Eco-SCC: From Theory to Practical Application

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Abstract: This paper presents the results of an experimental investigation on the application of self-compacting concrete (SCC) with reduced cement content and fine stone waste materials. Two SCC mixes containing stone waste material were designed for the application in a new formwork system developed for foundation beams. The designed mixes were tested on laboratory scale for their fresh and hardened properties and were compared with a standard SCC mix ordered by a local ready mix concrete plant. In addition to this, segments of the foundation beam were cast using SCC with reduced cement content and standard SCC. The results indicate that stone waste materials can be used for cement reduction without detrimental effects on the mechanical properties and that the designed mixes can be applied under practical conditions.

Key words: Self-compacting concrete; stone waste materials; concrete mix design; particle packing; cement reduction; foundation beam

1 Introduction

The application of self-compacting concrete (SCC) started in the Netherlands in the middle of the 1990s and a lot of experience was obtained with that type of concrete during the years [1, 2, 3]. Most of the SCC used in the Netherlands is produced by the prefab industry and the application of SCC on the construction site is limited to structural members with difficult shape, high amount of reinforcement or cases where placing of conventional concrete is difficult [1]. Powder type SCCs form by far the biggest part of the produced SCC in the Netherlands. This type of SCC is characterized by a high amount of fines smaller than 125 μm which are required for the self-flowing properties of SCC.

The high content of fines is usually obtained by high cement contents and the application of fine filler materials such as fly ash or limestone powder. High cement contents and low w/c ratios are required for the production of workable SCC mixes that follow the requirements given by European standards [4]. These high cement contents and low w/c ratios result in concretes with higher compressive strength than actually required and the emission of CO_2 during the clinker production increases the CO_2 footprint of these types of concrete. Therefore, the reduction of the clinker content is one of the major aims for the design of so-called eco-SCC.

Different approaches can be used for the design of eco-SCC with lower environmental impact. The applied methods are either based on material related improvements or the optimization of the concrete mix design. The application of materials with lower CO_2 footprint reduces the overall amount of CO_2 that is emitted during the concrete production. Successful applications in that field are given, for example, by the use of slag cement instead of ordinary Portland cement and the application of secondary filler materials such as fly ash. The application of fine stone waste materials, generated during the production of broken rock aggregates, is a further source for fine filler materials. The successful application of premixed sand having a high content of fines smaller than 125 μm in zero slump concrete was demonstrated in [5, 6]. This premixed sand, called Premix 0-4, is an unwashed sand that is generated during the production of broken rock aggregates. The fines are usually removed from the sand to fulfill the Dutch requirements on concrete aggregates. The remaining filter cake of the washing process is considered to be a waste material but shows a high potential for the replacement of standard fillers such as limestone powder. Therefore, the unwashed product is applied in this study. Further improvements regarding CO_2 reduction are obtained by optimized material use. In this respect, the optimization of the particle packing of all solid ingredients of the concrete mix resulted in higher cement efficiency and lower cement contents for concretes produced under laboratory conditions [2, 3, 5, 6].

The previous work of the research group on optimized particle packing is continued by the research presented in this paper and extended to a practical application. For this purpose, an eco-SCC was designed and used for the experimental casting of foundation beams applying the new developed formwork system called B-smart (see Fig. 1). The B-smart is an innovative formwork system for the casting of foundation beams on the construction site that was developed in close corporation with Eindhoven University of Technology [7]. The production as well as the manufacturing process of the formwork system are highly optimized and combined with an optimized cross section of the foundation beam. This optimization results in large time and cost savings. The innovative potential of the new developed formwork system was combined with the ideas of eco-SCC to demonstrate the practical applicability of these innovative solutions and their sustainability.

