MASS FLOW AND RISK ANALYSIS OF MODERN SUPERPLASTICISERS

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Abstract

Today quality concrete and mortars contain in most cases one or more admixtures. Concrete and mortar admixtures are designed substances with the aim of influencing their fresh and hardened properties by their physical or chemical action. For example, in the case of fresh concrete the flow, the cohesiveness and the setting behaviour are controlled; but also the hardened concrete properties such as strength, impermeability, shrinkage, or freeze thaw resistance can be positively influenced by the use of a concrete admixture.

The general trend towards "green" buildings and sustainability leads to a demand for environmental friendly construction chemicals. In addition the environmental behaviour of a newly developed chemical is usually unknown and bears public awareness and legal risks to the producer, distributor and/or buyer of the product. Therefore, understanding the movement and fate of new construction chemicals is a crucial step in state of the art risk management procedures (product stewardship). Moreover, analysing the mass flows and the risks of a chemical product enables the producer to understand the risk profile over the entire life-cycle of buildings and addressing the risks by appropriate measures.

The objective of this study was to assess the fate and risk of polycarboxylate (PCE) type superplasticisers during production and use throughout the entire life-cycle in Switzerland based on a mass flow analysis.

Keywords

concrete, concrete admixtures, superplasticisers, leaching test, biodegradation, mass flow analysis, risk assessment, life-cycle analysis

1. Introduction

In addition to cement, gravel, sand and water modern concrete normally contains one or more concrete admixtures. Depending on the nature of the admixture, it is possible to influence specific concrete properties such as flow behaviour, strength, resistance to freeze thaw cycles and deicing salts, sulphate resistance, setting characteristics, pumpability and others. Ecological demands on concrete as well as the continuous adaptation and development of construction and working techniques represent a constant challenge to researchers and developers of concrete admixtures. A "green concrete" is a concrete which according to ecological criteria has an optimized composition of the individual components (sand/gravel, cement, water, concrete admixture, additives) as well as a high durability meeting high technical specifications. The latter is positively influenced by the proper use of modern concrete admixtures [1]. According to FSHBZ (Fachverband Schweizerischer Hersteller von Betonzusatzmitteln) statistics approx. 15,000 t of concrete admixtures were sold in Switzerland in

2003, thereof approx. 75 % are superplasticisers. Today about half of the concrete manufactured in Switzerland has been modified with concrete admixtures.

Superplasticisers, also known as high range water reducing admixtures, are synthetic, water-soluble organic chemicals that significantly reduce the amount of water needed to achieve a given consistence in fresh concrete. This effect can be utilised to either reduce water content for increased strength and reduced permeability / improved durability or as a cement dispersant at the same water content to increase consistence and workability retention. With a slightly higher admixture dosage, both these effects can be achieved in the same mix. With a typical dosage of 0.8-4.0 % by weight of cement, superplasticisers increase the workability of concrete at a given water/cement-ratio significantly, leading to an easier placing and compaction. Alternatively, they can be used to give large reductions in water content in a range of 15-40 %. This reduction in water/cement ratio gives very significant durability enhancement and big strength increase at both early and later ages [2].

The use of polycarboxylate (PCE) type superplasticisers in high strength concrete, self compacting concrete or high-fluidity concrete has increased significantly within the last years. The new generation of superplasticisers based on PCE polymers containing long polyglycolether type sidechains allow not only for more water reduction up to 40 % - compared to the traditionally used materials like lignosulfonates, sulfonated naphthalene formaldehyde condensates (SNFC) or sulfonated melamine formaldehyde condensates (SMFC), which achieve a water reduction of about 25 % - but also notably extend the flow characteristics of the concrete paste. Therefore, the use of concrete with very low water/cement ratios is now possible and the dosage of the polymer can be reduced by up to 70 % compared to the traditional superplasticisers [3].

