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ASSESSMENT OF CONCRETE CHARACTERISTICS DURING THE DELIBERATE DEFORMATION OF A FLEXIBLE MOULD AFTER CASTING

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SUMMARY: Expensive CNC (computer numerical controlled)-milled formwork is required for the production of double-curved precast concrete elements for cladding or shell structures. The innovative flexible mould method for economically efficient and sustainable production of such elements, developed at Delft University of Technology, comprises the use of a flexible, CNC-controlled formwork, which is filled with self-compacting concrete (SCC). This paper describes how curved precast concrete elements can be manufactured in this open and reusable flexible mould. The proposed method reduces formwork costs of architectural freeform elements made with concrete. First, the method is described briefly, then tests are discussed, demonstrating that by measuring the rheological parameters of the concrete during the process, the right moment of deformation can be determined. The measurements show that thixotropic behaviour of concrete for this manufacturing method is very helpful, since it leads to a quick increase of the yield strength of the fresh concrete, but still leaves concrete deformable in order to prevent cracking caused by the deformation of the mould. The change of the rheological behaviour of concrete in the period between mixing and deformation of the mould was assessed; an additional study was executed in order to assess the integrity of the concrete after the deformation of the mould.

KEY WORDS: Flexible mould; rheology; thixotropy; deformation; cracking.

1 INTRODUCTION

Curvature offers a beautiful shape language for architecture, a language that would not exist if only straight lines and rectangular, flat surfaces made up the architect’s vocabulary. Double-curved structures in general, and monolithic concrete shell structures more specifically, can transfer forces very efficiently. Two famous examples of prefabricated shell structures are the Palazzetto dello

Sport [1] and the Heydar Aliyev Cultural Centre [2]. In practice, however, the number of shell structures is still limited because of higher costs of curved buildings due to both the extra efforts needed for handling complex geometry during the design and productions stages and the need for unconventional construction methods on the building site or in the factory. The flexible mould method is an alternative method for economically efficient and sustainable production of curved and double-curved elements. Renzo Piano [3] described the principle of producing deformed plastic cladding elements, using a pneumatic formwork. Based on Piano's principle, Vollers and Rietbergen [4] developed a computer-driven set of actuators, which by changing their position on their top could form a curved surface. The flexible mould system for the production of double-curved prefabricated concrete elements was further developed and studied at Delft University of Technology [5]; the up-scaling of the mould system is an ongoing project. The production comprises casting of an element in horizontal position and, after a waiting period, the mould is deliberately deformed and positioned on pre-arranged mould supports. The element hardens in the deformed mould, which can be re-used for the production of elements having the same or a different geometry. Casting of concrete in general takes place in a wide variety with regard to mixture consistency, placement and compaction methods. The deformability of concrete in the plastic stage is an important characteristic, which contributes to its widespread utilisation. In the period between mixing and de-moulding, the concrete behaviour changes from a plastic to a solid state with changing contributions to the yield strength in time of thixotropic structural build-up and progress of hydration. Roussel [6] defined three categories of flocculation rate dependent on the increase of yield stress in time: 1) Non-thixotropic SCC: A_{thix}<0.1 Pa·s, 2) Thixotropic SCC: A_{thix}=0.1-0.5 Pa·s and 3) Highly thixotropic SCC: A_{thix}>0.5 Pa·s. The element geometry and applied mix design determine whether the criteria can be fulfilled and if so, the duration of the open window for adequate deformation. Especially, the early phase before setting is very important for the production with the flexible mould system:

1) In the horizontal position, effective casting is realized by the use of self-compacting concrete. Placement does not require compaction, since the yield stress is very low.
2) During deformation, the yield stress of concrete has to be a) sufficiently high to prevent that concrete flows over the wall of the mould and b) sufficiently low to prevent that the elongation of the concrete localises in (large) cracks (Fig. 1).

