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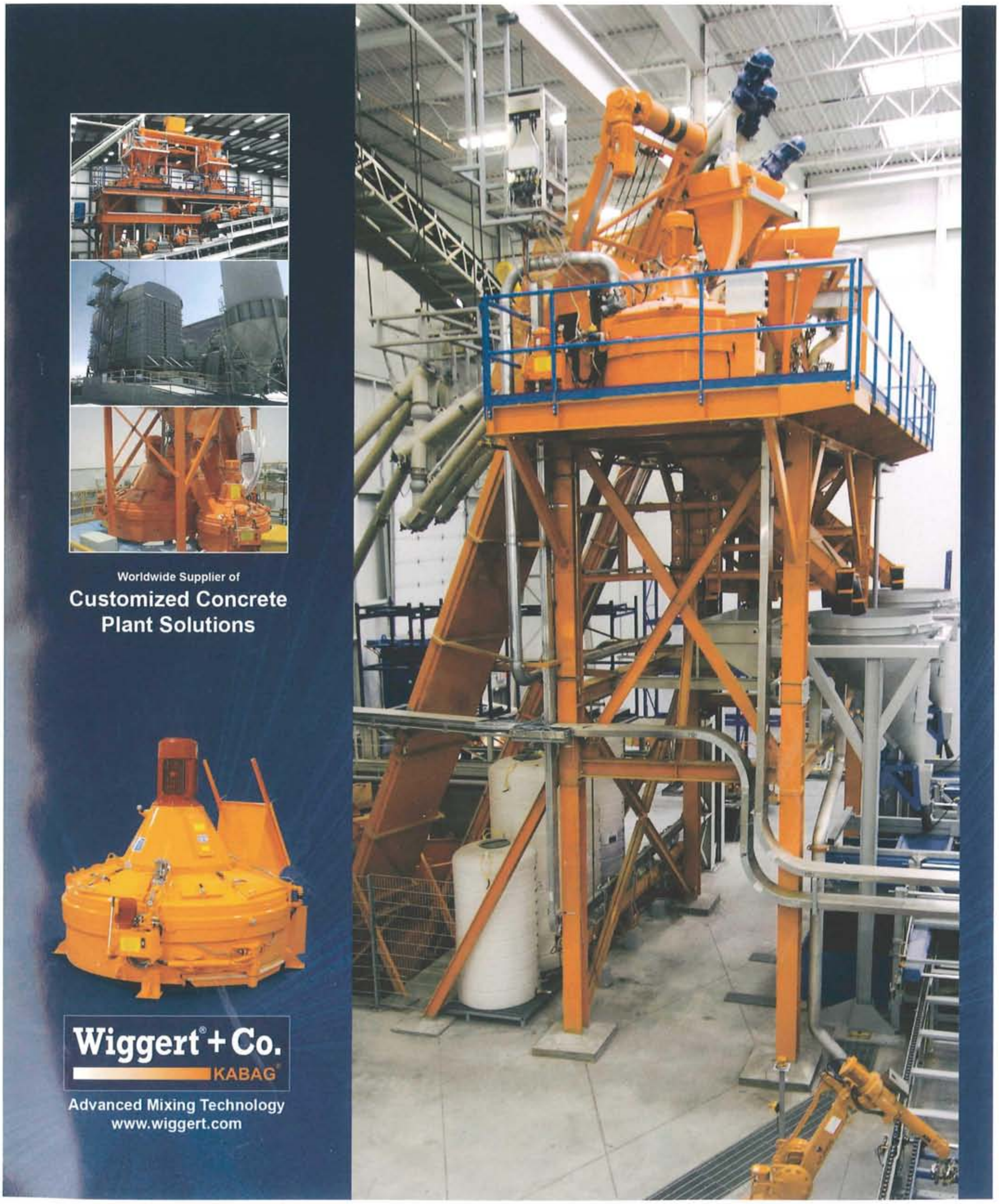

