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Sustainable Construction with UHPC – from Life Cycle Inventory Data Collection to Environmental Impact Assessment

Summary

The results of a research project aimed at developing a scientific basis for the life cycle assessment (LCA) of ultra high performance concrete (UHPC) are presented from which the environmental impact of UHPC production is derived for the first time. The environmental impact of UHPC production is mainly due to the manufacture of micro steel fibres, cement and superplasticizer. To reduce environmental impact it is necessary to lower the quantity of these materials used in the UHPC mix. Based on the results of this study, the environmental impact of existing UHPC bridges and comparable conventional constructions is being currently analysed.

Keywords: *sustainable construction, life cycle assessment, life cycle inventory*

1 Introduction

Structures made from normal concrete with a mass to strength ratio which ranges from 40 to 120 kg / MNm usually require considerable quantities of raw materials. In the case of UHPC, the mass to strength ratio of 15 kg / MNm is lower than that of normal concrete which provides for more economical deployment of resources. However, a disadvantage of UHPC when produced according to current technology is its high cement content which is well above that of normal concrete. Moreover, the high content of high-performance superplasticizer and the use of micro steel fibres increase demands on resources and energy. These factors partially offset the advantages of UHPC. However, the evaluation of the sustainability of building materials requires consideration of many parameters – not just mass to strength ratio. The aim of the research project presented here is the development of a scientific basis for the LCA of UHPC.

2 Environmental Impact Assessment with the Help of LCA

LCA enables estimation of the potential environmental impact of production processes. The procedure is laid down in the standards DIN ISO 14040 ff.. Owing to the large amount of data, LCA is carried out using software and databases for processes and materials. In this study, the software SimaPro and the Swiss ecoinvent database were used. The impact assessment can, in principle, be performed using different methods. Depending on the particular method, one or more impact category indicators are specified. In this study, the estimation of impact was performed using the CML method in SimaPro where results were obtained for the impact categories global warming (GWP), ozone depletion in the stratosphere (ODP), summer smog, i.e. photo chemical ozone creation (POCP), acidification (AP) and eutrophication (NP).

3 Composition of State-of-the art UHPC

The mean composition of UHPC was investigated based on the evaluation of literature covering the last 10 years. The mean cement content is roughly 750 kg/m^3. If all reactive components are included, the binder content is about 925 kg/m^3. This yields a mean water / binder ratio of 0.20 for a mean water content of 180 kg/m^3. A high content of superplasticizer on polycarboxylate ether (PCE) basis is necessary which is, on average, 30 kg/m^3, i.e. 3.4 wt.% with respect to the binder. The mean content of steel fibres used is 240 kg/m^3 or 3 vol.%. Another literature research [1] yielded similar results. To estimate the environmental impact of UHPC production in the scope of a LCA, production process data for the individual concrete components are required. Process data may be taken directly from or represented by appropriate values in the ecoinvent database for the production of cement, quartz sand and quartz flour as well as the provision of water. In this study, inert powder is represented by a dataset for inert finely ground limestone. The effect of polypropylene fibres is neglected since UHPC contains an average of only 2 kg/m^3 of this material. Process data are not available for the production of micro steel fibres and PCE so far. To obtain process data for these materials it is necessary to analyse the production method and prepare the information so that modelling using the basic ecoinvent modules is possible.

4 Production of Micro Steel Fibres

4.1 General

The production of high strength micro steel fibres can be divided into the subprocesses electric steel production, hot rolling, descaling, dry wire drawing, wet wire drawing, tempering, steel cord strand production and cutting to length, Figure 1. Ecoinvent process data are directly available for the first two subprocesses. In this study, the remaining subprocesses were modelled with the help of other ecoinvent subprocesses.

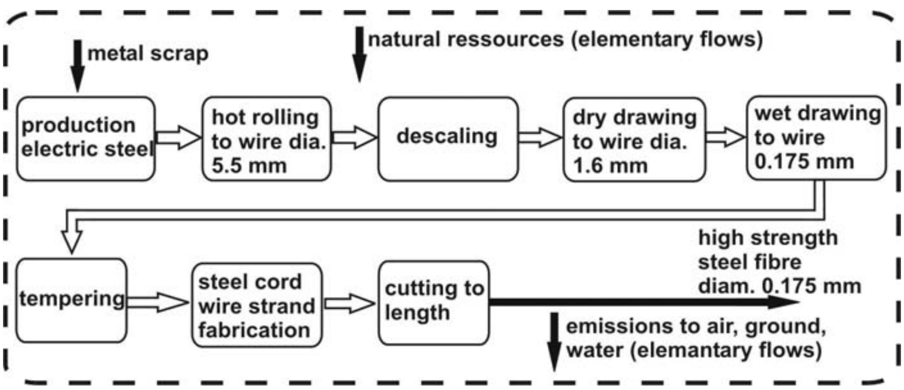

Figure 1: Process stages for the production of high strength steel fibres and system boundary (dashed line)