Former studies focussed on the environmental behaviour of superplasticisers of the SNFC and SMFC types, which were chosen because of their wide range of uses, the total quantity used in construction and their material properties. For these types of concrete admixtures mass flow analyses indicated that with correct use and disposal of these superplasticisers no adverse effects are to be expected for the health of man and the environment [1, 4, 5]. In the presented study the fate and risk of two PCE type superplasticisers throughout their life-cycle are modelled by applying a mass flow analysis. The objectives were:

- assessing the leachability of two model products, one with a methacrylic acid based backbone (stable bonds under high pH conditions - best case) and one with an acrylic acid based backbone (labile bonds under high pH conditions - worst case), the degradability of the leachable fractions and the degradability of the products;
- modelling the movement and fate of the two model substances by applying a mass flow analysis for Switzerland;
- calculation of the expected concentrations in different environmental compartments on a regional basis (Switzerland) and on a local basis (e.g. groundwater affected by storage of concrete rubble) and
- development of a risk assessment based on the estimated concentrations in the environment and the corresponding ecotoxicological data.

Based on the results of the study risk management measures are proposed to avoid any potential environmental risk by the use of PCE type superplasticisers.

2. Material and methods

2.1. Background data

Two different types of PCE superplasticisers were chosen out of six products, representing a product (polymer) with stable ester bonds (PCE I, methacrylic acid based - best case) and a product (polymer) with labile ester bonds (PCE II, acrylic acid based - worst case). It is expected that the product with

labile bonds (PCE II) reveals higher leaching from concrete than the product with stable bonds (PCE I). Properties of the two selected PCE type superplasticisers are summarised in Table 1.

Table 1: Properties of the two selected PCE type superplasticisers.

No.	Backbone	Sidechain	Molecular weight of sidechain	Total molecular weight	Distribution (Mw/Mn)	Case
PCE I	Methacrylic acid	Polyethylenoxides	1000	35.000	1.9	Best case (stable bonds)
PCE II	Acrylic acid	Polyethylenoxides	1000	21.000	1.8	Worst case (labile bonds)

The two selected products are each represented by four different fractions of chemicals, such as the active ingredient (polymer), and a smaller fraction of not reacted monomers, free polyethylenoxide sidechains and biocides. It was defined that each fraction represents a substance group with comparable physico-chemical behaviour and similar degradation characteristics. The product solutions contain 50 % (PCE I) and 60 % (PCE II) of water. The remaining solid content is represented by the active ingredient, its impurities (monomers and free polyethyleneoxide sidechains) and biocides (see Table 3).

To assess the environmental behaviour of the two PCE type superplasticisers concrete test cubes were prepared in the laboratory using standardised composition of sand/gravel, cement, water and concrete admixture. The concrete formula used to produce the sample cubes for the laboratory experiments and for the calculations in the mass flow analysis are shown in Table 2. From the concrete formula the concentration of the individual fractions (active ingredient, not reacted monomers, free polyethylenoxide sidechains and biocides) in the concrete could be calculated (Table 3).

Table 2: Concrete formula used to produce the sample cubes for the laboratory experiments and for the calculations in the mass flow analysis.

	Concrete I (with admixture PCE I)	Concrete II (with admixture PCE II)
Cement	300 kg	300 kg
Aggregate	1954.8 kg	1954.2 kg
Water	144 kg	144 kg
Admixture (solution)	1.2 kg (0.4% of cement)	1.8 kg (0.6% of cement)
Sum	2400 kg = 1 m^3	2400 kg = 1 m^3

Table 3: Concentration of the individual fractions of the two PCE superplasticisers in the concrete.

		PCE I (best case)			PCE II (worst case)		
Material	**Species**	**kg/m^3 concrete**	**g/kg concrete**	***%***	**kg/m^3 concrete**	**g/kg concrete**	***%***
Water	-	0.6000	0.2500	*50*	1.0800	0.4500	*60*
Fraction 1	Monomers	0.0003	0.0001	*0.025*	0.0004	0.0002	*0.025*
Fraction 2	Free Polyethylenoxide	0.0300	0.0125	*2.5*	0.0360	0.0150	*2.5*
Fraction 3	Biocides	0.0048	0.0020	*0.4*	0.0072	0.0030	*0.4*
Fraction 4	Active ingredient	0.5649	0.2354	*47.075*	0.6764	0.2819	*37.075*
Total		**1.2**	**0.5**	*100*	**1.8**	**0.75**	*100*