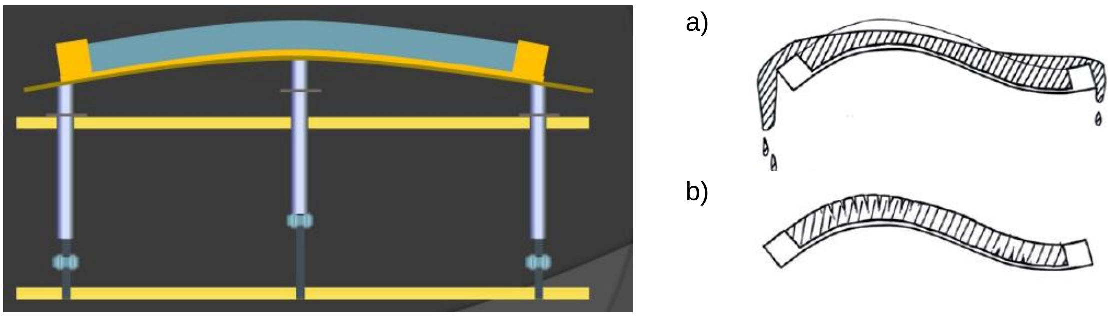

a)
b)

Figure 1: Flexible mould system during deformation, with two governing criteria – a) maintaining stability and b) prevention of significant cracking provide boundary conditions with regard to yield strength

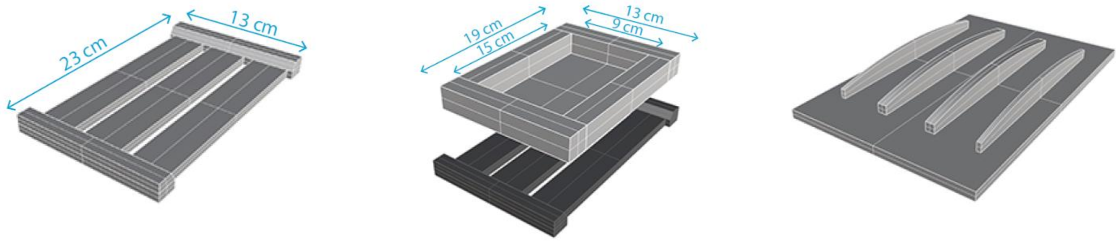
2 EXPERIMENTAL SET-UP

A reference self-compacting mixture was applied for the tests; the mix design took into account that within one hour sufficient yield strength had to be gained to deform the mould. The combination of applied powders and superplasticizer was adjusted for a short workability retention period. Slump flow [7] and slump [8] testing took place in parallel to the deformation of the mould; the workability decreased from a slump flow of 700 mm 7 min after mixing to a slump of only 5 cm 61 min after mixing. The dosage of superplasticizer was varied in the research. The rheological characteristics yield strength and plastic viscosity were determined directly after mixing with the BML-viscometer and were about 5 Pa and 40 Pa·s, respectively.

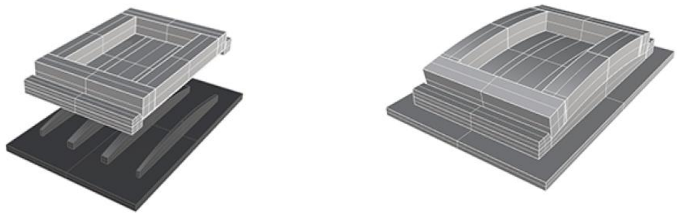
Table 1: Mixture components, dosage and characteristics

Mixture component	
Cement CEM I 52,5 R	400 kg/m^3
Fly ash	160 kg/m^3
Superplasticizer Premia 196	variable
Water	172 kg/m^3
Sand 0.125/4 mm	1046 kg/m^3
Gravel 4/8 mm	563 kg/m^3
Mixture characteristics	
Compressive strength (cube; 1/7/28 days)	45/65/80 MPa
Splitting tensile strength (cube; 1/7/28 days)	3.5/4.0/5.5 MPa
Flexural strength (prism; 1/7/28 days)	6.0/9.5/10.5 MPa
Slump flow / slump measurement at	7/30/45/61 min
Slump flow (7 min) - Slump (30/45/61 min)	700 mm - 20.2/16.8/5.2 cm

In order to determine the effect of different parameters on the risk of cracking as a result of the deformation of the mould a simple test system was developed [9], which consisted of three main components: (1) the casting surface (Fig. 2a), (2) a flexible mould (Fig. 2b) and (3) the deformation surface (Fig. 2c). Two deformation stages are shown by Figures 2d and 2e.