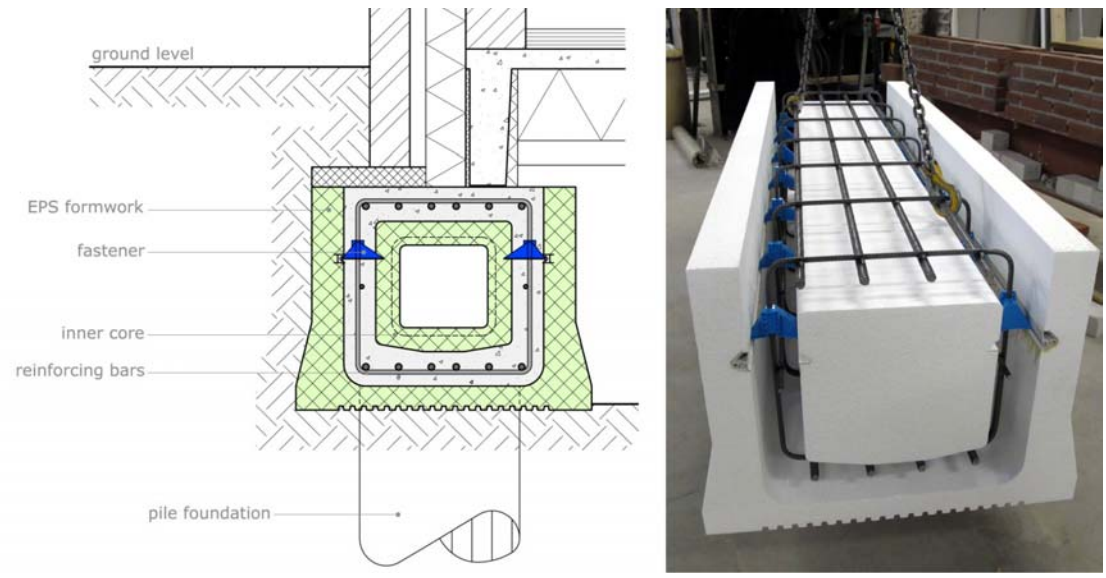

Fig. 1 Schematic illustration of the B-smart foundation system [7] (left) and assembled formwork segment (right)

The use of an eco-SCC and a classical SCC for the experimental cast of the B-smart foundation beam was decided during the preparation phase. Based on that decision, the basic demands on both SCCs were defined. The requirements listed in Table 1 form the basis for the design of an eco-SCC and were also used for ordering a standard SCC from a local ready mix concrete plant. Both SCC mixes have been tested extensively regarding their fresh and hardened concrete properties. The results obtained from these tests and the insights of the first experimental casting of B-smart elements were used to improve the designed eco-SCC for mixing a trial batch of about 9 m³ at a ready mix concrete plant under practical conditions. This batch was used for casting a foundation beam on real scale having a dimension of 8 x 4.5 m.

Table 1 Requirements on the designed SCC mixes

Condition	
Exposition class*	XC2
Min. strength class*	C25/30
Min. cement content* [kg/m³]	280
Max. w/c ratio*	0.60
Slump flow [mm]	750-850
Funnel time [sec]	~10.0

*: according to NEN-EN 206-1 [4]

2 Experimental

The experimental part of the SCC development discussed here comprises the following points:

- Design of a SCC mix according to the requirements given in Table 1 and subsequent concrete testing in fresh and hardened state
- Concrete tests in fresh and hardened state of a SCC mix ordered by a local ready mix concrete plant according to the requirements given in Table 1
- Design of a SCC mix suitable for the production of a trial batch in a local ready mix concrete plant considering the results obtained by the casting of segments of foundation beam on laboratory scale

2.1 Mix Design

The mix design of the tested SCCs is based on optimized particle packing. This approach for the mix design of SCC was introduced by [2] and further developed by [3]. The basic principle of this mix design concept is based on particle packing theories and applied for the proportioning of a performance based concrete mix. According to [2], highest packing fractions of the solids and superior flow behavior of the designed SCC are obtained when the grading of all solids in the mix follows a geometric progression. This geometric progression of the cumulative finer volume fraction is given by the modified Andreasen and Andersen equation [8] and follows from:

$$P(D) = \frac{D^q - D^q_{min}}{D^q_{max} - D^q_{min}} \qquad (1)$$

Where:

P(D)	Cumulative finer volume fraction
D	Particle diameter of the considered size class
D_{max}	Maximum particle diameter
D_{min}	Minimum particle diameter
q	Distribution modulus

