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Grunewald, Steffen; Schutter, G

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Design Considerations and Sustainability of Self-Compacting Concrete

Steffen Grünewald[1,2] and Geert de Schutter[1]

[1] Magnel Laboratory For Concrete Research, Ghent University, Ghent, Belgium
[2] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

Abstract Self-compacting concrete (SCC) differs from conventional vibrated concrete (CVC) in the rheological behaviour, which is achieved by adequate mix design. The application and production requirements also pose demands on the mix design and workability. Effective production requires adequate strength control. The use of Portland Cement promotes a rapid early age strength development, but it comes with a relative high impact on the environment since decarbonation and a high energy demand accompany cement production. Supplementary cementitious materials have been widely applied to improve the sustainability of concrete but the rate of early age strength development often is compromised. This paper discusses the application of SCC for concrete structures with regard to mix design and its environmental impact. 24 CVCs and SCCs with a variety of mix designs and rheological characteristics were selected from literature. The two objectives of this study were: 1) to determine the environmental impact with regard to the global warming potential and MKI-costs (calculated with the Dutch CUR-tool 'Green Concrete 3.2') and 2) to relate the environmental impact with the compressive strength at 24h and 28d. Quantifying the trade-off between the use of Portland Cement and other mixture components is important information to balance production requirements and to determine the environmental impact of concrete structures produced with SCC.

Keywords: *Self-compacting concrete, Mix design, Rheology, Environmental impact, Sustainability, Relative strength cost*

Introduction

The advantages of concrete are freedom of shape, possibilities to integrate other functions and components, to build structures with limited maintenance costs, ease of use and very high durability. A significant reduction of the environmental impact can convince owners to select concrete rather than other building materials.

Effective production of concrete structures requires adequate control of strength development in order to realize the scheduled production cycles with daily and seasonal changes of temperature. Demoulding of elements can take place only when sufficient strength is gained. The impact of Portland Cement on the global warming potential has been widely discussed in the past years; supplementary cementitious materials can enhance the sustainability of concrete but can come with negative effects on early age strength and decreased durability. Higher replacement levels of Portland Cement often have been compensated for by additional heat curing, an optimization of the granular skeleton and/or the use of a strength accelerator. Wallevik et al. [1] classified concrete with regard to binder content in SCC (Figure 1a) and the carbon footprint of concrete (Figure 1b). Both categories provide a framework for the discussion in this paper.

Category SCC	Binder: kg/m^3
Rich	575
Regular powder	515±40
Lean	425±40
Green	355±40
Eco-SCC	≤315
EcoCrete-SCC	≤260
EcoCrete-Xtreme	≤220

Carbon footprint	kgCO_2/m^3
Semi-LCC	≤300
LCC250	≤250
LCC200	≤200
LCC150	≤150
EcoCrete	≤125
EcoCrete-Xtreme	≤105

Figure 1: Two classes of categories - a, left) SCC (binder content) and b, right) Concrete carbon footprint (LCC: Low Carbon Concrete Class).

The behaviour of CVC is governed by friction between powders and aggregates, whereas for SCC fluid dynamics are more important. Typically, the paste volume in SCC is higher, the degree to what depends on the mix design, the application, the strength class and the required robustness of a system. In order to obtain a high flowability the paste volume and the viscosity have to be increased and the maximum aggregate size decreased. Five important criteria with regard to the mix design of SCC are:

- 1) For adequate mix design of SCC boundaries with regard to the rheological characteristics yield stress and plastic viscosity have to be respected.
- 2) The required rheological characteristics often depend on the application; use of the full spectrum of rheological characteristics is not always possible or desired.
- 3) Additional restraints are posed with regard to engineering properties, durability demands, production conditions, mixture components and client specification.
- 4) Segregation resistance can be achieved with a high yield value, a high plastic viscosity, thixotropy, stabilizing due to the lattice effect and/or reduction of the ability of liquid/slurry migrating to the shearing zone [2].
- 5) Ecological aspects and sustainability are becoming more important and will provide less freedom for mix design.

A classification of concrete is required for the quantification of sustainability, which needs to be included in the life cycle analysis (LCA) of structures. General agreement has to be achieved concerning the assessment method of the environmental impact of materials and structures; an example of an impact indicator is the Environmental Product Declaration (EPD). The development of such 'instruments' requires a coordinated and cooperative approach. A discussion of the environmental impact of concrete based on only the mixture composition might seem isolated not taking into account the total life cycle costs of a structure, but it indicates the potential for an optimization on the material level.

