Design of self compacting concrete by particle packing optimization

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Introduction mixture optimization
This research project aims at reducing the cement content in a self compacting concrete mixture. Reducing the cement content makes concrete mixtures more ecologic and it can result in an economic benefit as well [1]. The mixture optimization technique used for this project consists of two steps. In the first design step the packing density of the total particle structure is increased. With this increased packing density a higher flowability is expected. Then, the amount of water can be reduced to such extent that the reference flowability is reached again. The attained water reduction can either be used to increase the strength of a concrete mixture or to decrease the cement content [2].

Mixture requirements
In this project mixture optimization aimed at reducing the cement content of a standard Heembeton mixture (reference) under the following assumptions.

- Self compacting concrete (SCC)
- Slump flow between 600 and 800 mm
- Funnel time between 5 and 15 seconds
- 7 hour strength above 15 N/mm^2 (elevated temperature hardening at 40ºC)
- 28 day strength C35/45
  - The same materials are used as in the reference mixtures.
  - Amount of recycled concrete aggregates between 10 and 12% of total aggregates
  - Amount and type of admixtures is remained constant for this project

Mixture compositions

Five mixtures were tested within this mixture optimization project. The reference mixture of Heembeton, as produced in the Stevin Laboratory at Delft University of Technology, was taken as starting point. Mixtures A and B were designed to have the highest packing density of the particle structure. In mixtures C and D the cement and water content were reduced to balance the increased flowability in order to design a more ecological mixture. The mixture compositions are presented in Table 1. The particle size distribution of the aggregates is presented in Figure 1.

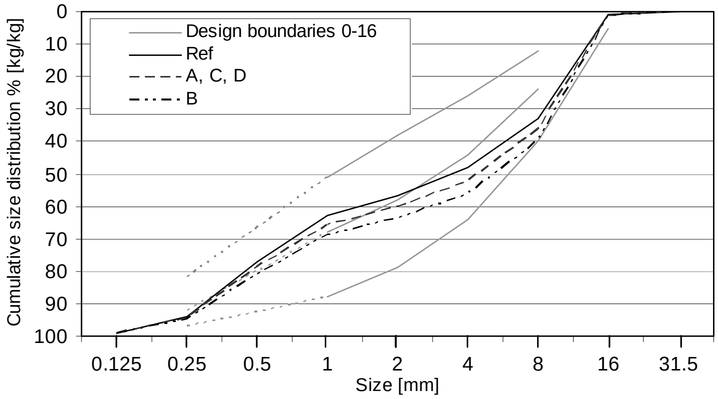

Figure 1 Particle size distributions of the aggregates

Results

The five mixtures were tested on slump flow (Abrahams cone, diameter 100-200 mm and height 300 mm) and V-funnel flow-time (V-funnel 515-65 mm and thickness 75 mm). The reference mixture had a slump flow of 640 mm and a V-funnel flow-time of 5.4 seconds, Table 1. As expected, mixtures A and B had a higher slump flow than the reference mixture. However, mixture B was not completely stable and showed some segregation, Figure 2. For that reason the second optimization step was executed on mixture A. Mixtures C and D have the same aggregate ratio as mixture A, but their amount of water and cement is optimized. Both mixture C and mixture D were evaluated as stable SCC mixtures; however, mixture D does not comply with the requested slump flow of 600-800 mm, Figure 3.