An algorithm for the concrete mix design was developed that allows for the proportioning of all solid ingredients inclusive air and water [5]. The composed concrete mix follows the grading line given by Formula 1 with lowest deviation. This algorithm was used for the mix design of the two SCC mixes, Lab 1 and Lab 2, listed in Table 2. These two mixes have been designed according to the requirements given in Table 1 and were tested in fresh and hardened state. Mix Lab 1 was designed for the laboratory casting of small segments of a foundation beam using the new formwork system (see Fig. 4) and compared with a SCC mix ordered by a local ready mix concrete plant for the casting of corner joints and T-joints (see Fig. 4).

Table 2 Proportioning and characteristics of SCC mixes

Material [kg/m³]	**Reference**	**Lab 1**	**Lab 2**	**Cast**
Cement	330.0	280.0	300.0	286.4
Limestone powder	-	215.1	150.0	133.7
Fly ash	210.0	-	-	-
Sand 0-4	800.0	-	-	-
Premix 0-4	-	1269.9	1190.4	1136.1
Gravel 4-16	796.0	-	-	-
Granite 2-8	-	369.9	554.9	524.0
Superplasticizer	4.30	5.04	7.00	6.40
Water	174.0	195.4	175.9	200.7
Mix characteristics				
Water cement ratio w/c	0.527	0.698	0.586	0.701
Water powder ratio w/p	0.322	0.305	0.300	0.365
Powder* volume [l/m³]	202.2	225.6	204.7	191.9
Powder* mass [kg/m³]	540.0	640.6	586.4	550.3
SP dosage (cement) [M.-%]	1.30	1.80	2.33	2.23
SP dosage (powder) [M.-%]	0.79	0.79	1.19	1.16

*: considering particles smaller than 125 µm

Based on the results of fresh and hardened concrete tests of mix Lab 1, mix Lab 2 was slightly modified for the casting of a complete foundation beam under practical conditions. However, problems with the manual dosage of the ingredients at the ready mix concrete plant appeared so that the mix proportioning of the cast concrete (Cast) deviates from the designed mix (Lab 2). Despite the reference mix, all SCCs are based on ordinary Portland cement (OPC) of the strength class 52.5 N (Lab 1) and 42.5 N (Lab 2 and Cast). A blend of OPC and slag cement was used for the reference mix. The total composition of the tested SCC is given in Table 2 and their PSDs are depicted in Fig. 2. The PSDs of the designed SCCs, Lab 1 and Lab 2, follows the grading line given by formula 1 with lowest deviation. Data on the grading of the reference mix were provided by the ready mix concrete plant only for the aggregate fraction (sand and gravel. All mixes listed in Table 2 were tested on laboratory scale for their fresh and hardened concrete properties.