2.2. Processes considered in the mass flow analysis

The mass flow analysis considers processes along the whole life-cycle of the PCE type superplasticisers. They can be divided into short-term or long-term processes. Short-term processes occur during the production of the PCE products, during the production of concrete containing PCE products and during the application of the concrete on construction sites. Long-term processes occur after 50-100 years, when buildings or structures will be decommissioned and the waste concrete will either be reused or disposed. For the mass flow analysis it was assumed that these processes occur simultaneously. The following individual processes were considered:

- Short-term processes (production of PCE superplasticisers and use of concrete):
  - production of superplasticisers
  - manufacturing of pre-cast concrete
  - manufacturing of ready-mix concrete (for construction sites excluding tunnels)
  - manufacturing of ready-mix concrete (for tunnels only)
  - manufacturing of concrete on-site (incl. construction of tunnels)
  - structure under construction (considering processes such as the bleeding of concrete)
  - tunnel under construction (considering processes such as rebound of sprayed concrete)

- Long-term processes (after about 50-100 years):
  - decommissioning of structure
  - temporary storage of waste concrete (assumption: during 1 year)
  - reuse (recycling or road building) and disposal

Each of the considered processes consists of individual steps representing the whole life-cycle of the product. The calculations in the mass flow analysis are based on actual data from the different construction processes and the reuse and/or disposal practice in Switzerland, or from laboratory experiments (leaching tests, biodegradability studies). Assumptions were made if data were missing. As an example the long-term processes (decommissioning of structure, temporary storage of waste concrete and reuse and disposal) are presented in more details (Figure 1).

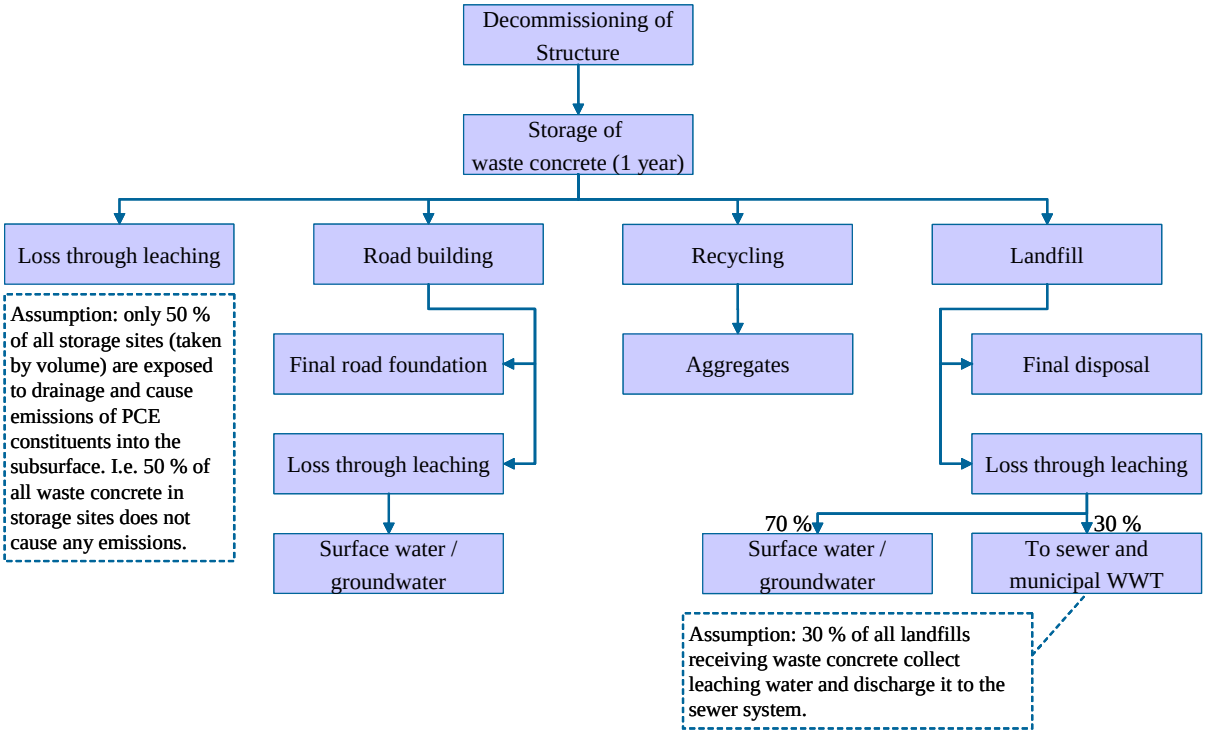

Figure 1: Long-term processes (reuse and disposal of waste concrete) and potential emissions of PCE type superplasticisers after decommissioning of structures.