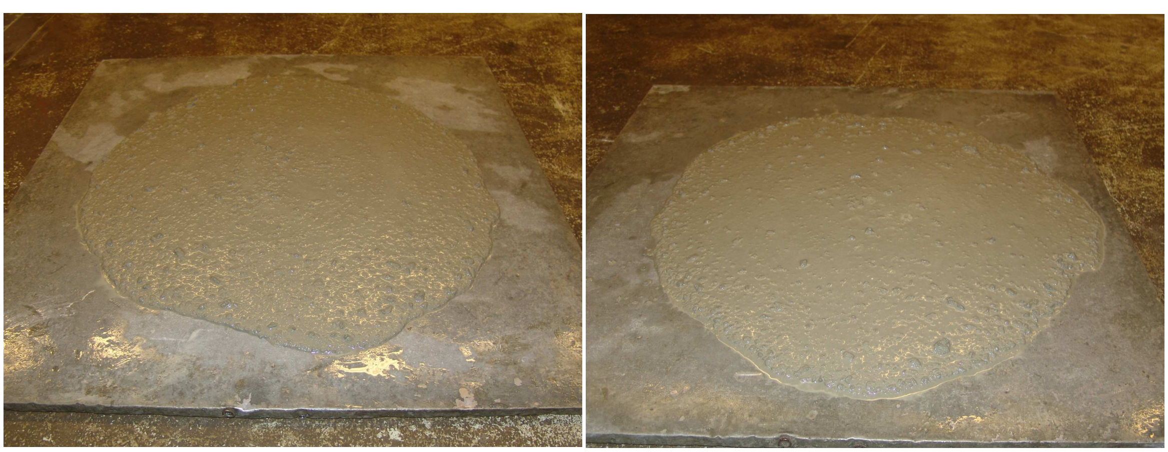

Figure 2 Slump flow mixture A and B

Figure 3 Slump flow mixture C and D

The strength development over time of the five mixtures is evaluated on the basis of 7 and 28-day cube compressive strength tests and maturity measurements. The strength tests show a 7-day strength of 25 MPa and a 28-day strength of 43.3 MPa for the reference mixture. All optimized mixtures have higher strengths at 7 and 28 days.

Table 1 Mixture compositions and rheological and mechanical properties

		Ref	A	B	C	D
Composition in kg/m³	ρ					
cement CEM I 52,5 R	3150	320	320	320	310	304
fly ash	2290	80	80	80	80	89
sand 0-4	2650	900	829	739	840	840
lime stone 2-14	2700	700	793	865	804	804
recycled concrete aggregates	2450	200	180	198	183	183
water	1000	164	164	164	158	156
Admixture 1		2	2	2	2	2
Admixture 2		0.8	0.8	0.8	0.8	0.8
Admixture 3		0.8	0.8	0.8	0.8	0.8
predicted air content [%]		2	2	2	2	2
water cement ratio [-]		0.51	0.51	0.51	0.51	0.51
water binder ratio ($k_{fly\ ash}$=0.4) [-]		0.47	0.47	0.47	0.46	0.46
calculated packing density aggregate structure [-]		0.695	0.705	0.710	0.705	0.705
calculated packing density particle structure [-]		0.830	0.844	0.851	0.839	0.841
Rheological properties						
Slump flow	mm	640	750	750	650	580
V-funnel flow-time	s	5.4	5.2	6.3	7.3	7.2
Mechanical properties						
7-day cube compressive strength	MPa	25.0	27.9	29.2	28.6	29.0
28-day cube compressive strength	MPa	43.3	48.3	52.8	48.0	47.2

The maturity of each mixture at 7, 15 and 24 hours is calculated from temperature measurements on cubes according to [3] with a C-value of 1.15. To enable mutual comparison, the temperature measurements were scaled to a constant starting temperature of 26 ºC, Figure 4. From the temperature and maturity measurements it follows that mixture C has a faster hydration and relatively higher maturity at 7 hours, compared to the reference mixture. At 24 hours the maturity of the reference mixture is the highest; however, this does not lead to highest strength at 7 or 28 days. For better comparison it is suggested to adjust the C-value of mixture C and D, since these mixtures have a relatively higher amount of fly ash.

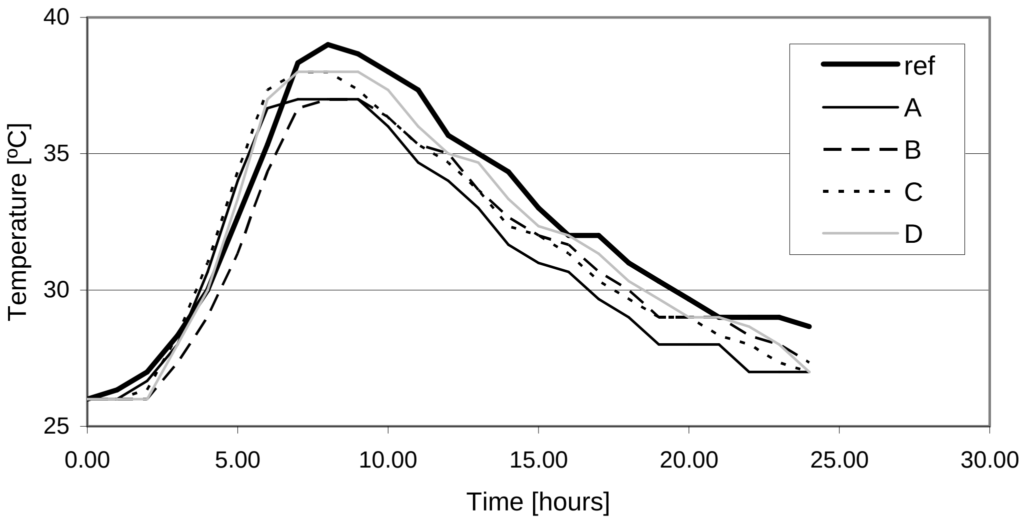

Figure 4 Temperature measurements

Table 2 Maturity measurements in ºCh and as percentage of the 24 hour maturity of the reference mixture