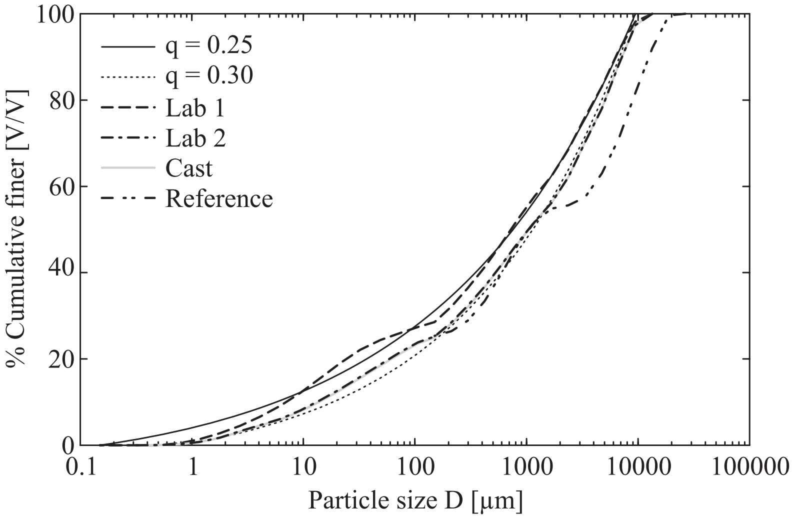

Fig. 2 PSD of designed SCC mixes

2.2 Fresh concrete tests

The fresh concrete properties of all SCC mixes were determined prior the casting of the foundation beam or segments thereof. The flow characteristics of the fresh SCCs were evaluated by the slump flow test. The slump flow gives an indication for the yield stress that needs to be overcome for the SCC to flow. The viscosity of the mixes was determined by the V-funnel time and their segregation resistance was assessed by the so-called stability time which is a calculated value that describes the difference in the flow out time of an immediately conducted V-funnel test and a second test conducted after 5 minutes. Within this period of time, the segregation of coarse aggregates can occur. This segregation of coarse aggregates leads either to longer flow out times and higher stability times or the blocking of the SCC in the V-funnel. The results of the fresh concrete tests are given in Table 3.

Table 3 Fresh concrete properties of the tested SCC

Measure	Reference	Lab 1	Lab 2	Cast
V-funnel time [sec]	6.5	6	-	20
Stability time [sec]	0.5	0.3	-	0.0
Slump flow [mm]	840	885	780	580
Air content [%]	1.6	1.6	1.5	2.5
Density [kg/m³]	2318	2327	2364	2331
Packing fraction [%]	80.6	78.9	81.0	78.4

2.3 Hardened concrete tests

Cubes of 150 x 150 x 150 mm have been produced and tested for their compressive and splitting tensile strength. The produced cubes were sealed during the first day, stripped from the mold after 24 hours, and subsequently cured underwater until their test age was reached. The average values of the 28 days test results are given in Table 4. The compressive strength development is depicted in Figure 3.

Table 4 Hardened concrete properties (standard deviations are given in parentheses)

Measure	Reference	Lab 1	Lab 2	Cast	Cores*
28 days compressive strength [N/mm²]	58.1 (2.7)	56.0 (4.7)	58.2 (0.8)	42.0 (0.5)	28.6 (1.9)
28 days splitting tensile strength [N/mm²]	3.9 (0.1)	4.0 (0.1)	4.3 (0.1)	3.5 (0.2)	-

*: determined on cores extracted from the cast foundation beam (see Figure 6)

In addition to the cubes that were cast, cores having a diameter of 100 mm and a height of 100 mm were drilled from the cast beam after 28 days and submitted to compressive strength. The results of the tested cores are also included in Table 4.

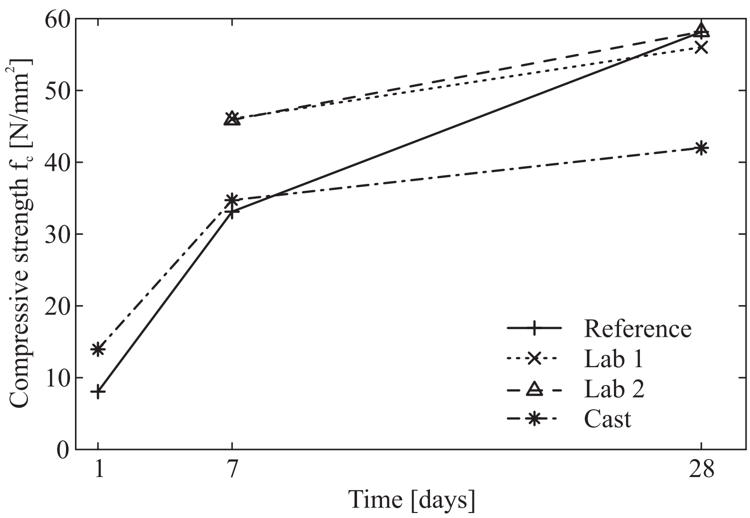

Fig. 3 Compressive strength development of tested SCC

2.4 Experimental casting of the foundation beam

The experimental casting of the foundation beam comprises investigations on small segments of the B-smart formwork system to study the influence of the hydrostatic pressure of SCC on the deformation behavior of the formwork at critical points such as corner joints, T-joints, etc. The development of a high hydrostatic pressure within the formwork is ensured by the low viscosity and the good flow properties of both SCCs (see fresh concrete properties listed in Table 3 for further details). Furthermore, insights on the filling behavior of the tested SCCs were obtained by tests carried on straight segments having a length of 2 m. The first casting of small segments and crucial points of the formwork system is depicted in Fig. 4.

