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Transition from fluid to solid concrete in the flexible mould process

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Abstract. The transition period between the mixing of concrete and the begin of setting increasingly receives attention, as special production processes can be developed with tailor-made fresh state characteristics. In this publication the two processes of 3D Concrete Printing (3DCP) and the production with the Flexible Mould Process (FMP) are discussed and compared.

The FMP is a relatively new manufacturing method that was developed to allow the efficient production of curved thin concrete panels for cladding or structural use. The term ‘flexible’ refers to the deformation into the required curved shape of both the compliant mould surface and the fresh concrete contained by the mould shortly after casting. After that deformation, both the mould and the concrete are left for further hardening until demoulding is possible. The development of the 3DCP technique progresses fast, hereby new perspectives are gained with regard to mix design, production and structural performance. Sideway, test methods need to be developed or re-evaluated. The early age strength and strain capacity are important parameters for both processes, although they are not the same with regard to magnitude, period or time after mixing. Both processes can be executed within an open window and with specific boundary conditions only. This publication discusses and compares both processes. The implications of these recent findings are translated to practical aspects with regard to the production with the FMP.

Keywords: Flexible Mould, 3DCP, Rheological Measurement, Concrete Production, Self-Compacting Concrete.

1 Introduction

The behaviour of concrete in the period between mixing and the begin of setting is crucial for the casting execution and the performance during service life (on the material and structural level). Many processes benefit from tailor-made plastic stage characteristics, see Table 1.

Table 1. Examples of concrete characteristics in the fresh state dependent on the application.

Consistency aspect	Benefit	Application examples
Very low yield strength	Improves casting rate, eliminates compaction, improved appearance	Prefabricated elements, architectural elements
Very low viscosity	Facilitates concrete placement	Floors, sandwich elements
Moderate yield strength	Casting in a slope	Bridge decks, ramps
Moderate segregation due to compaction	Production benefits, e.g. improved placement and strength of anchors	Prefabricated sandwich elements
Green strength	Demoulding directly after casting	Pipes, hollow-core slabs

Applications mentioned in Table 1 require specific characteristics at the moment of production immediately, within a few minutes or even hours after mixing. The production processes of FMP and 3DCP are special as they define specific boundary conditions at two different moments. Table 2 summarises both production processes.

Table 2. Comparison of two production processes: 3DCP and FMP.

Process	3DCP	Flexible mould process
Production	Extrusion process	Casting process
Application	3D structures	Thin panels, sandwich elements
Existence of open window	Yes	Yes
Period open window	Very short, dependent on extrusion rate and weight of material layers printed above concrete	Medium, e.g. 45 min dependent on curvature, panel thickness and concrete characteristics
Relevant material characteristics (at different stages)	1) Placing phase: pumpability and printability 2) During printing: buildability	1) Filling phase: Very low yield strength 2) Deformation phase: Sufficiently high yield strength and sufficient strain capacity
Potentially problematic	Collapse (strength, buckling), cracking, overly deforming, bond insufficient between layers	Cracking, deviating panel thickness due to material movements
Shaped by	Extrusion nozzle and material characteristics after extrusion	Mould dimensions, deformed position
Maximum aggregate size	Dependent on nozzle size, typically not larger than 2 mm	Dependent on element thickness, at least 4 mm
Paste content	Mortar-base. Larger time-dependent deformations	Concrete-base, smaller time-dependent deformations

Studies with regard to the FMP [1-3] are much rarer compared to research executed on 3DCP. Although the main target applications of the FMP are different from 3DCP, it is worth to evaluate the two production processes more in detail. Concrete for the production in the FMP has to be designed for high flowability, whereas 3DCP materials flow only, if they flow at all, in the pumping/feeding and deposition phases. Still, both types of material behave roughly as visco-plastic Bingham materials. The changes of properties in the plastic stage are discussed in the following sections and how they can be related to the requirements for the two different production processes.