After decommissioning of structures waste concrete is used and disposed in three different ways:

- Road construction: used as gravel substitute for foundations
- Recycling: used as gravel substitute in concrete production
- Landfill: final disposal in landfills

In this study the distribution of waste concrete to this three uses is based on statistical data and is defined as summarised in Table 4.

Table 4: Reuse and disposal of waste concrete in Switzerland and the values considered in this study.

	Zurich 2002 [6]		Switzerland 2001 [7]		this study
	tons/year		tons/year		
Road building	600'000	37%	4'700'000	49%	50%
Recycling	1'000'000	62%	4'100'000	43%	45%
Landfill	10'000	1%	700'000	7%	5%
Total	**1'610'000**	**100%**	**9'500'000**	**100%**	**100%**

2.3. Assumptions used for leaching calculations

The leaching of PCE constituents out of temporarily stored waste concrete into surface and groundwater is dependent on the area of each pile where percolating water from precipitation can actually reach the bottom of the piles and infiltrate into the ground or is emitted through run-off water into surface water. This depends on the average geometry and water retaining capacity of the piles of waste concrete [4, 7], and the bulk density of the waste concrete (taken in analogy to gravel). It was assumed, that:

- one pile has an average geometry of 5 m bottom radius and 5 m height;
- a pile is affected by rainwater down to a depth of 0.5 m (measured perpendicular to the surface), which leads to a volume affected by rainwater of 27 % of the total volume;
- only 30 % of the rainwater percolating through the pile finally reaches the bottom and causes drainage of leached PCE constituents into the subsurface.

The percentages of PCE constituents leaching out during the percolation of rainwater are taken (in the sense of a worst case scenario) as the maximum amount leachable as defined with the laboratory experiments. In reality, due to the low water/solid ratio of the drainage water from the pile, the leachable fraction is expected to be lower.
It is assumed that only 50 % of all storage sites (taken by volume) are exposed to drainage and cause emissions of PCE constituents into the subsurface. All other storage sites either are protected from precipitation or collect drainage water.

As in the case of storage piles, the leaching of PCE constituents from road foundations into surface and groundwater is dependent on the amount of concrete actually exposed to precipitation. This depends on the average geometry of the foundation (assumed thickness = 0.5 m, assumed width = 7 m) and the degree of coverage by asphalt (80 %) [4, 7], and on the bulk density of the waste concrete (taken in analogy to gravel). The percentages of PCE constituents leaching out of the exposed concrete during the percolation of rainwater are taken (in the sense of a worst case scenario) as the maximum amount leachable as defined with the laboratory experiments.

The percentages of PCE constituents leaching out of the exposed concrete in landfills during the percolation of rainwater are taken (in the sense of a worst case scenario) as the maximum amount leachable as defined with the laboratory experiments.

2.4. Laboratory tests performed

Sample cubes for the laboratory tests were prepared according to the concrete formula as summarised in Table 2. After a hardening time of 28 days the concrete cubes were broken with a hammer crusher. The crushed materials were sieved to gain fractions with particle size distributions of 0.063-1, 1-4 and 4-8 mm, respectively. Sequential leaching tests according to the Swiss Technical Ordinance on Waste [8] with some minor modifications (such as the extension of the test to 96 h or sieving of material) were performed with bi-distilled water and the emissions were quantified by the analysis of the dissolved organic carbon (DOC) concentrations using a TOC-Analyzer. The water in the leaching tests were exchanged every 24 h. For comparison a concrete sample containing SNFC type superplasticiser and a blank test cube without admixtures were also included in the leaching tests. For the calculation in the mass flow analysis the values obtained for the 4-8 mm fractions were used.