	Ref		**A**		**B**		**C**		**D**	
	[ºCh]	[%]	[ºCh]	[%]	[ºCh]	[%]	[ºCh]	[%]	[ºCh]	[%]
Maturity										
7 hours	320	*30.4*	321	*30.5*	301	*28.7*	324	*30.8*	321	*30.5*
15 hours	697	*66.3*	677	*64.4*	653	*62.2*	687	*65.3*	690	*65.6*
24 hours	1052	*100*	1013	*96.3*	989	*94*	1029	*97.9*	1038	*98.7*

Conclusions

- The packing density of the reference mixture can be increased from 0.830 up to 0.851 with 10% recycled concrete aggregates. It should be noted that the highest packing density can be achieved without recycled concrete aggregates, using 41% sand and 59% lime stone.
- The increased packing density of mixture A and B leads to higher slump flows. With the same amount of water and admixtures as the reference mixture, mixture A is stable and mixture B shows some segregation.
- Mixture C, with a decreased cement content, has a good slump flow and V-funnel flow-time. It reaches higher 7-day and 28-day strengths than the reference mixture. When the high strength of this mixture is not required for the 7-hours strength this mixture might be optimized even further.
- Mixture D reaches higher 7-day and 28-day strengths than the reference mixture. However this mixture does not reach the requested slump flow. Admixture optimization is recommended for this mixture.
- From temperature measurements it follows that mixtures C and D have a faster hydration in the first 7-hours, compared to the reference mixture. From strength and maturity measurements it is therefore expected that these mixtures will have a 7-hours strength which is comparable to or higher than the reference mixture.
- The 7-hours and 15-hours strengths to be reached at the elevated hardening temperature as imposed at Heembeton, should be calculated from mixture calibration graphs (strength – weighed maturity).
- Costs-optimization is recommended to investigate whether the extra costs from the increased amount of fly ash and limestone are balanced by the profit from cement and sand reduction. Other fillers might be considered in the optimization process. Especially fillers with a particle size smaller than cement can lead to higher packing densities.

Literature

[1] Glavind M., Munch-Petersen Chr., 2002, Green Concrete – a life cycle approach, Challenges of concrete construction: proceedings of the international conference held at the University of Dundee, Scotland, UK on 9-11 September 2002 / ed. by Dhir R.K., Hewlett P.C. and Csetenyi L.J.

[2] Fennis S.A.A.M., Walraven J.C., Uijl J.A. den, 2009, The use of particle packing models to design ecological concrete. (to be published)

[3] Rijpheid in ontwikkeling, Betoniek oktober 1999

Material properties

Materials: density and cumulative size distribution in % [kg/kg]

Materials	Density [kg/m^3]	µm 0.125	0.25	0.5	1	2	4	8	16	32	64
cement CEM I 52,5 R	3150	100	99.8	97.2	93.2	84.6	71.2	45.9	22.2	3.1	1
fly ash	2290	100	99.9	98.9	97.2	93.9	88.9	75	57.8	34.2	15.7
sand 0-4	2650	100	100	100	100	100	100	100	100	100	100
lime stone 2-14	2700	100	100	100	100	100	100	100	100	100	100
recycled concrete	2450	100	100	100	100	100	100	100	100	100	100

	packing density [-]	mm 0.125	0.25	0.5	1	2	4	8	16	32	64
cement CEM I 52,5 R	0.596	1	0.4	0	0	0	0	0	0	0	0
fly ash*	0.597	1.8	0	0	0	0	0	0	0	0	0
sand 0-4	0.600	99	89.8	57.6	31.9	21.9	22.2	0.1	0	0	0
lime stone 2-14	0.560	99.7	99.6	99.3	99	98.6	97.8	74.5	1.4	0	0
recycled concrete	0.567	97.4	93.5	86	76.7	67.4	55.5	35.9	4.8	0	0