2 Boundary conditions of the flexible mould process

The FMP system for the production of double-curved prefabricated concrete elements was further developed and studied at Delft University of Technology [1]. 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. An example of mould deformation is shown by Fig. 1.

Fig. 1. Flexible mould system before and after deformation [1].

The element hardens in the deformed mould, which, afterwards, can be re-used for the production of other elements having the same or a different geometry. In the period between mixing and de-moulding, the concrete behaviour changes from a Bingham fluid to a solid state with changing contributions to the yield strength in time of thixotropic structural build-up and progress of hydration. As the applied concrete has a very low yield strength, which is also obtained by the addition of superplasticizer(s), the main contribution to the increase in yield strength in the time until deformation comes from the flocculation of fine particles exerting a thixotropic action [4]; every movement of the mould has to be executed with caution not to unintendingly disturb the structure and reagitate the concrete. Two boundary conditions are:

1) Filling phase: In the horizontal position, effective casting is realized by the use of self-compacting concrete (SCC). A very low yield stress is required in order to avoid the compaction energy impact on the potentially fragile mould and to obtain a smooth surface texture;
2) Deformation phase: During deformation, 1) the yield stress of concrete has to be sufficiently high to prevent that concrete flows over the edge of the mould (Fig. 2 a) and 2) concrete has to retain sufficient strain capacity to prevent that the elongation of the concrete localises in (larger) cracks (Fig. 2b).

The element geometry and applied mix design determine whether the criteria can be fulfilled and if so, what the duration is of the open window for adequate deformation.

Dependent on the geometry (curvature, dimensions, slope) of a panel produced with the FMP the open window for deforming the mould can be longer or shorter, different in time after mixing or, in some cases, deforming cannot be realised without cracking.

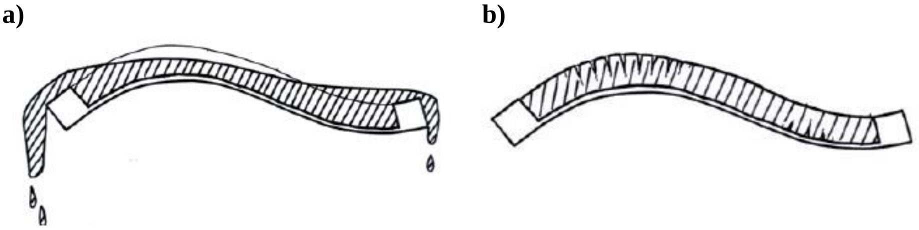

Fig. 2. Two boundary conditions for the mould deformation a) maintaining stability through an adequate yield strength and b) prevention of significant cracking through strain capacity [1].

Critical yield strength

Especially, the early phase before setting is very important for the production with the FMP (Fig. 3). The open mould locally can be in a steep slope after the deformation, the concrete then has to support its own weight. The original Equation (1) (left part), proposed by [5], was applied to calculate the required yield strength for a given slope of concrete and it was extended for the prediction of the yield strength in the FMP (right part of Equation (1)) [1] in relation to the geometry of a mould with length L and circular shape R after deformation (for a circular mould curvature: sin(θ) = L/2R).

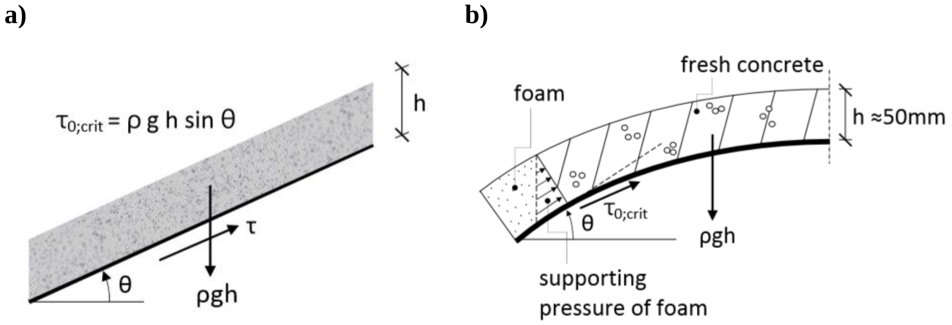

Fig. 3. Critical shear yield strength $\tau_{0;crit}$ of concrete under a slope (a) model proposed by [5] and b) modified model [1].

