mixture. The goal was 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 in addition the following environmental impact indicators were considered in a quasi LCA approach for UHPFRC:

- Global warming potential, GWP
- Acidification potential, AP
- Eutrophication potential, EP

The influence of ozone in the stratosphere (ODP) and the photochemical creation process (POCP) was not taken into account. Data reflecting the energy and environmental impact indicators were taken from literature (Haist, 2012; Aßbrock, 2011; Swiss Centre for Life Cycle Inventories, 2013; WECOBIS, 2013).

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 more than 800 kg/m³ in its mixture proportions UHPC has a critical impact on the environment if compared with NSC. By substituting the cement content with SCM´s, attention was directed to workability and mechanical properties. 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 UHPFRC members.

2.1 Proportions of the reference mixture. 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 (C_3A free) was used. The range of the grain sizes was 0.1 to 0.5 mm for quartz sand, below 40 µm for quartz powder and for the finest grain, microsilica (97% SiO_2), 0.1 to 0.3 µm. The steel fibres had a length of 9 mm and a diameter of 0.15 mm. As superplasticizer a special formulation provided by SIKA Austria was applied. The volume based mix design is shown in Figure 1; the numbers refer to percent by volume of its ingredients. The development of the mixture proportions was strongly based on the maximization of the packing density of the fine grain, thereby reducing the required amount of water. The used methodology was the setup developed by Puntke (Puntke, 2002), 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.

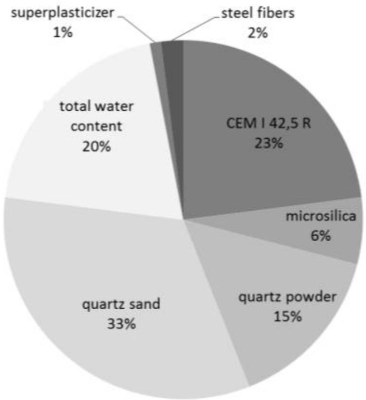

Figure 1. Reference mixture UM-5, percent by volume

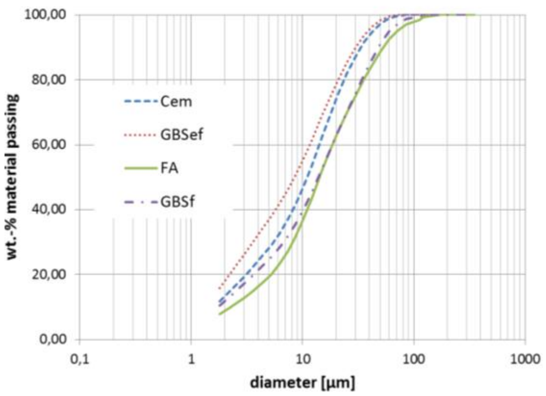

Figure 2. Grain size distribution by laser granulometry

2.2 Characterization of supplementary cementitious materials used. The material characterization of the SCM´s was performed using specific surface analysis (Blaine value, cm²/g), material density and grain size distribution by laser granulometry. The material properties for the SCM´s used in the UHPC mixtures are shown in Table 1.

Table 1. Material properties of cement and SCM

	CEM I	GBSf	GBSef	FA
density [g/cm³]	3,24	2,74	2,90	2,51
Blaine value [cm²/g]	4.387	4.790	5.620	4.410
D_{50} :MMD (mass-median-diameter) [µm]	11,05	14,71	8,47	14,29

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

The grain size distribution of the SCM´s and the cement is shown in Figure 2. Due to their latent hydraulic properties, granulated blast furnace slag (GBS) and fly ash (FA) provide favourable 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 SCM´s is accounted for in the industry where they first appear and is not taken into account for the environmental impact balance of concrete.

3. MATERIAL PROPERTIES OF UHPFRC WITH SUPPLEMENTARY CEMENTITIOUS MATERIALS

3.1 Degree of substitution. The degree of substitution of Portland cement by SCM in UHPC mixtures was previously studied based on the concept of the particle packing density by Puntke (Puntke, 2002). An optimum substitution rate in this respect was obtained at 31 % by weight (Schmölzer, 2011).