Curved concrete elements

The use of SCC and textile reinforcement

In an earlier article (CPI issue of August 2011 [1]) a method was presented for producing precast curved panels with a thickness of a few centimeters using the 'flexible mould method'. This method is the central theme in the PhD study of the first author on the realization of free-form architecture in concrete (see fig. 1). The concrete panels manufactured with the flexible mould method can be applied for many architectural purposes in which curvature is present, such as façade cladding, precast plank floors or roof elements. The method essentially comprises a reusable and bendable smooth surface that can be deformed into a wide range of geometries, including variable curvatures in one or two directions and freely shaped edge contours. In the earlier article in CPI it was concluded that some aspects needed further research, among which were the choice of suitable concrete mixtures and the investigation of fibre reinforcement. This article discusses the results of experiments investigating these aspects: the mixture choice was guided by measuring the workability in time and the ability to undergo deformations after casting without cracking. Furthermore, AR-glass textile was used to strengthen the panels with a flexible reinforcement that allowed deformation in the non-hardened state. Experimental work has been done to check the position of the reinforcement after deformation and the contribution of the textiles to the strength of thé panels.

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Double curved panels, e.g. like the ones used in the buildings shown in fig. 1, are more difficult to produce for acceptable prices than orthogonal and flat concrete panels. Free-form architecture would benefit from economically feasible manufacturing methods of such elements [2]. Mass production of double curved concrete elements has often been regarded only possible after the realization of a flexible mould: an adjustable formwork consisting of an elastic material that can be formed into the desired curved surface by the use of pistons, actuators, gravity, pin beds or other means. Several concepts for a flexible mould have been designed over the years, starting with the sketch of Renzo Piano (fig. 2a), already made in the 1960's. Others also have worked on the concept, among which Lars Spuybroek (fig. 2b, [3]) and Florian-Peter Kosche (fig. 2c).

At Delft University of Technology, a number of MSc thesis students and researchers have been working in the past years on conceptual or real models of the flexible mould, resulting in a gradual improvement and practical realization of the idea in working prototypes. A number of results of this work are shown in fig. 3.

All of these flexible moulds work according to the same principle, outlined schematically in fig. 4. The flexible materials of the mould are supported by a subsystem controlling the desired final shape (step 1). The mould is filled with self-compacting concrete (SCC) (step 2); fibres or textile can be used as reinforcement. During a short period of structural build-up, the yield strength of concrete increases (step 3). Then the mould is carefully deformed into its final shape (step 4). During this deformation, the fresh concrete has to follow the strain and stay stable under a certain slope. Concrete hardens in the deformed mould (step 5) and finally the element is demoulded (step 6). The flexible mould can be reused to produce more elements, with identical or with altered curvature and geometry.

Experiments on deformation, rheology and reinforcement

Test setup

For the experiments (see fig. 5) moulds were prepared to produce small concrete panels (length x width x thickness: 800x400x25 mm or 800x400x50 mm). With this test setup different curvatures and slopes could be realized. By using a setup with four identical moulds, it was possible to independently vary parameters, such as time of deformation or curvature for each separate mould, which allows comparing the effect of mould setup.

In the laboratory equipment was available for dosing, mixing, casting and curing the desired concrete mixture, as well as for measuring the rheological behaviour and strength of the concrete.

Figure 1: Two examples of free-form architecture (left: Verdana, NL Architects, right: Heydar Aliyev Cultural centre, Zaha Hadid Architects)