4.2 Descaling

When hot rolled wire cools down a hard, brittle surface oxide layer known as scale forms which must be removed before the wire can be drawn to smaller diameters. The conventional descaling method is to bend the wire in different directions in order to loosen the scale which is then removed by brushing. Based on data in [2, 3], the descaling machine was assumed to weigh 1 500 kg and operate at a feed rate of 1.25 m/s being electrically powered by 30 kW. It is assumed that 1 g scale per metre wire is removed. The service life of the machine is taken to be 25 years which, when running for 23 hours a day, means an output of 105.68×10^6 kg. The descaling process was modelled using the ecoinvent process data sets for an industrial machine and the energy mix needed for its operation.

4.3 Dry Wire Drawing

Dry wire drawing is performed to pull hot rolled wire down to a diameter of approximately 1.8 mm [4]. Mostly calcium and sodium soaps are used as a dry lubricant. Since friction can cause temperatures as high as 400 °C, the drawing dies are cooled with water and the wire with compressed air. Dry wire drawing machines have as many as 14 consecutive drawing dies each usually separately driven. In this study, it was assumed that the complete machine weighs 25 t and operates at an electric power of 164 kW to draw wire at a speed of 20 m/s. Thus assuming the same operating conditions as for the descaling machine, the total output is 181.11×10^6 kg steel wire. The dry wire drawing process was modelled with ecoinvent process data sets for an industrial machine and the energy mix necessary for its operation. The lubricant was taken into account by a data set for soaps.

4.4 Wet Wire Drawing

During wet wire drawing the wire diameter is reduced to its final value of appr. 0.175 mm. In wet wire drawing machines, a series of drawing and deformation cones are placed beside each other in a “parallel” arrangement and driven by a common electric motor [2, 3]. The wire and dies are cooled with a drawing liquid consisting of an aqueous emulsion of vegetable oils and fats (lubricant). The machine considered in this study draws wire at a speed of 24 m/s and is electrically powered at 40 kW. A machine weight of 2 t was assumed. The drawing liquid is in a bath with a capacity of 700 l and is used over a period of 3 months before renewal. Thus a total of 42 000 l liquid is used during the service life of the machine. A consumption of 2 kg lubricant per tonne of wire is assumed. Applying the same operating conditions as for dry wire drawing, the total output of the wet drawing machine is 2.05×10^6 kg steel wire. The wet wire drawing process was modelled with ecoinvent process data for an industrial machine and the energy mix necessary for its operation. Moreover, the lubricant was taken into account by a data set for lubricating oil and the drawing liquid by water.

4.5 Tempering

Although wire drawing enables tensile strength as high as 4 000 N/mm^2 ductility is lost. To improve ductility, the wire is tempered in a continuous feed method by heating to 500°C and cooling in water or oil [3]. Tempering is performed under an inert gas blanket to avoid unwanted oxidation reactions. The tempering machine in this study weighs 2.2 t and is able to treat simultaneously 16 wires with diameters around 0.175 mm [5]. The total electrical power for heating is rated at 22 kW. The mean feed speed may be assumed to be 16 m/s so that the total output is 21.91×10^6 kg for the same operating conditions as the above machines. The tempering process was modelled with ecoinvent process data for an industrial machine and the energy mix necessary for its operation.

4.6 Steel Cord Wire Strand Fabrication

Single steel wires are laid in strands by twisting around a common central axis. Strand is easier to handle than wire thus enabling a larger output in fibre production in the last stage of manufacture. Laying is performed by so-called double-twist bunching machines. The pay-off bobbins are located outside the machine and the steel wire cord is produced and spooled inside the laying system. The weight of the stranding machine considered was appr. 15 t and the electric power 43 kW. The laying speed is 2.5 m/s if a twist length of 2 cm and 7 500 wire twists per minute are assumed. A total output of 5.78×10^6 kg results for operating conditions the same as the above machines. The laying process was modelled with ecoinvent process data for an industrial machine and the energy mix necessary for its operation.