Environmental Impact Quantification

According to the Dutch law 'Bouwbesluit' the depletion of raw materials and emission of greenhouse gases has to be determined for new buildings and renovation projects. Worldwide, large differences can be identified with regard to the methods applied for the quantification of the environmental impact in the construction sector and the recognition thereof. In the future, it probably will be common practice to include instruments such as EPD's in tenders and contracts. A LCA has to consider many aspects. In order to compare buildings or concrete structures it is necessary to weight different aspects (i.e. EN 15804 [3] distinguishes seven environmental impact parameters, but does not provide any help with regard to their weighting). In the Netherlands, a national database [4] has been established, which can be applied to quantify the environmental impact of infrastructures. In addition, the CUR-tool 'Green Concrete' [5] was developed to quantify the environmental impact, to weight different environmental aspects, which are then expressed in the same unit (costs in Euro) with the help of conversion factors. Table 1 lists 11 considered parameters and conversion factors.

Table 1: Eleven environmental impact categories and MKI-conversion factors [5].

Nr.	Impact category	Abbre-viation	Unit	Factor [Euro/kg]
1	Abiotic Depletion, fuels	ADP1	kg Sb eq	0.16
2	Abiotic Depletion, minerals	ADP2	kg Sb eq	0.16
3	Acidifying Pollutants	AP	kg SO2 eq	4
4	Eutrophication Potential	EP	kg PO4 eq	9
5	Freshwater Aquatic Eco-Toxicity Potential	FAETP	kg 1,4-Dichlorobenzene eq	0.03
6	Global Warming Potential (100 years)	GWP 100 Y	kg CO2 eq	0.05
7	Human Toxicity	HTP	kg 1,4-Dichlorobenzene eq	0.09
8	Marine Aquatic Eco-Toxicity Potential	MAETP	kg 1,4-Dichlorobenzene eq	0.0001
9	Ozone Depletion Potential	ODP	kg CFC11 eq	30
10	Photochemical Ozone Creation Potential	POCP	kg Ethylene eq	2
11	Terrestrial Eco-Toxicity Potential	TETP	kg 1,4-Dichlorobenzene eq	0.06

CO_2-emissions (Global Warming Potential; GWP) have a major influence on the environment; GWP often is referred to as the 'carbon footprint'. The CUR-tool aims at users that want to determine the environmental impact of structures and structural elements made with concrete. It covers: production of components, transport, concrete production, construction phase and demolishing. It is also a tool to optimize concrete and concrete structures with regard to the environmental impact. The user chooses the building materials and processes from a database. With own data, the database can be extended. For the calculation of the environmental cost parameter MKI (Dutch: Milieu-Kosten-Indikator) eleven environmental impact categories from LCA data in a building product EPD are taken into account with conversion factors that reflect their relative effect. The outcome is costs in Euro/unit. The MKI is a factor already taken into account in the Netherlands for the tender of community works as well as for office buildings.

Reference Mixtures

Three reference mixtures (Table 2: R1-R3) were selected with deviating compressive strengths and environmental impact, which represent examples of typical CVCs containing common components applied in the Netherlands. Mixture R1 contains a CEM I 42.5 and might be applied by the prefab-industry; a blast furnace slag cement was used for Mixture R2, which is often the case for in-situ cast concrete structures. The strength class of both mixtures was C35/45. Mixture R3 contains a higher dosage of CEM I 52 R, and as a result, the highest early age strength of all mixtures was obtained (67.7 MPa at 1 day; strength class C67/75). A variety of mix designs for SCC was selected from literature in order to discuss differences and to compare them with CVC; the 21 SCC-mixtures were selected from eight different sources. With regard to the compressive strength, the following was specified as selection criteria: 1) use of cubic moulds with 150 mm size and 2) availability of compressive strength results at 1 day and 28 days (1 day strengths were not determined for S14-S17). No specific requirement was defined for the workability of CVC. Mixtures R1-R3 were 'easy compactable'(Slump > 15 cm); no consistency measurements were carried out. The paste contents of R1, R2 and R3 were 27.8, 27.9 and 29.6 Vol.-% (including air), respectively. The slump flow of the SCCs was at least 630 mm. Not all mixture components could be directly linked with components of the database. The following was assumed:

- the CEM II cement of S3 contains 85% CEM I and 15% GGBS (slag);
- the CEM II of S10&S11 contains 85% CEM I and 15% limestone powder;
- in some cases (S1,S2,S12,S13) the aggregate fraction (i.e. 2-8 mm) did not match the sand 0-4 mm and coarse aggregate 4-12/16 mm grouping of the database, with an assumed distribution these fractions were divided in the available groups.