In a recent research project the substitution of cement of > 30 % by weight by quartz filler material was investigated (Vogt, 2010). The mixtures with reduced cement content had similar workability and compressive strength. The increase in packing density by the ultrafine filler material and the large content of unreacted cement due to the low water-binder ratio was discussed as being responsible for this behaviour.

Results of another study with similar focus were presented by Heinz (Heinz, 2011), substituting Portland cement by using GBS at different percentage by volume. The effect on workability and mechanical properties of the UHPC mixtures is discussed. For not-heat treated mixtures the best results were obtained at a substitution range between 35 and 55 % by volume.

In the present study, Portland cement was substituted by GBS in fine and extra fine quality, as well as by fly ash with material properties according to Table 1. The test results, gained on the basis of a substitution rate in the UHPC mix design of 45 % by weight corresponding to 38 % by volume, are discussed in the following paragraphs.

3.2 Fresh concrete properties of UHPC mix design with reduced cement content. For the workability of UHPFRC, the slump-flow test was performed according to the European Guidelines for Self-Compacting Concrete (The European Guidelines for Self-Compacting Concrete, 2005). The slump-flow test was performed on a glass plate as depicted in Figure 3; the results are summarized in Figure 4.

Taking into consideration the manufacturing technique, the UHPFRC should allow sufficient time before hardening. For the mixtures under investigation it was found that the workability was given for approximately 10 to 20 minutes after addition of water. The temperature plays an important role and should not exceed 30°C during the mixing process.