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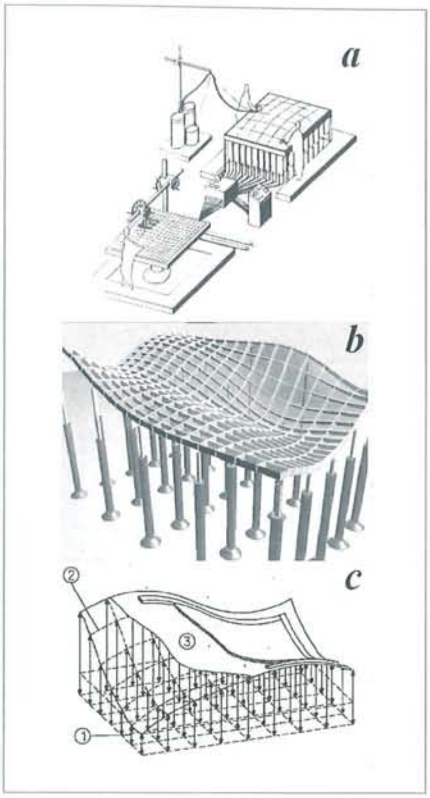

Figure 2: Three conceptual designs for a flexible mould

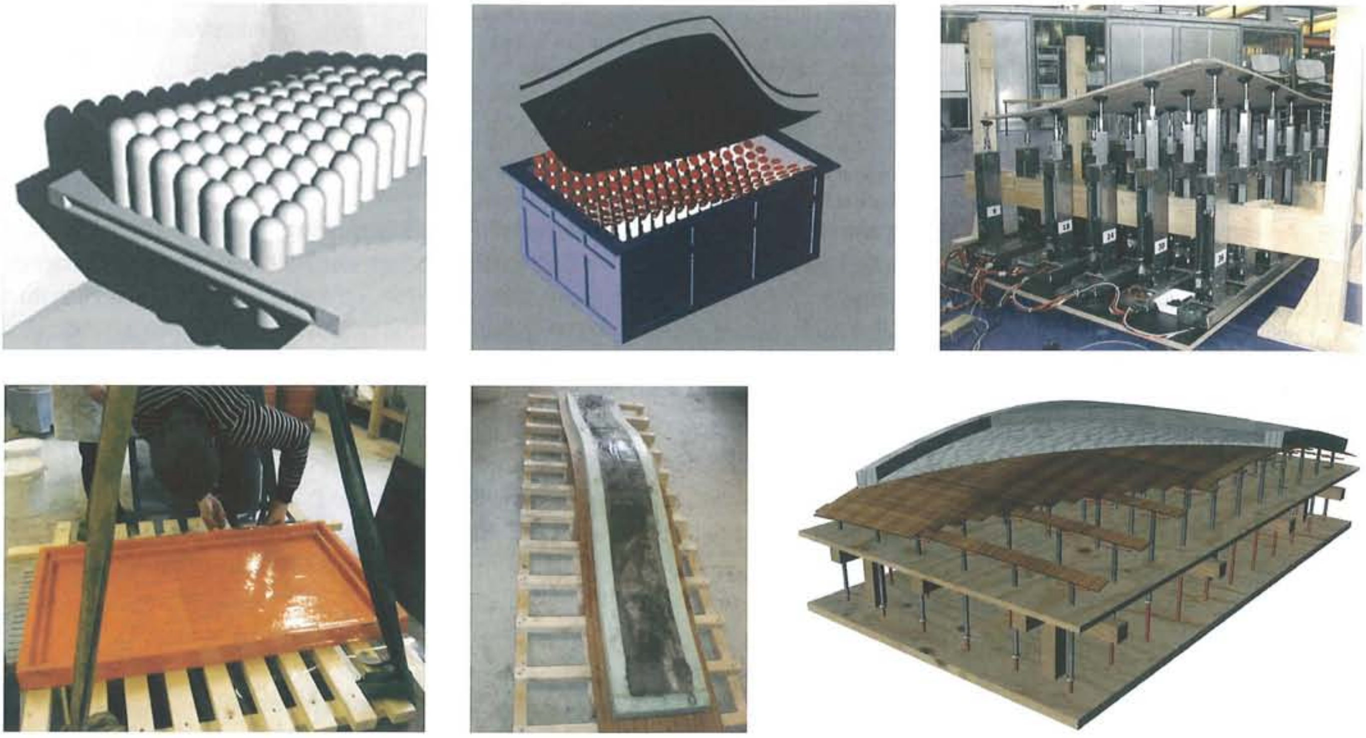

Figure 3: Six prototypes of the flexible moulds designed and/or built at Delft University of Technology (clockwise, starting top left: Jansen, 2004; Quack, 2009; Vollers and Rietbergen, 2009; Janssen, 2011 (2x); Schoofs and Huyghe, 2010)