Table 3 shows the reference database-sets of the Green Concrete tool [5] for the eleven impact parameters and the applied concrete components. The numbers are industry-averages and might be lower or higher for the materials applied. Not all components are included in the database; the following assumptions were made: 1) granite powder has the same conversion factors as limestone powder and 2) air-entrainer and viscosity agent have the same conversion factors as superplasticizer for the same weight.

Table 2: Mixture composition and characteristics of 3 reference and 21 self-compacting concretes (dosage of components in kg/m^3).

Mixture component	**R1**	**R2**	**R3**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
Reference	[6]	[6]	[6]	[7]	[7]	[8]	[9]	[9]	[10]	[10]	[10]	[10]
CEM I 42.5/52.5	300		370	267	368	340		185	600	316	318	386
CEM III B		300					270	184				
GGBS						60						
Limestone powder				248	218	250				202	228	222
Fly ash							273	185		35		43
Silica fume												
Granite powder												
Sand, river	860	856	836	790	722	870	670	662	754	1010	962	719
Crushed aggregates						710			837	541	619	786
Gravel, river	1051	1046	1022	864	873		870	900				
Water	159	159	155	185	150	170	174	177	190	191	184	181
Superplasticizer	0.75	0.45	2.09	6.70	3.04	4.81	2.27	3.14	10.5	10.0	11.8	12.4
Air entrainer					0.02							
Viscosity agent												
Binder content	300	300	370	515	586	650	543	554	600	553	546	651
w/b-ratio [-]	0.53	0.53	0.42	0.36	0.26	0.26	0.32	0.32	0.32	0.35	0.34	0.28
Slump flow [mm]	-	-	-	700	660	740	688	665	>750	>750	>750	>750
$f_{c,cube}$ 1 d [MPa]	10.9	5.5	67.7	18.5	21.4	42.0	4.3	18.5	27.7	12.2	13.5	23.0
$f_{c,cube}$ 28 d [MPa]	51.6	54.1	86.7	45.5	71.6	69.0	36.9	65.0	50.0	33.5	33.7	45.0

Mixture component	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**	**S21**
Reference	[11]	[11]	[12]	[12]	[13]	[13]	[13]	[13]	[14]	[14]	[14]	[14]
CEM I 42.5/52.5	374	374	379	394	302	218	169	274				300
CEM III B									270	400	270	
GGBS												
Limestone powder	66	186	253					30			243	184
Fly ash	100			263		75	131		216			
Silica fume					12	11		15				
Granite powder												100
Sand, river	1110	1110	896	896	925	922	916	911	710	792	714	807
Crushed aggregates	430	430			909	907	900	895				
Gravel, river			596	596					1078	1094	1074	796
Water	200	200	177	155	204	198	195	203	129	143	133	164
Superplasticizer	4.4	4.4	2.4	2.0	2.25	2.19	1.91	2.03	3.4	2.8	4.1	3.5
Air entrainer												
Viscosity agent										2.4	2.6	
Binder content	540	560	632	657	314	304	300	319	486	400	513	584
w/b-ratio [-]	0.37	0.36	0.28	0.24	0.65	0.65	0.65	0.64	0.27	0.36	0.26	0.28
Slump flow [mm]	800	750	730	780	660	650	630	645	730	665	750	730
$f_{c,cube}$ 1 d [MPa]	17.0	17.0	13.2	8.1	-	-	-	-	6.1	12.1	8.2	22.3
$f_{c,cube}$ 28 d [MPa]	44.0	40.5	54.2	43.2	40.0	40.0	28.9	44.4	50.4	62.5	54.6	57.8

Table 3: Conversion factors for eleven environmental impact categories [5].