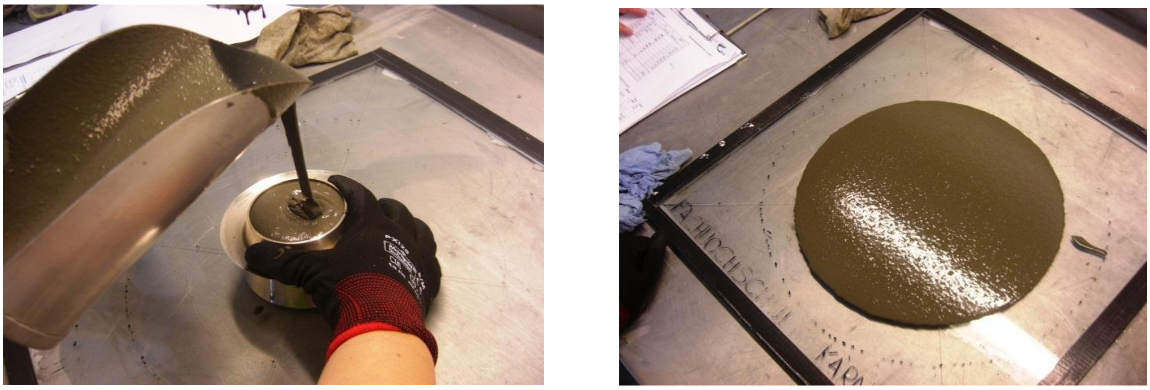

Figure 3. Slump flow test of UHPFRC mixture

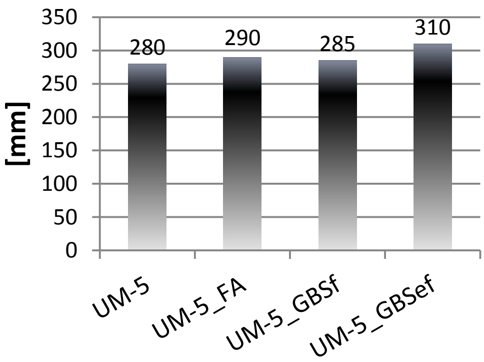

Figure 4. Results of slump flow test after 2 min

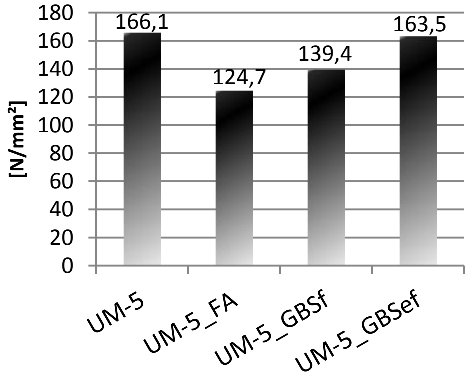

Figure 5. Compressive strength

3.3 Hardened concrete properties. Under the conditions applied, the compressive strength of the reference mixture UM-5 was found at 166.1 MPa. A similar result with only 2.6 MPa below was obtained for the mixture UM-5-GBSef with the substitution of 45 % by weight of the cement by the extra fine GBS. The other two substitution mixtures reached values of 139.4 MPa (UM-5-GBSf) and 124.7 MPa (UM-5-FA) respectively, which is below the compressive strength limit for being classified as UHPC (see Fig. 5). Due to not applying any heat-treatment in the present study, samples with coarser SCM´s like UM-5_FA and UM-5_GBSf missed the 150 MPa UHPC strength limit by 17 and 7 % respectively.

The results indicate the decisive influence of the particle size in the substitution process and the importance of the packing density in the UHPC mixtures which is also linked to the Blaine value of the SCM´s in Table 1. The best results in terms of workability as well as compressive strength were obtained from GBSef with a Blaine value near 6,000 cm²/g.

4. COMPARISON OF THE ECOLOGICAL PROPERTIES OF DIFFERENT UHPFRC MIXTURES

Based on the promising mechanical properties, the developed UHPFRC mixtures using SCM were being evaluated in terms of environmental impact indicators. In net diagrams the ecological data are displayed to indicate the influence of the substitution of cement in UHPFRC mixtures and to position UHPC towards the concept of “green concrete” according to (FIB bulletin No.67, 2012).

4.1 Comparison of UHPFRC with NSC. The main target of this chapter is the comparison between the relevant UHPFRC 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 procedure applied is a simplified LCA approach according to EN ISO 14040, focusing only on the influence of the materials used for 1 m³ compacted concrete. For the sake of better comparability to NSC, for the UHPC mixtures the influence of potential steel fibres was not considered. The environmental impact parameters taken into account are listed in Table 2, including the scaling factors applied for creating the graphs in Figures 6 and 7.

Table 2. Energy and Environmental Impact Indicators

Environmental impact indicators	Unit	Scaling factor
Primary Energy Input - renewable, PEI_{re}	[MJ/m³]	10^{-2}
Primary Energy Input - not renewable, PEI_{not-re}	[MJ/m³]	10^{-4}
Global Warming Potential, GWP	[kgCO_2-eq/m³]	10^{-3}
Acidification Potential, AP	[kgSO_2-eq/m³]	1
Eutrophication Potential, EP	[kgPO_4-eq/m³]	1

The net diagram in Figure 6 shows the effect of the environmental impact indicators in the mix design of 1m³ 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 in the net diagrams the scaling factors listed in Table 2 for illustration reasons (see figures 6 and 7).

In comparison to normal strength concrete C30/37, the data show a significant increase for UHPC in all parameters. Comparing the two UHPC mixtures UM-5 and UM-5-GBSef a significant reduction in the parameters towards the substitution of cement can be seen as the result: In detail about 32% of PEI-not renewable, 24% of PEI renewable, 42% of GWP and 20% of AP reduction is calculated. The results in Figure 6 thus demonstrate clearly the effect in the UHPC mix design towards mixtures of less ecological impact when substituting cement with SCM’s. 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 loadbearing capacity and the increase of the durability has to be taken into account.