Deformation

More than 50 elements were cast with single or double curvature (curved in two directions, leading to e.g. a saddle shape or spherical shape). The radii of the curvature were in the range between 1.5 and 2.5 meter. Many elements were successfully deformed after which they hardened and were demoulded. In some tests, the concrete appeared to be too fluid at the moment of deformation, leading to concrete flowing out of the mould. In fig. 6 the placement of textiles in the mould, a number of hardened panels and a sawed cross-section with view on the textile are visible. Generally, no cracks were detected due to the deformation. In some cases small cracks, similar to the ones usually visible as a result of plastic shrinkage, were visible. These cracks appeared not to be caused by the deformation itself, but most likely by the evaporation of water from the concrete surface in the period between casting and deformation. After changing the procedure and covering all freshly cast elements with plastic to prevent evaporation from occurring, these cracks no longer appeared. The aesthetic quality (e.g. surface smoothness and color, panel edges, air bubbles) was good. The mould material however, a two-component silicone with Shore value 30, chosen for its maximum flexibility, appeared vulnerable for small damages, leading to quick wear after multiple casts. The amount of air bubbles was limited, and the edges of the panels were smooth and accurate in shape. To examine the influence of the mould surface quality, in some tests the same mixture as used for the panels was also cast in a smooth, hard-plastic (PE) container, leading to an extremely smooth and shiny concrete surface. Also a flexible polyurethane mould was used in a number of tests. It is likely that further improvement of the mould material will further improve the aesthetic quality. The deformation process itself appears not to affect the quality of the concrete.

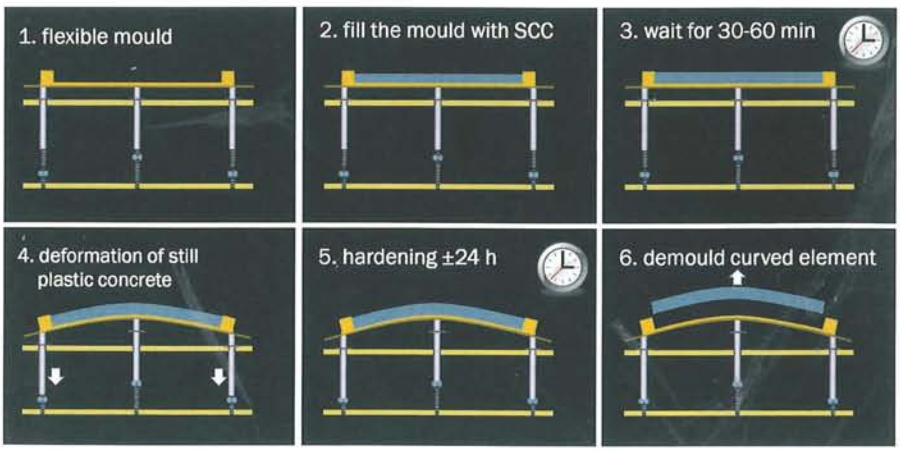

Figure 4: The flexible mould production process for double curved precast concrete panels explained in six steps

Rheology of the concrete

The typical process of deformation after casting requires specific workability characteristics of the concrete during the different steps: preferably self-compacting and self-leveling during the casting stage (step 2 in fig. 4), but viscous with a plastic behaviour during deformation (step 4 in fig. 4). Due to the slope of the edge of the mould after deformation (up to an angle of 40 degrees with the horizontal) also a minimal yield strength is necessary, to prevent the concrete from flowing out of the mould (figure 7).