Mixture component *Database reference*	ADP 1	ADP 2	GWP	ODP	POCP	AP	EP	HTP	FAE-TP	MAE-TP	TETP
CEM I 42.5/52.5 *SBK CEM-I NL c2*	6.7E-07	5.7E-04	8.2E-01	5.2E-09	2.1E-04	2.7E-03	3.6E-04	5.0E-02	6.9E-04	5.1E+00	6.8E-04
CEM III B *SBK CEM-III NL c2*	6.7E-07	8.5E-04	3.0E-01	5.4E-09	9.0E-05	1.0E-03	1.0E-04	2.7E-02	3.4E-04	8.2E+00	3.6E-04
GGBS *SBK Hoogovensl.*	7.6E-10	1.7E-04	1.9E-02	1.1E-09	1.0E-06	5.8E-06	1.4E-06	3.6E-03	4.6E-06	2.0E+00	2.7E-06
Limestone powder *Kalksteenmeel (DE)*	2.0E-08	2.3E-04	3.2E-02	2.4E-09	1.0E-05	8.5E-05	2.2E-05	7.4E-03	2.1E-04	1.1E+00	8.2E-05
Fly ash *Poederkoolvl. c2*	8.5E-10	2.3E-05	3.3E-03	2.6E-10	1.2E-06	1.5E-05	3.5E-06	6.7E-04	2.1E-05	2.1E-01	7.4E-06
Silica fume *SBK silica fume*	4.8E-09	3.9E-05	5.2E-03	3.9E-10	1.6E-06	1.4E-05	3.3E-06	1.5E-03	3.0E-05	3.2E-01	4.8E-05
Granite powder *Kalksteenmeel (DE)*	2.0E-08	2.3E-04	3.2E-02	2.4E-09	1.0E-05	8.5E-05	2.2E-05	7.4E-03	2.1E-04	1.1E+00	8.2E-05
Sand, river *SBK Betonz. (NL)*	1.3E-09	2.0E-05	2.9E-03	3.1E-10	2.3E-06	1.8E-05	4.2E-05	1.9E-03	3.1E-05	2.0E-01	1.1E-05
Crushed aggregates *Steenslag (BE)*	3.1E-09	4.3E-05	6.2E-03	6.8E-10	7.1E-06	5.7E-05	1.3E-05	1.7E-02	8.9E-05	4.4E-01	1.7E-05
Gravel, river *Grind (DE)*	7.1E-09	2.7E-05	3.8E-03	3.1E-10	2.0E-06	1.6E-05	3.9E-06	2.2E-03	3.3E-05	1.7E-01	1.3E-05
Water *Leidingwater*	2.6E-10	2.7E-06	3.4E-04	1.6E-11	1.1E-07	8.0E-07	1.4E-07	8.3E-05	1.3E-06	2.2E-02	1.5E-06
Superplasticizer *Superplastificeerder*	0.0E+00	8.1E-03	7.2E-01	9.6E-08	1.4E-03	9.7E-03	4.6E-04	8.2E-02	3.0E-02	9.1E+00	3.6E-04
Air entrainer *Superplastificeerder*	0.0E+00	8.1E-03	7.2E-01	9.6E-08	1.4E-03	9.7E-03	4.6E-04	8.2E-02	3.0E-02	9.1E+00	3.6E-04
Viscosity agent *Superplastificeerder*	0.0E+00	8.1E-03	7.2E-01	9.6E-08	1.4E-03	9.7E-03	4.6E-04	8.2E-02	3.0E-02	9.1E+00	3.6E-04

Discussion of the Environmental Impact

Figure 2 shows the GWP of the 3 reference concretes and 21 SCCs.

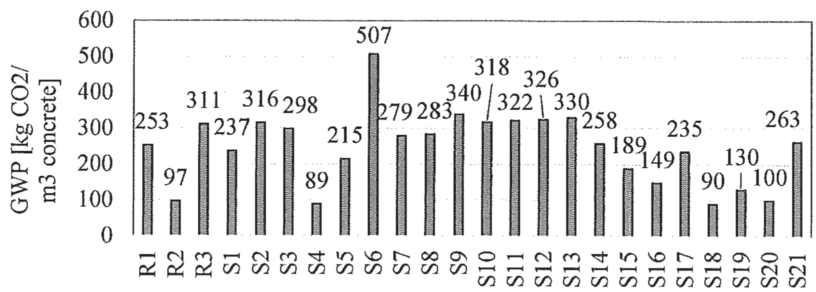

Figure 2: GWP of 3 reference and 21 self-compacting concretes.