Fig. 4 Experimental casting using the new developed formwork system: straight segment of the foundation beam (left); casting of corner joint and T-joint (right)

The cast elements were stored under laboratory conditions and cut after four weeks at several points perpendicular to their longitudinal axis to investigate the filling behavior of the concrete and to control the position of system's components such as reinforcing bars, stirrups, fasteners, and the inner core of the formwork. Furthermore, the segregation resistance of the cast concrete can easily be assessed on the cut cross sections. The cut cross section in the area of a fastener is depicted in Fig. 5 for a beam cast with mix Lab 1.

The preliminary experimental investigations carried on laboratory scale were followed by the casting of a complete foundation beam under practical conditions. For that purpose, a small ground plan of a standard foundation beam was designed and assembled on a location for test buildings at the campus of Eindhoven University of Technology. An SCC was mixed at a ready mix concrete plant according to the mix proportioning given in Table 2 (Cast), transported to the construction site by a standard concrete transport truck, and placed using a concrete pump. Details on the placing of the concrete and the cast foundation beam are given in Figure 6.

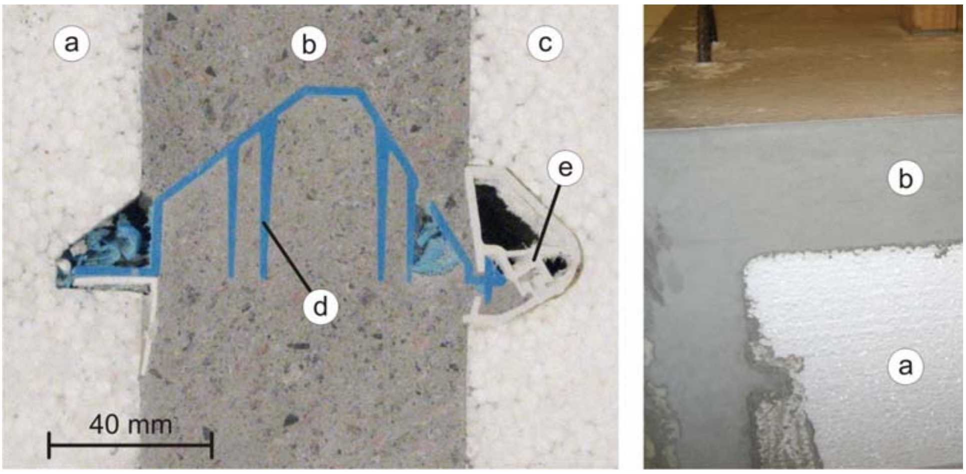

Fig. 5 Cut cross section of a cast foundation beam using mix Lab 1 (left) and surface cast against an acrylic glass pane (right): a) inner core; b) concrete; c) outer mold; d) fastener; e) plastic profile

Fig. 6 Cast foundation beam (lower picture) and placing of the SCC (upper pictures)

3 Results and Discussion

3.1 Concrete properties

Two SCCs were designed and tested regarding their fresh and hardened concrete properties. The designed SCCs were compared with a standard SCC mix ordered by a ready mix concrete plant. The ordered reference mix and the designed eco-SCC, Lab 1, showed equal fresh concrete properties as depicted in Table 3. Both mixes differ not in their workability properties and are characterized by their good flow properties, low segregation potential, and high packing fractions. Significant differences in the 28 days compressive strength were also not observed for the reference mix and mix Lab 1. However, the strength development of both mixes differs to a large extent. The ordered reference mix is characterized by lower compressive strength in the early age. The 7 days strength of the reference mix amounts to 57% of the 28 days strength whereas the designed SCC, Lab 1, obtained already 82% of its 28 days compressive strength after 7 days. The difference in the strength development of these two mixes is strongly influenced by the type of cement and fillers used. The reference mix uses a blend of OPC and slag cement in combination with fly ash. The high content of slag cement results in a slower strength development and allows for pozzolanic reactions in combination with the flay ash. In contrast to this, the designed SCC, Lab 1, shows a rapid strength development due to the use of OPC of the strength class 52.5N. In addition to this, the use of limestone powder is known to have an accelerating effect on the strength development at early ages as the fine limestone particles act as nucleation sites for calcium silicate hydrates [9].