The PCE products were assessed in a biodegradation test according to the OECD test procedure 302 B [9]. This test was used for assessing the potential biodegradation of the PCE polymers in a wastewater treatment plant. The ordinary test procedure comprising the assessment of the DOC elimination was supplemented with the analysis of the produced carbon dioxide (effective biodegradation, mineralization). The leachable fraction from the concrete was assessed in a biodegradation test according to the OECD 301 A [10]. In this test procedure only the DOC elimination in the presence of a low bacteria concentration was assessed. Since the tests with the products (OECD 302 B) showed no significant DOC elimination under high bacteria concentration, it can be assumed that a potential DOC elimination in the OECD 301 A test can only be attributed to biodegradation.

3. Results and discussion

3.1. Biodegradability tests

In the biodegradability tests with the PCE products according to the test procedure OECD 302 B no significant DOC elimination was observed after 28 days of incubation indicating that neither significant biodegradation nor elimination by adsorption to the activated sludge microorganisms occurred (Figure 2).

However, the DOC in the leachable fraction from concrete could almost completely be degraded within 28 days (Figure 2) indicating that these compounds are readily biodegradable. It has to be assumed that the leachable fraction only comprises monomers or oligomers, but no polymers. This could be confirmed with molecular weight distribution analysis of the leachates where no polymers could be detected (results not shown). For the calculation in the mass flow analysis it was assumed as a worst case that the biocides are not biodegradable.

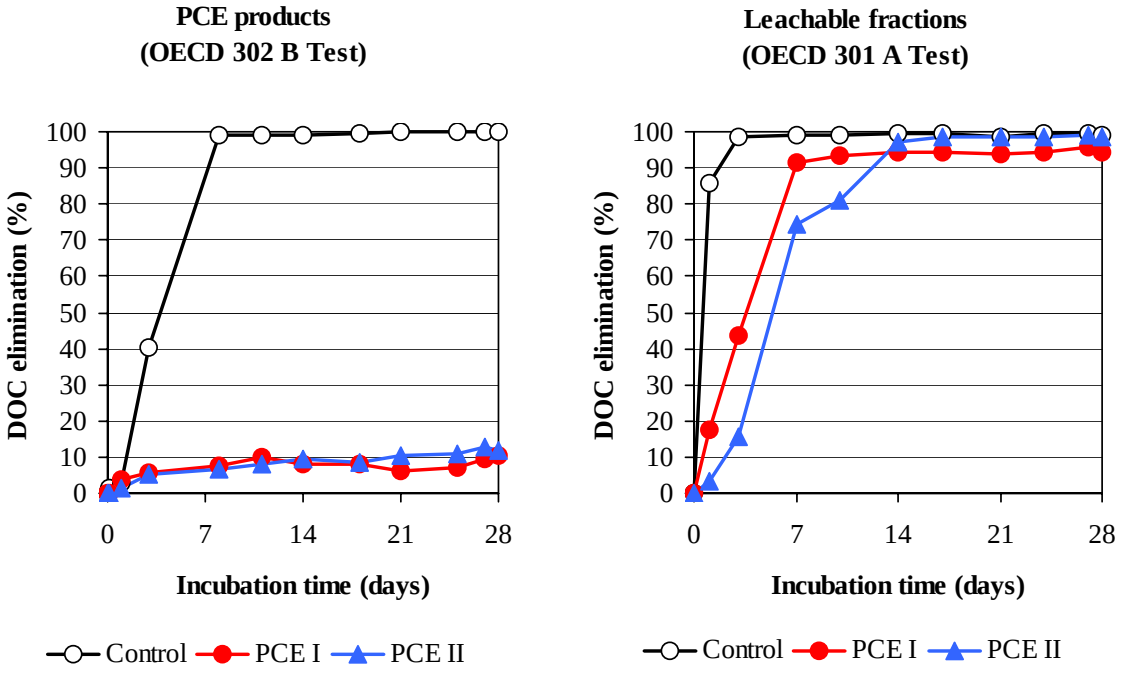

Figure 2: Results of the biodegradation tests with the PCE products and the leachable fractions from concrete. Reference compounds (controls) were diethylene glycol in the OECD 302 B Test and sodium benzoate, respectively, in the OECD 301 A Test.