Significant differences are obtained, as the range of GWP was from 89-507 $kgCO_2/m^3$ concrete, which is a factor of 5.7. The five mixtures with the lowest GWP all were produced with a blast furnace slag cement (cement only: R2&S19; also with fly ash: S4&S18; also with limestone powder: S20). 300 kg/m^3 of CEM I contribute 97.2% to the GWP of Mixture R1. A CO_2-reduction often is expressed in literature as a percentage compared to a reference concrete; R1 might be a good choice for a reference concrete, although, the share of applications produced with concrete containing only CEM I as a binder is decreasing. The MKI-costs in Euro/m^3 (contribution of mixture components only) were also calculated and are compared in Figure 3 with the GWP of the 24 mixtures. A good correlation between both parameters is obtained, which reflects the fact that the dosage of Portland clinker is dominant on both numbers.

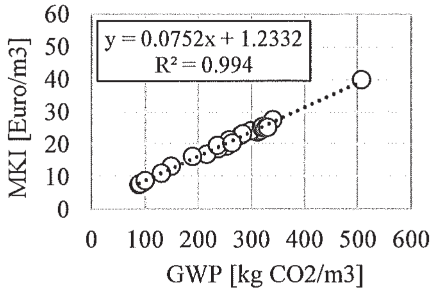

Figure 3: Relation between MKI-costs and GWP for 24 mixtures.

The contribution of the eleven impact parameters to the MKI is shown in Table 4 for Mixtures R1 and S18. The MKI-costs were 19.5 Euro/m^3 for R1 and 7.9 Euro/m^3 for S18, which is a factor of about 2.5. The GWP contribution to the MKI was 64.9% and 57.5% for R1 and S18, respectively. Next highest contributors after the GWP were AP, HTTP and EP (Table 1 lists abbreviations); the contributions of the four highest numbers to the MKI are 98% for R1 and 95% for S18.

Table 4: Contribution of the eleven impact parameters to the MKI for Mixture R1 (19.5 Euro/m^3) and Mixture S18 (7.9 Euro/m^3).

Mix	ADP1	ADP2	GWP	ODP	POCP	AP	EP	HTTP	FAE-TP	MAE-TP	TETP
R1	0.000	0.002	0.649	0.000	0.007	0.174	0.069	0.088	0.000	0.010	0.001
S18	0.000	0.006	0.575	0.000	0.008	0.171	0.073	0.131	0.001	0.033	0.001

The environmental impact of concrete needs to be related to its performance in order compare the real impact and to provide a base for the optimization of the mix design. As a performance criterion, Aïtcin [15] defined the economic efficiency of concrete as cost for 1 MPa or 1 year of service life; Damineli et al. [16] applied the CO_2-intensity indicator and related the CO_2-emission and the compressive strength at an age of 28 days. The CO_2-emissions (production of the concrete components only) divided by the cube compressive strength for different concrete ages was defined in this study as the 'relative strength cost, RSC'; this parameter is time-dependent, since the strength increases more or less in time. The more mature the concrete the relatively lower the RSC becomes. Figure 4 shows the RSC of the 24 mixtures for the age of 28 days. The lowest numbers (1.79-2.41 kgCO_2/m^3

concrete/MPa) are obtained for mixtures R2, S4 and S18-S20. CVC Mixture R2 has a GWP of 97 kgCO_2/m^3. The results indicate that similar low values can be achieved also with SCC. A RSC of 2 means that for a compressive strength of 45 MPa only 90 kgCO_2/m^3 concrete are emitted, which is a very low number according to Table 1 (class: EcoCrete-Xtreme).

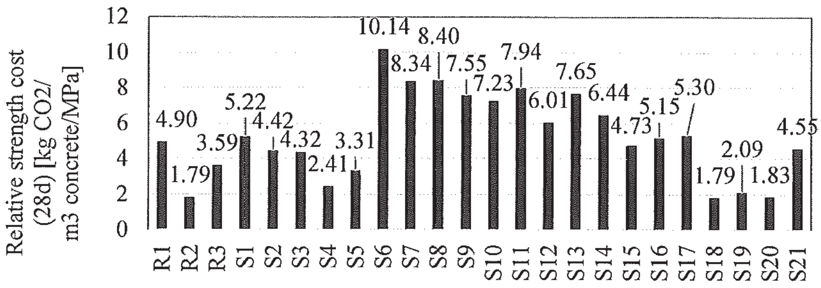

Figure 4: Relative strength costs for GWP at an age of 28 days.