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

where:

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

The yield stress of SCC is in the range of 0-50 Pa, dependent on the mix design. Table 3 indicates the critical yield strength of concrete dependent on the height and curvature (radius) of the panel. A reference with regard to the yield strength of concrete for 3DCP is a value of 3.0 kPa which is the initial static yield stress with a thixotropic build-up A_{thix} of 1.1 Pa/s and a short-term re-flocculation rate of 6.7 Pa/s [6]. Such thixotropic increase is much higher compared to what is typically observed in SCC, where an A_{thix} of 0.5 Pa/s already is considered a characteristic value of highly thixotropic SCC [7]. In another study, the yield strength of extrudable concrete was found to be in the range of 1.0-2.6 kPa [8], of which the upper boundary is much higher than the maximum values shown in Table 3.

Table 3. 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) [3].

Slope θ and $\tau_{0;crit}$		**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 structural build-up of the applied concretes was determined with the BML-viscometer and was in the range of 0.20-0.25 Pa/s [1,3]. With an initial yield stress of 10 Pa and a thixotropic increase of 0.2 Pa/s the time can be calculated after which the critical yield stress determined with Equation 1 is reached; this time is the minimum time at rest until the mould can be deformed. In Figure 4, the time of deformation of the mould (X-axis) is compared to the theoretically derived time of deformation (Y-axis) with the 1:1 line being the minimum time before deformation.

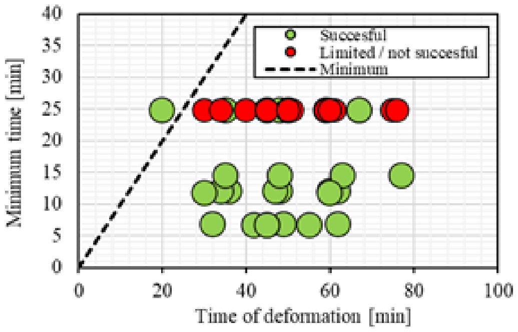

Fig. 4. Time of deformation of the mould compared to the time required to reach the theoretical yield stress indicated in Table 3 (initial yield strength: 10 Pa, A_{thix}=0.2 Pa/s).

With the exception of a single point all dots are located at the right side of the minimum line. However, a number of experiments was not successful, as the red dots indicate and accordingly a second criterion is required for complete specification, which is discussed in the following section.

Critical strain capacity

Dependent on the interaction of the concrete with the mould, possible strain distributions are 1) at the left side of Fig. 5a) the neutral axis is at $h_2/2$ (flat sections remain flat after curvature, Bernoulli hypothesis) or 2) at the right side of Fig. 5a) the neutral axis is in the bottom of the mould, in which case $\varepsilon_{max} = h \cdot \kappa = h/R$. The second strain distribution corresponds with the idea of 'wrapping' the mould around a cylinder, since the mould surface itself is not stretched, but only curved, and a 'no-slip' situation is assumed. It was concluded that the second assumption of strain distribution fits best the boundary conditions [1]. In the transition period between fluid and solid states the allowable deformation angle $\theta_{allowable}$ is assumed to linearly increase over time due to the increasing yield strength of concrete, whereas the strain capacity of concrete decreases, e.g. as shown by the curved line, see Fig. 5b.