3.2. Leaching tests

The results of the leaching tests showed that a significant fraction of the total organic carbon in the concrete sample is leaching out of the crushed concrete mostly in the case of the polycarboxylates with labile bonds (PCE II, worst case). These emissions are dependent on the particle size distribution (Table 5).

In the case of the PCE product with the stabile bonds (PCE I, best case) 4 % of the total organic carbon was leaching from the fraction 4-8 mm within 48 h of exposure which was in a similar range than the respective fraction of the SNFC test sample. However, in the case of the PCE product with the instabile bonds (PCE II, worst case) 18 % of the total organic carbon was leaching from the fraction 4-8 mm within 48 h of exposure (Table 5). Nevertheless, the values fulfil the criteria (mean value of 24 and 48 h leachate: 20 mg C/L) for disposal of the waste concrete in landfills for inert materials [8].

It has to be pointed out that the performance of such leaching tests (continuous mixing of concrete fractions and bi-distilled water) represent worst case conditions which do not reflect realistic conditions in a storage pile or a landfill. Nevertheless the cumulative data after 96 h were used for calculation in the mass flow analysis.

Table 5: Results of the leaching tests with the two PCE type superplasticisers and comparison with a blank cube and a concrete cube with SNFC type superplasticiser.

Test sample		**Blank**	**SNFC**	**PCE I**			**PCE II**		
Fraction (mm)		**4-8**	**4-8**	**0.063-1**	**1-4**	**4-8**	**0.063-1**	**1-4**	**4-8**
DOC in leachates									
after 24 h	mg C/L	**1.12**	**1.67**	4.20	3.31	**1.74**	19.3	5.38	**3.17**
after 48 h	mg C/L	**0.82**	**0.90**	1.40	0.95	**0.73**	3.10	2.07	**1.60**
after 72 h	mg C/L	-	-	1.21	0.90	0.69	1.76	1.41	1.05
after 96 h	mg C/L	-	-	1.63	0.86	0.81	1.75	0.89	0.47
Leachable carbon fraction									
TOC in concrete	mg/kg		**231**			**134**			**161**
net leachable DOC after 48 h	mg/kg		**6.3**			**5.3**			**28.3**
net leachable DOC after 48 h	%		**3**			**4**			**18**

3.3. Mass flow analysis (worst case scenario)

In the scenario with polycarboxylate PCE I (best case – stable bonds) a total of 591 tons/year are applied in Switzerland. In the scenario with polycarboxylate PCE II (worst case – labile bonds) a total of 710 tons/year are applied in Switzerland. Of the PCE I applied in Switzerland ~48 tons/year or 8.2 % would get lost during the whole life-cycle of concrete. Due to its higher dosage in concrete formulation (factor 1.5 more) and its better leachability (factor 1.9 better) ~77 tons/year of PCE II or 10.8 % of all PCE II applied in Switzerland would get lost during the whole life-cycle of concrete. Including the emissions from the municipal sewage treatment plant a total of 3.1 % or approx. 18 tons/year of all applied PCE I and a total of 5.5 % or approx. 39 tons/year of all applied PCE II are emitted to natural water bodies (surface waters or groundwater). However, due to their ready biodegradability both PCE I and PCE II emissions are expected to be eliminated in natural waters by approximately 90 %. This means that ~2 tons/year of PCE I and ~3.5 tons/year of PCE II would remain in natural water bodies in Switzerland.

Emissions to natural waters are more important in the late stage of the life-cycle of concrete (emissions originated after decommissioning of structures account for 90 % of all emissions for PCE I and 95% for PCE II, respectively). These emissions would occur more than 50 years after the construction of buildings and other structures. However, the leaching factors of 15 % (PCE I) and 28 % (PCE II), which were measured in the grinding fraction 4-8 mm of the leaching tests, have to be interpreted as a worst case scenario. In reality the average grain size is larger and thus significantly less emissions are expected from storage piles, landfills and road foundations.