The criteria on the mechanical properties as defined in Table 1 are fulfilled by both the reference SCC and the designed SCC Lab 1. However, mix Lab 1 was designed under ecological considerations and lowered cement content. Therefore, the cement content of mix Lab 1 is oriented on the minimum value required by NEN-EN 206-1 [4] for structural members of the exposition class XC2. This low cement content was resulting in a conflict with the maximum w/c ratio prescribed for the exposition class XC2. The high content of fines as well as the use of the Premix 0-4 requires a w/p ratio of 0.305 to produce a SCC with a slump flow value of about 850 mm. The w/p ratio of the mix Lab 1 is still lower than the value of 0.322 as calculated for the ordered reference mix but was resulting in a w/c ratio of 0.698 that exceeds the limit of 0.60 as given for the exposition class XC2. For that reason, the cement content of mix Lab 1 was slightly increased and the total powder content was reduced to a comparable volume as applied for the reference mix (cp. mix characteristics given in Table 2). Furthermore, OPC of the lower strength class 42.5N was used in order to consider as much as possible materials available at the ready mix concrete plant. This modification of mix Lab 2 was resulting in equivalent compressive strength after 28 days compared to the strength of the reference mix. The flow characteristics of the mix Lab 2 were slightly decreased due to the low water content but sufficient for the experimental casting. Therefore, mix Lab 2 was suggested for the casting of a foundation beam under practical conditions.

As mentioned before, problems appeared with the manual dosage of the concrete ingredients at the ready mix concrete plant so that the mix proportioning of the cast concrete (Cast) deviates from the designed mix (Lab 2). These problems caused not only a deviation from the original mix design, but increased also the total time of concrete mixing and transport to 1:45 hours and exceeded the expected duration by far as the amount of the applied superplasticizer as well as its additional dosage was determined for a total mixing and transport time of about 1 hour. Furthermore, the delayed placing of the concrete requires the use of a retarding admixture which was not considered by the original mix design. The delayed placing of the concrete resulted therefore in a low slump flow value of 580 mm and a highly viscous SCC having a V-funnel time of about 20 sec. The lower workability of the cast concrete and the deviations from the original mix design are also reflected by the hardened concrete properties. Here, both 7 days and 28 days compressive strength were reduced. The 28 days compressive strength is reduced by 28% and amounts to 42 N/mm² for the cast concrete. A further reduction in the compressive strength was observed on the cores extracted from the cast foundation beam. The lower strength of the extracted cores is caused by the difference in the geometry of the samples and their curing conditions. Cores having a diameter of 100 mm and a height of 100 mm were tested instead of cubes with a side length of 150 mm. The produced cubes were cured underwater according to EN 12390-2 [10] whereas the cast foundation beam was exposed to outside weather conditions and a desiccation of the fresh concrete was not prevented. This curing represents one of the worst conditions that can occur on the construction site and can be prevented by covering the fresh concrete with plastic foil.

Despite the before mentioned negative conditions, a complete foundation beam was cast. The designed mix, Lab 2, showed a high robustness against changes in the concrete mix design and a placing of the concrete was still possible. The cast foundation beam was cut after 28 days in elements of 4.5 m length. These elements are used for further tests on the mechanical resistance of the foundation beam. The results of these tests will be published elsewhere.

3.2 Experimental casting

The cut cross sections of the 2 m segments cast in the lab showed a good filling behavior for both the reference mix and mix Lab 1. The aggregates are homogenously distributed over the entire cross section and the designed SCC was stable and segregation of coarser aggregates was not observed. The designed mix Lab 1 was able to flow around the fasteners, used for fixing the reinforcement cage in the formwork, and no air was entrapped around the fasteners as depicted in Fig 5. Due to the filigree structure of the fasteners only fine particles were able to flow around the fasteners and to fill the space here. However, unfilled parts inside the fasteners caused by the blocking of bigger aggregates were not found on the cut cross sections.