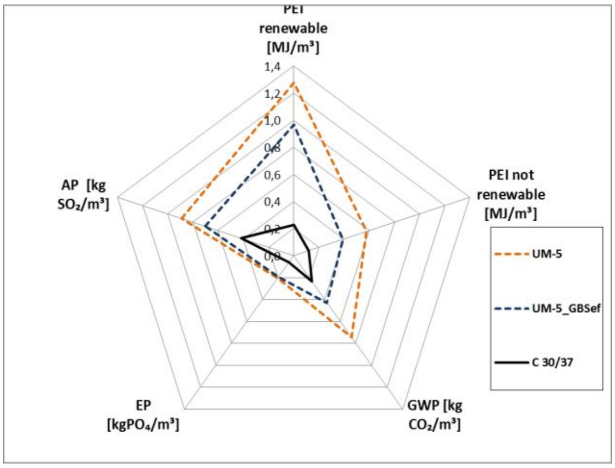

Figure 6. Comparison of ecological indicators in UHPC mix design

4.2 Comparison of RC members made of UHPFRC with such of 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 (Racky, 2003). 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 centre of the compression zone, in the case of flexural members the cross sectional reduction potential may range from less than 10% to about 20%. Slender compression members like typical building columns, where buckling is the predominant failure mode and cast-in reinforcement bars overtake usually substantial parts of the compression force, allow for reductions of the cross section by 30-50% when assuming standard reinforcement degrees between 2 and 4%. On the other hand, for rather compact members under compression without risk of buckling failure the possible material savings are much 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. 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 (Fehling, 2005), compared to standard NSC, the carbonation process under outdoor conditions is 3 to 6 times slower in UHPC. Therefore in the present study as a realistic assumption for roughly considering the increased lifetime of UHPC members versus NSC a factor of 3 was chosen.

Taking into account both cross-sectional reduction and enlarged lifetime in the mentioned way, the so generated resulting net diagram shows that the ecological impact of several parameters is significantly reduced (Figure 7) and thus UHPC building members may finally cause less environmental impact than NSC. Additionally linked factors like reduced cross sections of foundations or savings in floor space due to the use of e.g. slender columns (Racky, 2003) are thereby not yet taken into account.

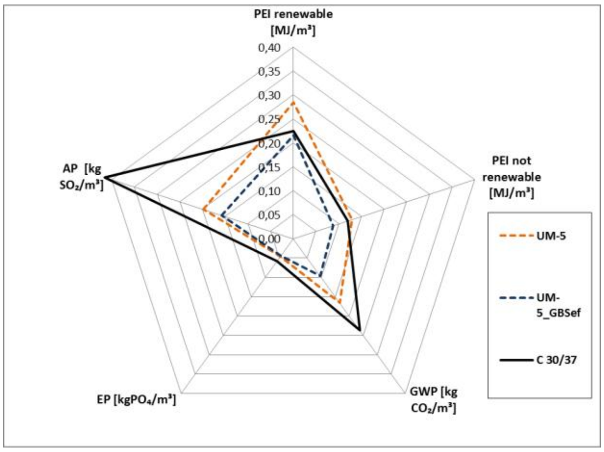

Figure 7. Comparison of environmental impact parameters between 1 m³ of C30/37, UHPC reference mixture UM-5 and UHPC with GBS extra fine (considering a reduction of the cross- section and increased durability of UHPC)

In addition it has to be mentioned that another important aspect when comparing building members is the incorporation of reinforcing steel and / or steel fibres. 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 fibres. Based on tensile tests with fibre reinforced UHPC (Randl, 2012), a steel fibre amount of at least about 2 % by volume may lead to a strain-hardening tensile behaviour of the UHPFRC rather than strain-softening. In addition UHPC members will usually also contain a somewhat reduced amount of steel reinforcement bars. The incorporation of both fibres 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 (Stengel, 2009). Considering the environmental impact of the steel ingredients makes only sense in conjunction with real building members and will be in the focus of the next phase of the present investigations.

5. CONCLUSIONS

The present study investigates the substitution of cement in UHPFRC by less energy-intensive latent hydraulic concrete additives, focusing on its effect on the mechanical properties and the environmental impact parameters. The production-related CO_2 emission of such alternative additives is in this context not relevant as they are by-products of the blast furnace process of steel or from caloric power stations fired with coal. 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 an adequate increase in the packing density 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 parameters of UHPC with that of NSC, the substitution of cement by SCM's is only a first step towards improving the sustainability of UHPC from the ecological point of view. However, when considering building members and taking into account also the reduction of material consumption and the increased durability and lifetime, the picture improves substantially.

(4) Further optimization of the partial substitution of the cement and the use of alternative fibre materials are required to increase the acceptance and competitiveness of UHPFRC from the environmental point of view.

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