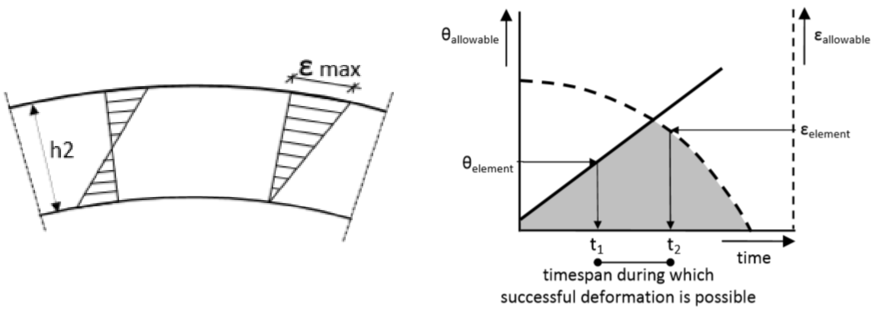

Fig. 5. Deformation of concrete a) two potential strain distributions over the element height of the cross-section and b) open window for the deformation of the mould (t_1 being the earliest moment and t_2 the latest moment before cracking occurs) [1].

Dependent on the geometrical boundary conditions, the 'open time' is the period within which the deformation capacity is sufficiently large and the concrete remains in the original shape of the mould after deformation (deformation and strain capacity decrease in time and the allowable slope goes up as the yield strength increases). The thickness and the curvature of an element determine the required strain capacity and not in all cases the two criteria with regard to yield strength and prevention of cracking can be balanced. The order of magnitude of strains in the research at Delft University of Technology was in the range from −75‰ (shortening) to +35‰ (elongation). Taking into consideration, though, that in the present research SCC with a very low yield strength was applied a relatively large strain capacity is expected. Evidence for larger strain capacities of flowable concrete was found by Troian [9], where elongation-strains of around 100000 με were applied in the first hour after mixing without visible cracking. Figure 6 compares the maximum strain (positive radius = positive strain of the concrete surface) of deformation experiments executed. With a maximum strain of about17 promille all elements successfully were deformed, whereas with the largest strain of 33 promille the experiments in almost all cases were not successful. Obviously, below such material-related maximum (not depending on the yield strength), the open window mainly depends on the yield strength criterion and it increases the smaller the radius of the curved element is (or being negative). A study is ongoing with regard to the time-dependent changes during the deformation process.

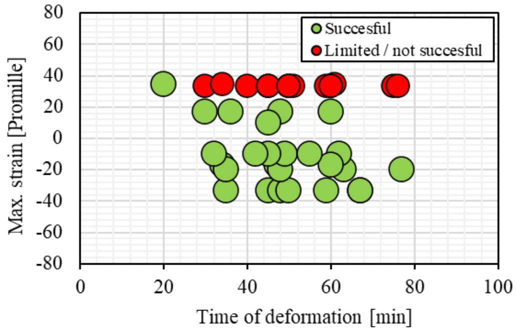

Fig. 6. Influence of time on the maximum strain capacity of self-compacting concrete.

3 Transition from the fresh to hardening state

3.1 Mechanisms acting during the transition

With the advance of the 3DCP technology, important knowledge was gained with regard to the mixture optimization, fresh and hardened state properties, test methods and prediction of structural performance, a development which is still in progress. Such knowledge was limited before to only a few areas, e.g. pumping, rheology of flowable concretes, utilisation of green strength for concrete production or the prevention of bleeding and segregation. This knowledge can be further exploited to improve other (new or existing) production processes. 3DCP poses two main requirements with regard to the concrete 1) printability and 2) buildability. Only within a short period of time (open window) optimized processing can take place [10]. Buckling as well as the surpassing of the material strength (or a combination of the two) are potential reasons for failure after material deposition. Flocculation and structuration processes are ongoing and contribute to the build-up of structure over time [11]. Different properties in time and under different shearing conditions have the following important reasons:

- Structural build-up due to thixotropy caused by colloidal attractive forces;
- Progress of degree of hydration with contact points between binding grains;
- Chemical acceleration of binding rate;
- The addition of components with faster growing reaction products;
- (Micro)fibres can be added to increase the yield strength.