(a) Casting surface (b) Flexible surface (c) Deformation surface



(d) Complete mould (e) Deformed mould

Figure 2: Mould construction in five different steps

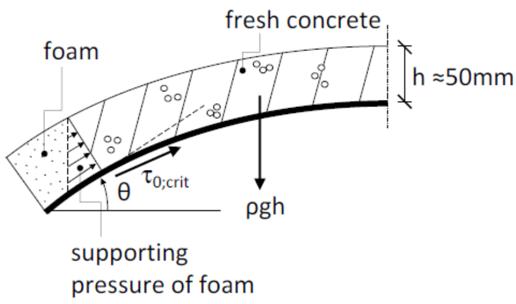
Several moulds were filled in parallel in order to deform the moulds at different moments after casting. In order to prevent evaporation a plastic foil was placed to cover the cast elements; the plastic foil was not in direct contact with the concrete surface. A flexible mould consists of polyether-mattress foam (ρ=25 kg/m^3) glued to co-polyester sheets. The inner surfaces of the mould were treated in advance with bi-component silicone rubber P58510 (produced by Poly-Service) in order to avoid direct contact of the co-polyester sheets with cement paste. The aforementioned materials were selected in order to assure proper flexibility. The dimensions of the specimens were 15 cm in length and 9 cm in width, which were selected to allow placing specimens in the vacuum machine during specimen preparation. The casting and deformation surfaces (Fig. 2) were built from 4 mm thick MDF(Medium-Density Fibreboard)-panels and cut using a laser cutter, which assured that the shape and dimensions were highly accurate. Four arc-shaped ribs with the required curvature were arranged on the deformation surface. The flexible mould was fixed during production to the casting surface. The supports of the deformation surface fit in the openings of the casting surface. The deformation of the mould can be quickly executed by positioning the casting surface and flexible mould on the deformation surface (Fig. 2e).

After 7 days of hardening under normal room conditions the specimens were de-moulded and prepared for the assessment of cracks by epoxy impregnation. The specimens were placed one by one in a vacuum installation. Under vacuum conditions the elements were impregnated with a mix of liquid epoxy resin and hardener. The aim of the impregnation process is to fill the micro-cracks and micro-pores with the epoxy mixture, which has a high fluorescence under UV light. After the elements were impregnated, characteristic sections of the specimens were selected and cut; the element was cut in half using a diamond saw with a thickness of 3 mm, thus obtaining two very similar impregnated surfaces. The section surfaces were ground and polished to obtain high quality images. A stereo-microscope was applied to investigate micro-cracking on the top surface of the specimens (magnifications: 6.3x & 12.5x); under the UV light the epoxy-impregnated areas become fluorescent and are clearly visible. The images were studied and analysed with the stereo microscope. Each sample was investigated separately and the cracks were counted and measured. It is important to mention that only the cracks formed on the exterior curved surface of the deformed concrete element were inspected, those being the ones most responsible for limiting concrete’s service life.

3 RESULTS AND DISCUSSION

3.1 Yield strength development

Concrete has to support its own weight after the deformation of the mould. Equation 1 (Fig. 3), proposed by De Larrard [10], was applied in this research and relates the geometry of the mould after deformation (slope θ) and the required yield strength. The thickness and the curvature of an element determine how high the yield strength has to be during the deformation of the mould. As the discussion in this paper will show, not for all cases the two criteria with regard to yield strength and prevention of cracking can be balanced. The main parameters studied by Schipper [5] were concrete mix design, time of deformation as well as curvature, height, geometry and scale of elements.



$$\tau_{0;crit} = \rho \cdot g \cdot h \cdot \sin(\theta) = \rho \cdot g \cdot h \cdot \frac{L}{2R} \quad \text{(Equation 1)}$$

$\tau_{0;crit}$	Critical yield strength of concrete under slope [Pa]
ρ	Density of the concrete [kg/m^3]
g	Acceleration of gravity [kg·m/s^2]
h	Height of concrete [m]
θ	Slope angle [rad]
L	Length of element [m]
R	Radius of element [m]

Figure 3: Critical shear yield strength $\tau_{0;crit}$ of concrete under a slope

Table 2 indicates how the critical yield strength of an element is affected by differences in height and curvature (radius).