The addition of supplementary cementitious materials enhances the strength beyond 28 days often more compared to concrete with a 100% CEM I binder composition, which further decreases the RSC. However, at an early age CEM I is very effective; early age strengths are especially important for prefabrication and applications, which have high demands with regard to this aspect. Parameters RSC,1d and RSC,28d differ less for mixtures containing only CEM I binder. Figure 5 summarises the RSC-values for 1 day compressive strength results. With the very high early age strength of R3 (67.7 MPa), a very low RSC,1d of 4.6 kgCO_2/m^3 concrete/MPa is obtained (RSC,28d: 3.6 kgCO_2/m^3 concrete/MPa). The RSC,1d of R1, a more common mixture in the prefab industry, is 23.2 kgCO_2/m^3 concrete/MPa which is much higher; lower values were obtained with several SCCs.

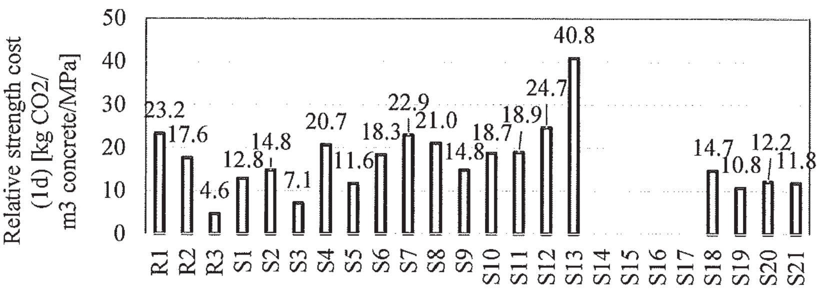

Figure 5: Relative strength costs for GWP at an age of 1 day.

Heat curing usually increases the early age strength. The MKI-approach is very useful for the comparison of different concrete production methods and structural solutions (including heat curing and effect of mixture components). By accumulating all life cycle steps and environmental impact parameters in a single number (MKI), mix design criteria and sustainability aspects can be balanced. Specific studies with regard to heat curing and the related impact on the environment and MKI need to be executed. Early age strength costs, RSC,28d and other relevant parameters need to be considered for the mix design. With a demoulding strength of 10 MPa at 1 day (curing at 20°C), the RSC,28d (for MKI) of R1 (19.5 Euro/m^3) can be used as a reference to select more sustainable solutions; both criteria are fulfilled for mixtures S1 (97% MKI with regard to R1), S5 (87%) and S19 (57%). Figure 6 compares the RSC,1d and RSC,28d for GWP and MKI. A low RSC,28d is preferred, but dependent on the boundary conditions a low RSC,1d could also be relevant for the selection of the production process and mix design. Figure 6 shows that some SCC can compete with CVC with regard to environmental impact, whereas others are less sustainable. Since the mixture composition of SCC varies widely, a general conclusion should be avoided. The strength of concrete largely depends on the water-cement/binder ratio, which has to be considered for mix design. Mixtures S18-S20 have a relatively low water-binder ratio compared to other SCC's, which makes them competitive with regard to CVC. Consequently, the granular optimization with regard to the water demand is a major key for making concrete more sustainable.

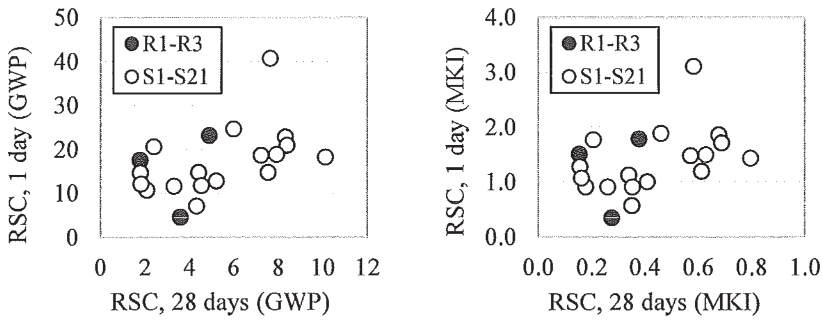

Figure 6: Comparison of relative strength costs for CVC and SCC at an age of 1 day or 28 days (units: GWP; $kgCO_2/m^3/MPa$ & MKI: $Euro/m^3/MPa$).

Conclusions

Sustainability adds an additional but important dimension to the list of requirements for SCC. This paper discussed the relation between mix design and the environmental impact for SCC. The calculations showed that with regard to the relative strength costs SCC can be competitive with CVC. Weighting of different environmental impact parameters was executed with the Dutch CUR-tool and resulted in a single parameter MKI. When only the effect of the mixture composition of the total life cycle is considered, this parameter is correlated with the CO_2-emissions coming mainly from the production of Portland Cement.

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