The yield strength and plastic viscosity of the mixture are two rheological parameters that objectively characterize the workability [4]. In a number of tests using both traditional slump (flow) tests and the BML

Figure 5: Test setup for parameter study in the laboratory of TU Delft (Stevin 2): four silicone moulds on a flexible base with adjustable slope and curvature. On the background the concrete mixture dosage equipment is visible.

Viscometer [5] different mixtures where examined, with respect to the development of the rheological properties in time and to their behavior during deformation.

For the experiments, two types of mixture were used: a medium-grained and a fine-grained concrete with a maximum aggregate diameter of 8 mm and 1 mm, respectively. Concrete and cement paste in particular are thixotropic materials, which means that a time-dependent structural build-up of fine particles takes place when the concrete is at rest. To enhance this thixotropic behaviour, fly ash and Omya Betoflow (ultra-fine calcium carbonate) were used as fine particles in addition to cement CEM I 52,5 R. Utilizing this characteristic allows casting concrete at a much lower yield value (a higher fluidity) than the critical yield stress. After that, the thixotropic structural build-up is utilized to allow deformation of the mould in the period between 30 to 60 minutes after casting. The use of SCC is an obvious choice for relatively slender precast architectural concrete elements. SCC initially has a very low yield strength, but due to the high powder and fine particle content thixotropy increases the yield strength quickly after casting. This results in the ability of the concrete to keep its position after the deformation of a mould. The workability was first tested by determining the slump flow with Abram's cone. Both mixtures were self-compacting with slump flows of 700 and 685 mm respectively, measured directly after mixing, for the medium-grained and

Figure 6: left: laminating of AR-glass textile as reinforcement prior to deformation of the panels; middle: curved, demoulded and aligned elements; right: 4 layers of textile visible in cut section

fine-grained mixtures. However, already in the first hour, the quick structural build-up increases the yield strength. Repeated slump tests were carried out during the first hour, still using Abram's cone, filled directly after mixing, but kept at rest in the cone during a certain time span until the cone was lifted. The slump values of both mixtures clearly decreased from a slump of 20 to 21 cm at t=30 minutes after mixing to a slump of only 5 to 8 cm at t=60 minutes after mixing. Within 30 minutes both mixtures changed from fluid to half-plastic (from class S5 to class S2 according to [7]). The contribution of hydration progress to the increase in the yield strength in the dormant period is small. The concrete would become very flowable again after slightly tapping the slump cones (see fig. 8).

To relate the slump values to SI-values of yield strength (Pa) and plastic viscosity (Pa·sec) BML viscometer tests were carried out. The BML is a coaxial cylinder viscometer with which the rheological values can be determined by creating a controlled and measured shear flow pattern in the concrete mixture. This is done by rotating a cylindrical container with concrete around a stationary torque sensor and plotting rotation speed against torque in a graph. From this graph the rheological parameters can be calculated through regression. Directly after mixing, the yield strength was in the range of 0 to 10 Pa and the plastic viscosity was about 40 Pa·s. During a period of rest of about 30 minutes, the yield strength increased to about 600 Pa as a result of thixotropic behaviour. This yield strength is sufficient for the start of the deformation process, depending on the exact curvature and panel size.