Table 2: Critical yield strength $\tau_{0;crit}$ required for casting under a slope θ, depending on the mould radius R, the element length L and the element height h (for ρ = 2 400 kg/m^3)

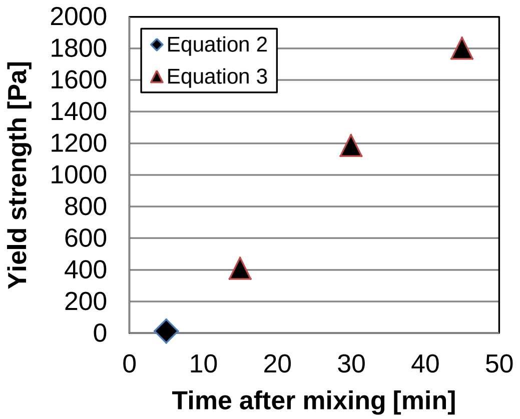
Slope θ and critical yield strength $\tau_{0;crit}$		**R =1.5 m**		**R =2.5 m**		**R =5.0 m**	
Horizontal length L [m]	Element height h [m]	θ [°]	$\tau_{0;crit}$ [Pa]	θ [°]	$\tau_{0;crit}$ [Pa]	θ [°]	$\tau_{0;crit}$ [Pa]
0.80	0.025	15.5	157	9.2	94	4.6	47
0.80	0.050	15.5	314	9.2	188	4.6	94
0.80	0.100	15.5	628	9.2	377	4.6	188
2.00	0.025	41.8	392	23.6	235	11.5	118
2.00	0.050	41.8	785	23.6	471	11.5	235
2.00	0.100	41.8	1570	23.6	942	11.5	471

The development of the yield strength in time was assessed by Slump flow and Slump testing. The yield strengths were calculated with Equations 2 and 3 (Table 3).

Table 3: Empirical equations for the calculation of the yield strength

Empirical formula	**Equation for**	**Reference**
$\tau_0 = \frac{225 \cdot \rho \cdot g \cdot V^2}{128 \cdot \pi^2 \cdot R^5}$	**Slump flow** (Equation 2) (V: Concrete volume; R: Spread radius)	[11]
$\tau_0 = \frac{\rho}{17.6} \cdot (25.5 - S)$	**Slump** (Equation 3) (S: Measured slump [cm])	[12]

With a desired deformation time in production after 30-60 minutes (1800-3600 s) the required structural build-up rate A_{thix} can be in the range of 0,01 Pa·s (R = 5 m, h = 0.025 m, L = 0.8 m & waiting period = 60 min) up to 0.87 (R = 1.5 m, h = 0.1 m, L = 2 m & waiting period = 30 min) dependent on the boundary conditions (Table 2). The yield strength increased from almost zero directly after mixing to more than 550 Pa·s after a rest period of 45 minutes during a reference test with the BML-viscometer; the thixotropic increase A_{thix} was about 0,2 Pa/s, which is an intermediate thixotropic behaviour according to the definition of Roussel [6]. When a relatively high yield strength is required the risk of cracking should also be assessed by experimental testing. The curved elements produced in this research had a length of L = 0.80 m and a height of h ≤ 0.05 m; dependent on the radius the critical yield strength is in the range of 94 to 314 Pa (Table 2). Figure 4 shows that already in the first hour the yield strength significantly increased. The yield strengths were determined with empirical formulae given in Table 3. The test results show that a significant yield strength was build up in the period between 15 and 45 minutes after mixing, which is in agreement with the deformation experiments (the concrete did not flow out of the mould). It can also be concluded that the applied mixture shows a clear change of workability in the first hour from being self-compacting to a very low-slump state.