4.7 Cutting to Length

In this last sub process the high strength steel wire strand is cut to length producing individual fibres having the required length. This is performed with a wire cutting machine where the required fibre length is set by adjusting feed speed and the speed of a rotating cutter. The wire feed and cutter are powered by an electric motor with a continuously variable rotational speed. The machine considered weighs 700 kg and has an electric power of 5 kW. The total operating time was assumed to be 30 000 h and the mean throughput 150 kg/h [6]. This results in a total output of 4.5×10^6 kg. The cutting process was modelled with ecoinvent process data for an industrial machine and the energy mix necessary for its operation.

4.8 Impact Assessment of the Production of High Strength Steel Fibres

The results of the environmental impact assessment for the production of 1 kg of micro steel fibres are presented in Table 1. Figure 2 shows the contributions of the different sub processes to each impact category.

Table 1: Results of the impact assessment for the production of 1 kg high strength steel fibres

Impact category	Result	Unit
GWP	2,68	kg CO_2-eq
ODP	$1{,}41 \times 10^{-7}$	kg CFC_{11}-eq
POCP	$6{,}86 \times 10^{-4}$	kg C_2H_4-eq
AP	$1{,}41 \times 10^{-2}$	kg SO_2-eq
NP	$1{,}02 \times 10^{-3}$	kg PO_4^{3-}-eq

The largest contribution to the impact indicators is from the wet wire drawing process which lies between approximately 35 and 52%. This is followed by the production of electric steel and steel cord wire strand fabrication which both range approximately from 14 to 32%.

Hot rolling contributes about 6 to 15% and dry drawing approximately 3%. The contributions of the remaining subprocesses are all below 1%.

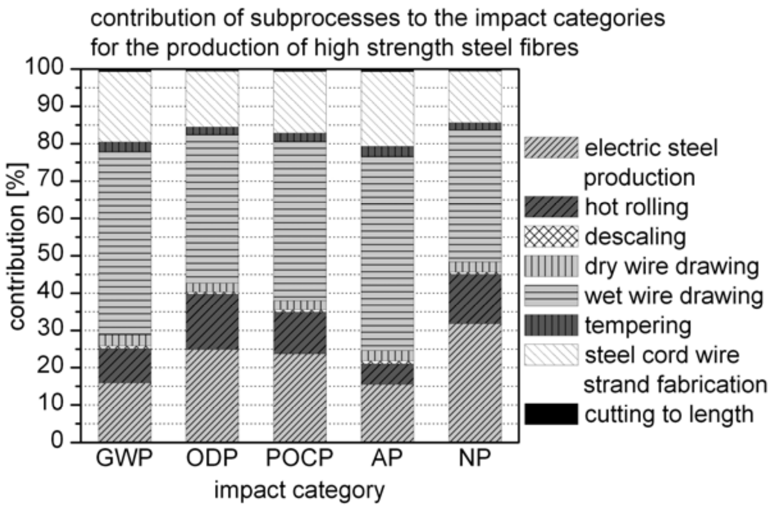

Figure 2: Results of dominance analysis for the production of micro steel fibres

5 Production of Superplasticizer Based on Polycarboxylate Ether

5.1 Raw Materials and Constituents

Polycarboxylate ethers (PCE) contains groups with polyoxyalkylene, especially polyethylene or polypropylene glycol groups as well as carboxylic acid and/or carboxylic acid anhydride monomers, e.g. acrylic acid , methacrylic acid, maleic acid and its anhydride, itonic acid and its anhydride. In addition monomers based on vinyl or acrylate can contribute to the chemistry of PCE. The raw materials and the molecular chaining hierarchy of the constituents for the synthesis of PCE are shown in Figure 3 in a schematic flow diagram. The constituents are represented by ecoinvent process data for acrylic acid, maleic acid, ethylene glycol, sodium hydroxide and hydrogen peroxide. The final product, superplasticizer based on PCE, also contains water and biocides which were also represented with the help of ecoinvent process data. The batch polymerisation process requires a polymerisation plant and suitable industrial buildings. The necessary infrastructure and energy for this was determined in this study.