Due to the production of the B-smart formwork system by an extrusion process, the open cross sections were closed with acrylic glass that was removed after 2 days to evaluate the surface quality of the hardened concrete. The amount of pores smaller than 1 mm is low and the cast elements show a high surface quality (see Fig. 5). The high surface quality of the cast concrete offers another application of the designed SCC as fair-faced concrete.

As mentioned before, the SCC produced at the ready mix concrete plant deviates in its composition from the original mix, Lab 2, and its properties were therefore not in the range as determined for the SCC produced under laboratory conditions. However, the placing of the highly viscous SCC was still possible without using a poker vibrator.

4 Conclusions

Based on the results of the performed experiments on the design of an eco-SCC for the application in the B-smart formwork system, the following conclusions can be drawn:

- The design of an eco-SCC with reduced cement content was possible. The designed SCC showed equivalent properties in fresh and hardened state compared to a standard SCC that was ordered from a local ready mix concrete plant.
- The grading of the designed SCC was optimized and follows the grading line described by the modified Andreasen and Andersen equation (Formula 1). The optimization of the grading of all solids in the mix with respect to their granulometric properties resulted in denser particle packing and the potential for cement reduction.
- The reduced cement content lowers the environmental impact of concretes produced that way. A further improvement was achieved by the application of fine stone waste materials in the form of premixed sand called Premix 0-4.
- Segments of a foundation beam using the B-smart formwork system were successfully cast on laboratory scale using both a standard SCC ordered by a local ready mix concrete plant and the designed eco-SCC that showed excellent filling abilities in narrow spaces.
- The designed SCC showed a high robustness against changes in the mix proportioning that occurred when the trial batch was mixed at a ready mix concrete plant. The manual material dosage resulted in a mix with lower content of fines and higher water content. In addition to this, the placing of the concrete was delayed so that the applied superplasticizer lost is full activity. However, it was possible to place this highly viscous SCC and to finish the casting of the foundation beam using the B-smart formwork system.

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Reference

[1] Walraven, J.C. Anwendungen von SCC in den Niederlanden, Proceedings of 8. Holcim Betontagung 2002, Zürich, Switzerland (in German)

[2] Brouwers, H.J.H. and Radix, H. (2005). Self-compacting concrete: Theoretical and experimental study. *Cement and Concrete Research*, 2005, 35(11): 2116–2136.

[3] Hunger, M. An integral design concept for ecological Self-Compacting Concrete. PhD thesis, Eindhoven University of Technology, Eindhoven, The Netherlands, 2010

[4] Dutch Normalization-Institute. NEN-EN 206-1: Concrete - Part 1: Specification, performance, production and conformity; Dutch version EN 206-1:2000. Nederlands Normalisatie Instituut, Delft, The Netherlands, 2001

[5] Hüsken, G., Brouwers, H.J.H. A new mix design concept for earth-moist concrete: A theoretical and experimental study. *Cement and Concrete Research*, 2008, 38(10): 1246-1259

[6] Hüsken, G. and Brouwers, H.J.H. Development of eco earth-moist concrete. Proceedings International Conference Excellence in Concrete Construction through Innovation, 9-10 September 2008, London, United Kingdom

[7] Product information on the B-smart foundation system obtained from the B-invented website visited on June 5, 2010, URL: http://www.b-invented.com

[8] Funk, J.E., Dinger, D.R. Predictive Process Control of Crowded Particulate Suspensions: Applied to Ceramic Manufacturing. Kluwer Academic Press, Boston, US, 1994

[9] Domone, P.L. A review of the hardened mechanical properties of self-compacting concrete. *Cement and Concrete Composites*, 2007, 29(1): 1-12

[10] EN 12390-2: Testing hardened concrete - Part 2: Making and curing specimens for strength tests. CEN European Committee for Standardization, 2000

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