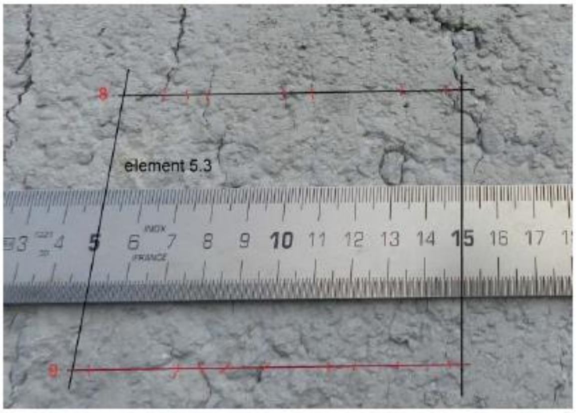


Figure 4: (left): Development of the yield strength during the first 45 minutes; calculation of yield strength for slump flow with Equation 2 and for slump with Equation 3; (right) cracked element deformed after 60 minutes

When the concrete was too stiff to deform, cracks appeared. In a number of deformation tests, this was indeed observed. Figure 4b shows the surface of an element which was deformed after 60 minutes; the yield strength, calculated with Equation 3, at this moment determined with the slump test (zero slump), was at least 3000 Pa according to Equation 3. The resulting cracks had a width of 0.05-0.20 mm and were found at a distance of 30 to 40 mm.

3.2 Concrete deformability

The required yield strength of concrete depends on different parameters, as was elaborated in Section 3.1, among which are the geometrical parameters of an element (height, length and curvature). The occurrence of cracks is discussed in the following paragraphs in detail. This paper focusses on the number and frequency of cracks; the maximum and average crack widths are also presented. A more detailed analysis of the results is provided by Troian [9].

Effect of the radius of deformation: At increasing curvature and decreasing panel radius the maximum strain of the concrete increases. The total strain is composed of strain of plastically deformed concrete and strain that is located in cracks. In time, the plastic deformability of concrete decreases and more and wider cracks are expected. The results with regard to the effect of the radius of deformation are shown in Figure 5 for a panel thickness of 25 mm. The radius has an important influence on the number of cracks propagating from the surface of the bend concrete. A high number of cracks and the largest maximum and average crack widths are obtained for a radius of 0,25 m. The increase of crack widths in time was especially pronounced for the 0.25 m radius, whereas for the radii of 0.5 and 1.0 m the maximum crack widths even after 90 min were smaller than 0.1 mm. Radii of 0.5 and 1.0 m caused very similar outcomes with regard to crack widths.

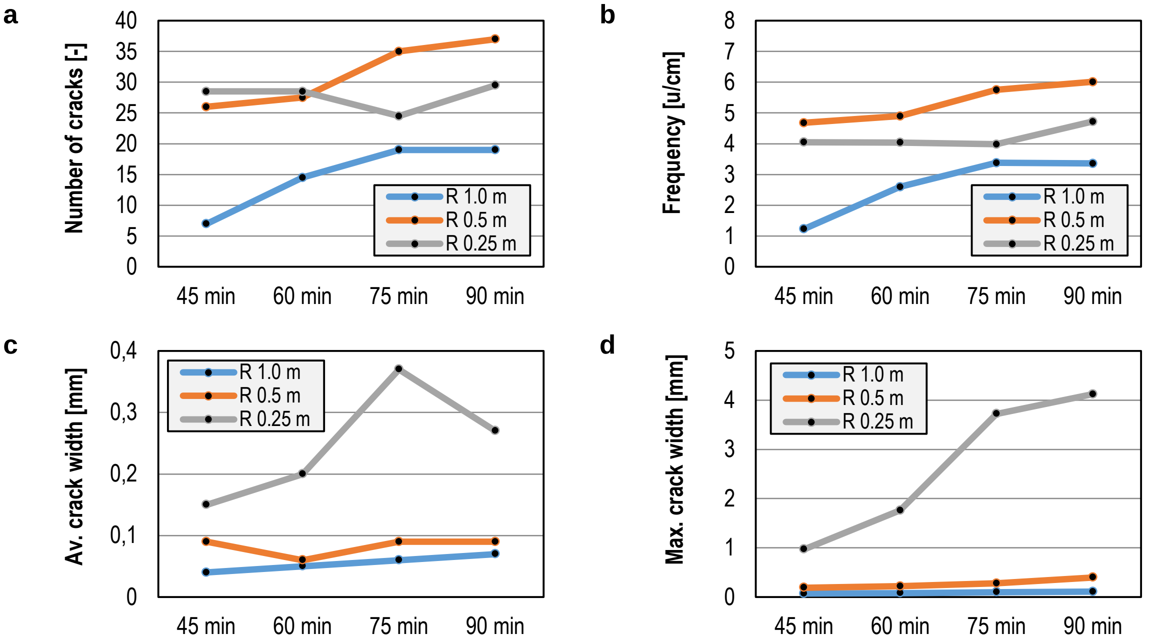


Figure 5. Effect of curvature (panel thickness: 25 mm): (a) number of cracks, (b) crack frequency, (c) average crack width and (d) maximum crack width

Effect of the panel thickness: Two types of panels having a thickness of 25 or 50 mm were investigated; the results are presented in Figure 6.