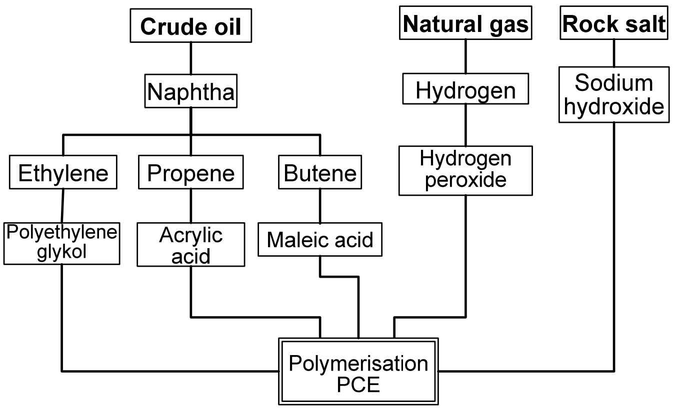

Figure 3: Flow diagram for raw material and chaining hierarchy of constituents for polymerisation of PCE

5.2 Polymerisation Plant

The following information on process engineering for the production of PCE is taken from [7, 8, 9, 10]. PCE plants comprise a number of storage and supply vessels as well a chemical reactor with a capacity usually around 20 m^3. The lid of the reactor is fitted with a cross beam stirrer complete with motor. A supply system is used to charge the reactor with the constituents from above. Beforehand, some of the monomers are transformed into macromonomers in a small agitator container and then transferred with the main charge to the reactor. The main polymerisation reaction is controlled by the dosage of initiator and a heating and cooling system. The temperature of the reactor is maintained at 60 to 80 °C during polymerisation. In this study, the reaction time was set at 5 h. After a cooling phase lasting one hour, neutralisation and the addition of substances such as defoamer and biocides, the reactor can be recharged. The plant in this study weighs 95 325 kg and has electric motors with a total power of 135 kW as well as operation and production buildings with a volume of 35 000 m^3. The service life of the plant is set at 25 years. Working in three shifts, the plant synthesises approximately three times 20 t PCE per day. This corresponds to a total production of 390×10^6 kg aqueous polycarboxylate solution for a total operating time of 156 000 h. The polymerisation plant was modelled with ecoinvent process data for an industrial machine, a general operating building and the energy mix necessary for operation.

5.3 Impact Assessment for the Production of PCE

The results of the impact estimation for the production of 1 kg PCE are presented in Table 2. Figure 4 shows the contributions of the different subprocesses to each impact category. The production of maleic acid contributes with 42% most to GWP. This is followed by the production of ethylene glycol, approximately 26%. Acrylic acid and sodium hydroxide each contribute between 10 and 12%, respectively. ODP is dominated by the production of maleic acid , approximately 62%. The production of sodium hydroxide, biocides and ethylene glycol also contribute with between 8 and 11% significantly to this indicator. 99% of POCP comes from the production of acrylic acid.

Table 2: Results of the impact assessment for the production of 1 kg PCE

Impact category	Result	Unit
GWP	1.11	kg CO_2-eq
ODP	6.09×10^{-8}	kg CFC_{11}-eq
POCP	1.97×10^{-2}	kg C_2H_4-eq
AP	4.81×10^{-3}	kg SO_2-eq
NP	1.75×10^{-3}	kg PO_4^{3-}-eq

With 35%, ethylene glycol production has the largest effect on AP. It is followed by the production of acrylic acid, maleic acid and sodium hydroxide which each contribute between 13 and 21% to AP. With 83%, ethylene glycol production clearly dominates NP.