Glass-fibre textile reinforcement

Since the use of concrete without reinforcement is only acceptable in situations where brittle behaviour would not lead to safety problems, it is generally necessary to add reinforcement to improve the ductility and the strength of the concrete. For example, in façade cladding, stresses due to self-weight, wind and temperature differences could lead to sudden failure of elements. For this reason, a study was carried out on the usability of textile reinforced concrete (TRC) in combination with the typical production method of the flexible mould [7]. Since little concrete covering of the reinforcement is necessary, TRC has the advantage of being suitable for thin elements, such as the ones manufactured in this research. Research at RWTH Aachen ([8], [9]) indicated the possibilities and mechanical properties of TRC. It was decided to perform a number of deformation experiments, using a very flexible alkali resistant (AR) glass fibre textile obtained from 3T TextilTechnologieTransfer GmbH in Aachen, a spinoff company of the RWTH Aachen research group. The textile (cem-FIL 5325) consists of 2,400 tex AR-glass fibre yarns structured in a bi-axial mesh. The distance between the yarns is 8.3 mm in both directions. Each yarn consists of 1,600 fibres with a cross-sectional area of 0.027 mm². The tensile strength of the textile is 1,700 MPa. The textiles were placed in the (earlier used) fine grained concrete using a lamination process, alternating thin layers of concrete (3-6 mm) with a layer of textile, until the desired element thickness and number of textile layers was reached (see fig. 6). After this, the standard deformation procedure, as explained earlier in fig. 4, was followed. Both single-curved and double-curved elements were cast. It was observed that the textiles follow the deformation into the desired geometry without problems. After hardening, the elements were sawed in smaller strips to investigate whether the textiles had remained in the expected positions, which indeed was the case. The load bearing behavior of TRC depends on a specific combination of textile and fine grained concrete. To investigate the mechanical properties of the TRC used in the deformation tests, bending and tensile tests were conducted. As expected the rein-

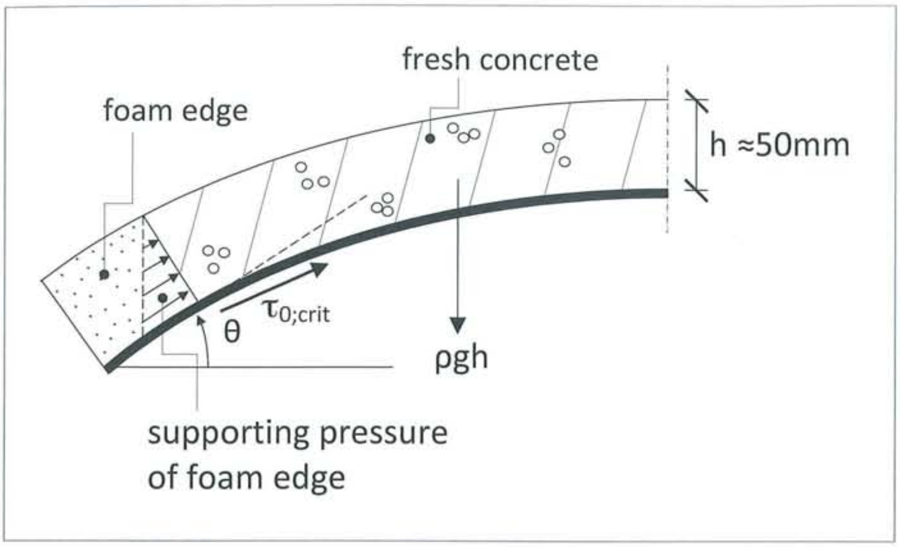

Figure 7: Minimal yield strength necessary to prevent concrete from flowing out of mould

forced concrete showed strain hardening behavior, increasing both strength and ductility.

Conclusion

The production method of the flexible mould promises to be a feasible addition to the already available manufacturing techniques for free-form concrete elements. By using a concrete mixture with self-compacting and thixotropic behaviour, the deformation of elements after casting into accurate single- or double-curved shapes is possible. By measuring the workability using slump tests or measuring rheological parameters using a viscometer, the right moment of deformation can be determined. Elements with a radius between 1.5 and 2.5 meter were manufactured without problems. The deformation process does not cause cracking or other damage of the concrete. By using glass fibre textiles, the elements can be reinforced to fulfill the design requirements. The glass fibre textile does follow the deformation accurately. The number of textile layers can be chosen based on the stresses expected from structural calculations. The mechanical properties of the TRC were checked and were according to the expectation.

Figure 8: Slump tests on a thixotropic mixture: slight vibration by tapping the cone increases the fluidity of the fresh mixture

Acknowledgements

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