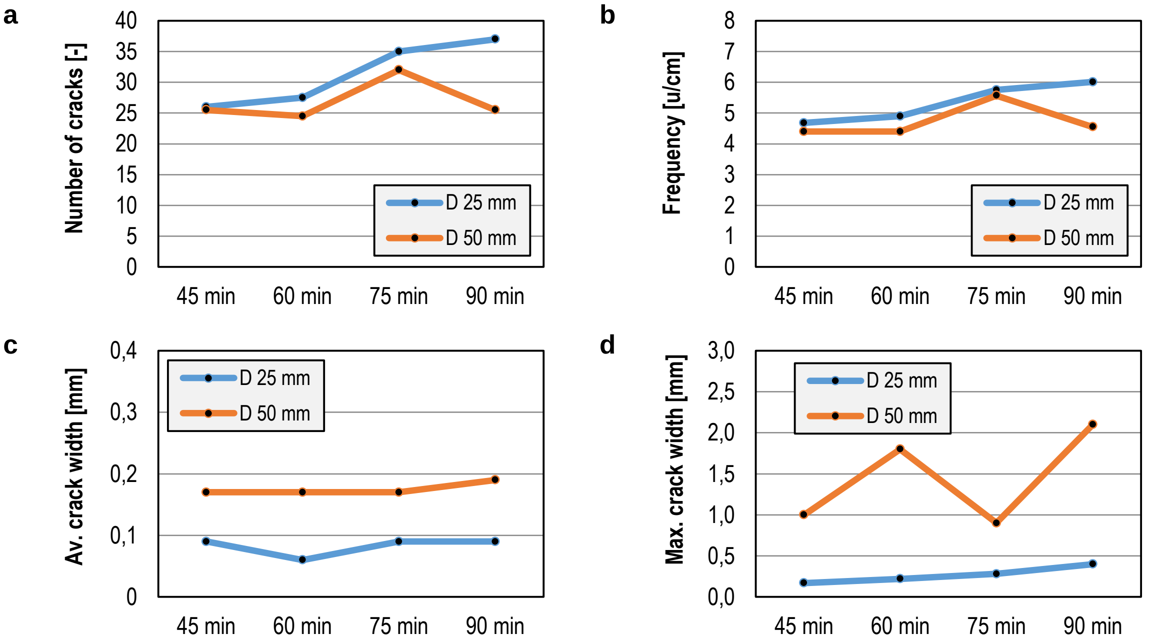


Figure 6. Effect of the panel thickness (radius: 0,5 m): (a) number of cracks, (b) crack frequency, (c) average crack width and (d) maximum crack width

Until 75 minutes, the panel thickness had a relatively small effect on the frequency of cracks formed on the surface of the element. The strain during deformation is larger for thicker panels. However, this effect is not reflected in the number of cracks; the number of cracks was slightly higher for the thinner panel. In contrast, larger crack widths were found for the thicker panel which were in most cases significantly larger (about twice the crack width). As expected, with a thicker panel wider cracks were obtained, but the number of cracks was lower.

4 CONCLUSIONS

High quality facades, roofs and precast shuttering for buildings and infrastructure with complex geometry can be produced with the flexible mould method. In an experimental study the effect of mixture characteristics and geometrical boundary conditions were assessed and the following conclusions can be drawn:

(1) Under consideration of the geometry of an element and a rheological analysis the right moment of deformation can be determined;

(2) The strain of concrete is the sum of the contributions of plastic deformation, and the localised deformation in cracks if cracks appear. With an optimized mix design and production conditions that take into the rheological behaviour of concrete in time, curved or double-curved elements can be produced without any cracks or with very small crack widths.

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