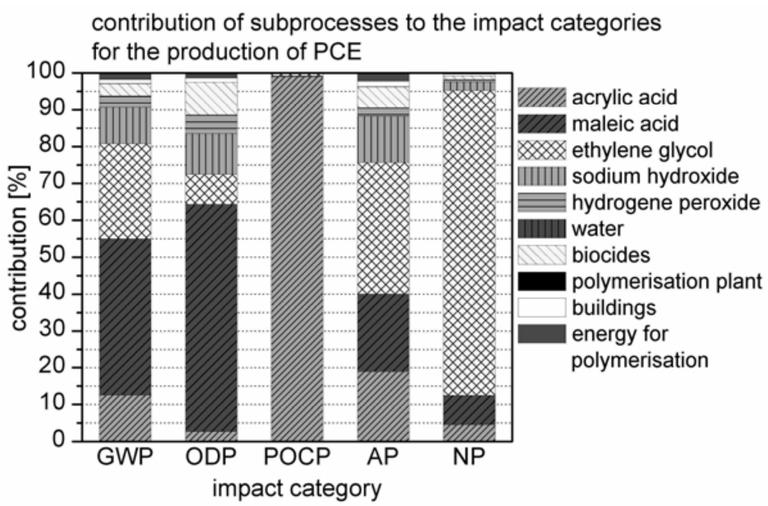

Figure 4: Results of dominance analysis for the production of PCE

6 LCA for a mean UHPC

Based on the process data derived in this study and the ecoinvent process referred to in section 3, it is now, for the first time, possible to estimate the environmental impact of UHPC. The mean UHPC composition in section 3 is used in this calculation. The results of the LCA for the production of 1 m^3 UHPC are presented in Table 3. The corresponding contributions of the subprocesses are shown in Figure 5. The manufacture of micro steel fibres dominates with 48 to 76% the categories GWP, ODP, AP and NP. The contribution from cement production, approximately 20 to 47%, is also considerable for these categories. The impact POCP is essentially due to the production of PCE, 75%, and the production of micro steel fibres, 21%.

Table 3: Results of the impact assessment for the production of 1 m³ UHPC

Impact category	Result	Unit
GWP	1.35×10^{3}	kg CO_2-eq
ODP	5.64×10^{-5}	kg CFC_{11}-eq
POCP	8.12×10^{-1}	kg C_2H_4-eq
AP	4.53	kg SO_2-eq
NP	4.45×10^{-1}	kg PO_4^{3-}-eq

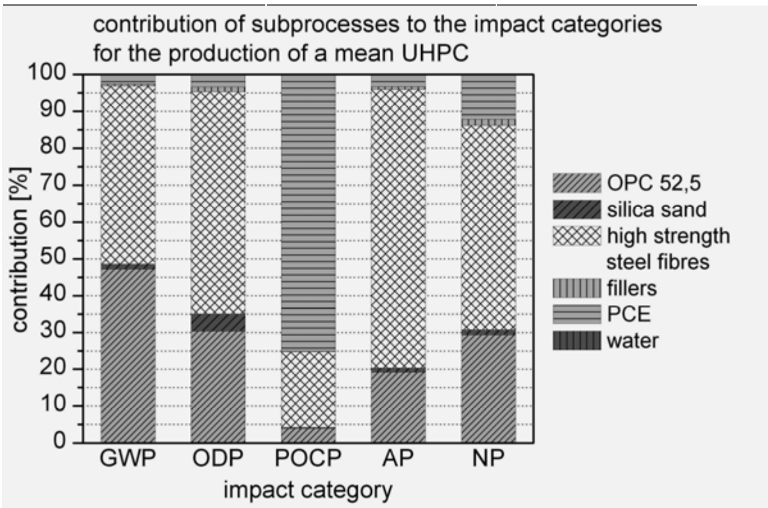

Figure 5: Results of dominance analysis for the production of state-of-the-art UHPC

7 Discussion

The main effect of UHPC production on the environment is caused by the manufacture of micro steel fibres, cement and PCE. Lowering the amount of these materials in UHPC is the easiest way of producing UHPC which is more environment friendly. The amount of fibres could be reduced to an optimum by improving the bond between the fibres and the binder matrix as well as the distribution and orientation of the fibres in UHPC. Since the contribution of wet wire drawing down to diameters around 0.175 mm to the environmental impact of steel fibre production is very large, the use of fibres with larger diameters is recommended. This would also be economically advantageous because micro steel fibre currently cost between 1 800 and 2 000 Euros per tonne and therefore present a high proportion of UHPC production costs. The production of PCE and its constituent acrylic acid cause the most part of POCP in UHPC production. This study did not consider whether use of other basic monomers for PCE production could reduce POCP.

8 Conclusions

The present research project aimed at developing a scientific basis for the LCA of UHPC. The results enabled, for the first time, the estimation of the environmental impact of UHPC production within LCA. It was found that the environmental impact of the UHPC production is mainly due to the production of micro steel fibres, cement and superplasticizer. The verification of the process data, determined in this study for the production of UHPC components, could be performed by process monitoring at the factory. This was not within the scope of the present research project. Moreover, the environmental effect of heat treatment, which is often carried out during UHPC production, was not taken into account. At present, the environmental impact of existing UHPC bridges and comparable conventional constructions is being investigated. Soon an answer could be given to the question as to whether building with UHPC is more sustainable than with conventional materials.

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10 References

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