It was assumed that from concrete exposed to leaching monomers, free polyethyleneoxides and biocides are leached entirely, while 10 % of the active ingredient (polymer) in case of PCE I and 23 % in case of PCE II is leached at the same time. Consequently, it was assumed that a total of 15 % of the sum of all fractions in the case of PCE I and of 28 % in the case of PCE II is leached out of the concrete. The product impurities and by-products (monomers, free polyethyleneoxides and biocides) are assumed to leach predominantly in relation to the active ingredient. Consequently once emitted to natural water bodies this implies a higher relative importance of these constituents. Since biocides were assumed not to be biodegradable in natural water bodies (worst case), they account for up to 50 % of all constituent remaining in the aquatic environment. According to these assumptions, biocides are, therefore, the dominant fraction remaining in surface waters and groundwater.

For illustration the mass flow analysis of the product PCE I (summary of all fractions) is presented in Figure 3.

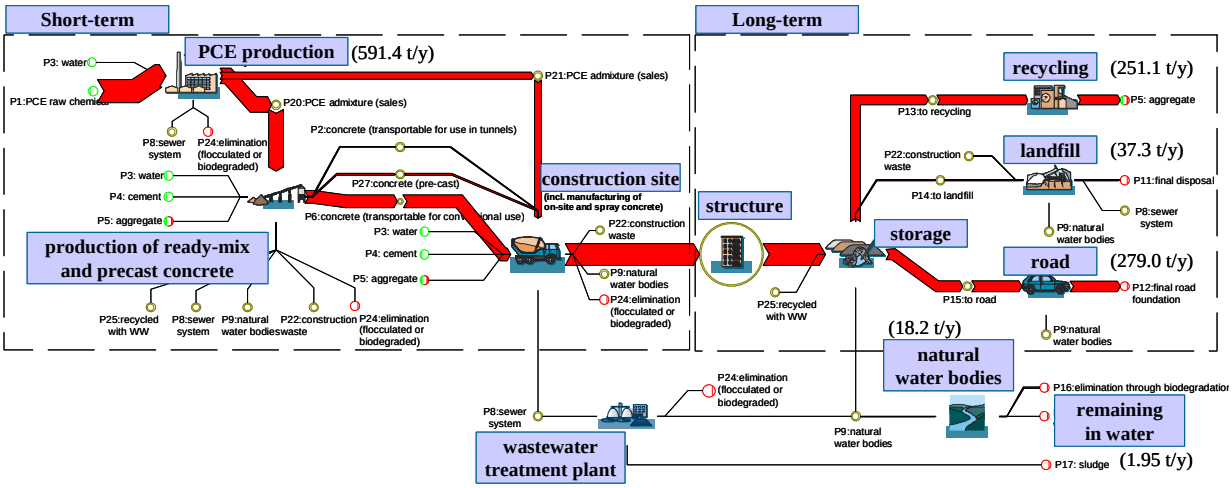

Figure 3: Mass flow analysis of product PCE I (in tons per year). The data are shown proportionally. The mass flows include all fractions of the product PCE I. The water content (50 % for PCE I) is not included.

4. Estimation of risk

The following estimation of the risk is based on mass flow calculations for Switzerland, which are based on the worst case scenario described. Therefore, it is important to realize the basic aspects of this scenario that contain conservative assumptions and estimates:

- The complete life-cycle is calculated for one period of time (1 year), and all corresponding emissions are added up. While emissions from production and application are likely to occur in the same year, emissions resulting from decommissioning of buildings and subsequent activities will occur much later. This has the effect that emissions will be distributed over prolonged periods of time.
- In several stages of the life-cycle (storage of waste concrete, landfilling, use in road construction) the total leachable amount determined in laboratory experiments is considered as emissions. In reality, this amount may be smaller (much longer hardening, larger particle size and lower water/solid ratio than used in the laboratory experiments) and may only leach totally over much longer time periods.

It is also important to note that within Europe, use of concrete admixtures per total amount of concrete manufactured is highest in Switzerland [5]. On the other hand, wastewater and waste concrete cycles are clearly less closed in most EU countries compared to Switzerland, which will lead to higher emissions per unit volume of admixture sold.

The risk assessment procedures are described by EU guidelines where predicted environmental concentrations (PEC) are compared with the toxicologically based predicted no-effect concentrations (PNEC) for the aquatic environment [11]. PNEC values used in this study are summarised in Table 6. The risk assessment was performed on a regional level, i.e. Switzerland, and on a local level e.g. below a storage pile of waste concrete.

Table 6: Predicted no-effect concentrations (PNEC) of the ingredients for the aquatic environment used in the risk assessment.

Fraction	Species	Ingredients (typically)	$PNEC_{aq}$ (µg/l)	Ref.
1	Monomers	Methacrylic Acid	164 [1)]	[12]
		Acrylic Acid	3 [1)]	[13]
2	Free Polyethylenoxide	Polyethyleneoxide	*Worst case assumption: same properties as monomers*	
3	Biocides	Formaldehyde derivates	25.0 [2)]	[14]
		Isothiazolinone derivates	1.6 [2)]	[15]
4	Active ingredient	Polycarboxylate	*Worst case assumption: same properties as monomers*	

[1)] PNEC values as defined in the respective EU risk assessment
[2)] PNEC values estimated using the equation PNEC = lowest acute EC_{50} / 1000

4.1. Risk on a regional level (worst case scenario)

The risk at a regional level was estimated assuming uniform distribution of emitted PCE constituents over all natural water bodies in Switzerland. At this regional level the predicted environmental concentrations (PEC) were ~0.4 µg/L (PCE I) and ~0.9 µg/L (PCE II) neglecting biodegradation and at ~0.05 µg/L (PCE I) and ~0.1 µg/L (PCE II) assuming biodegradation. Compared to the corresponding PNEC values (1.6 µg/L for a selected biocide – worst case) it can be concluded that there is no risk associated with the application of PCE type superplasticisers on a regional level in Switzerland.

4.2. Risk on a local level (worst case scenario)

The risk at a local level was estimated assuming direct emissions through leaching from a storage site (no surface drainage) into the subsurface. In the groundwater directly below the storage site the PEC was calculated at ~280 µg/L (PCE I) and ~630 µg/L (PCE II) neglecting biodegradation and at ~30 µg/L (PCE I) and ~60 µg/L (PCE II) assuming biodegradation. These values are clearly above the PNEC values of single worst case constituents, such as a selected biocide. However, taking into account all limitations and worst case assumptions of the model calculations it is not likely, that there is a local risk, associated with the application of PCE type superplasticisers under realistic conditions.

Nevertheless a risk could occur locally under a few special circumstances:

- if the formula of the product includes a high content of biocides of environmental concern;
- if the product can be leached out of waste concrete from locations without any emission controls and i.e. emitted directly to groundwater or surface water (assumptions: low dilution, drinking water well very close to waste concrete storage site)

Concentrations downstream from a road with a foundation of granular waste concrete can be assessed in a similar manner. A previous study for SNFC type superplasticisers showed that similar PEC values can be expected as from the scenario with storage piles.

5. Risk management measures

The risk assessment as presented in the previous section has shown that risks associated with the application of PCE type superplasticisers are not likely under realistic conditions. However, to avoid any risk from waste concrete storage sites, landfills and the reuse of waste concrete in road foundation the following risk management measures can be taken:

- storage of waste concrete on paved areas with collection of drainage water and subsequent treatment in wastewater treatment plants;
- collection of drainage water from landfills and subsequent treatment in wastewater treatment plants;
- use of waste concrete in road foundations only in cementious bound form;
- monitoring of groundwater and surface water at large storage sites and landfills.

Biocides are the most relevant constituents emitting into the environment. Therefore, the use of biocides with low toxicity and acceptable biodegradability is the most effective preventive measure at the beginning of the life-cycle.

Most emissions occur after decommissioning of structures. Control measures for the drainage of waste concrete storage sites and landfills are the most effective preventive measure at the end of the life-cycle.

Concrete production sites and construction sites generally already possess a well established emission control systems and, therefore, emitted mass flows from these sites are of minor concern.

6. Conclusions

Large amounts of concrete is manufactured by the use of concrete admixtures today. However, buildings last for 50 up to >100 years. This implies that depending on the reuse of old concrete large emissions could be possible after the demolition of the buildings. New legislation will be in force in the future and it might be possible that up to 100 % of the concrete will be recycled. Since the future cannot be predicted it is advised to eliminate potential problems already during the development phase of products or to apply risk management measures as described above.

Mass flow analysis, risk assessment and life-cycle analysis are valuable tools to support future developments in the construction industry.

7. Acknowledgement

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