The chemistry of cementitious materials can be significantly altered by the addition of admixtures. For production, temperature effects also have to be taken into account, in order to have sufficient time to place the material. During the production of test elements with the FMP the deformation of the mould frequently was executed after about 45 minutes; this period can be essentially shortened with acceleration of hydration (essentially also shortening the effective time of the superplasticizer) or by design of a more thixotropic concrete. For 3DCP the acceleration of the increase of stiffness and strength is subject of many research projects. In [11] accelerators are reviewed: the desorption of retarders, the use of C-S-H seeds, soluable inorganic salts or organic compounds are effective measures for mix design. In particular, silicate and aluminium salts are admixtures that can produce a very quick setting. The use of alternative binders (e.g. alkali-activated binding, rapid setting calcium-aluminate or calcium sulfo-aluminate cements) also yield a faster strength increase. Beside rapid-hardening mix designs, execution measures can be supportive in optimizing the production conditions (e.g. heat curing or microwave acceleration).

3.2 Development of strength and reduction in strain capacity transition

The flowability of printed concrete is not comparable with flowable concretes, as their first task is to remain in the position where they were placed. The initial part of deformation of a Bingham material (before flow is initiated) is therefore more relevant for the extrusion process of 3DCP. For the filling of the flexible mould first the critical strain has to be surpassed and flow initiated. Over time, the yield strength increases and the strain capacity decreases, both parameters are essential to consider for the deformation of the mould. Locations with up-bending of the mould are characterized by important strains in the concrete, whereas at down-bend locations, the tensile stress is carried by the formwork. Strain can be distributed over a wider area, or it locates at the position with the largest strain.

An important difference between 3DCP and the FMP is the period after mixing, during which the transition from a flow behaviour or visco-elastic behaviour towards elastic deformation takes place. After mixing, concrete in 3DCP often does not exceed the range of critical strain to reach the material yield strength (flow), with the exception of the slipping layer in contact with the pumping pipe, whereas this is very important for the production with the FMP during the filling phase. Furthermore, the waiting time before deforming the mould compared to the time required to obtain sufficient buildability for 3DCP is significantly longer for the initially flowable concrete used for the FMP. The difference can be a factor of 5 or more in time, which makes the flexible mould process more robust. Not only is the transition time later after mixing, but also the period of transition (open window) can be longer (dependent on the geometry of the panel to be produced). Tests can be executed during the initial phase to determine the yield strength e.g. with the slump or slump flow test, while the concrete remains in horizontal position, to determine the appropriate moment of deformation. Fig. 7 shows a typical result of a vane test executed with a material having a yield stress [10], where the material exhibits a more or less elastic behavior until the shear stress is reached, beyond which flow is initiated.

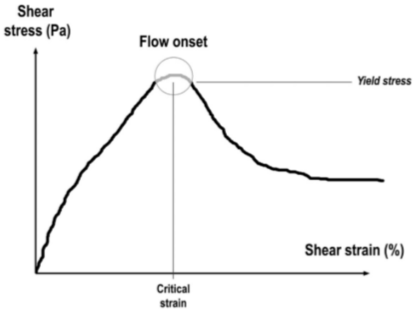

Fig. 7. Shear stress as a function of shear strain [10].

Similar curves can be obtained from triaxial compression testing [12], with which the transition in the plastic stage of relatively stiffer materials can be assessed. Yield stress, modulus of elasticity and critical strain are time-dependent and over time the hydration process has a larger contribution compared to the structural build-up [13]. Instead of Bingham flow behavior determined with a rheometer, which is more applicable for flowable materials, the material characterization of collapse was assessed with the Mohr-Coulomb criterion applied on compression / shear test results [14]. However, the initial critical strain is relevant for both vane and triaxial compression tests and it indicates the deformability until the maximal stress is reached at a specific moment of time. The higher the yield stress, the smaller the strain capacity becomes [14]. An initial stiffness is required for 3DCP to limit the deformation after the extrusion, which is therefor a lower bound. In contrast, the FMP has an upper bound with regard to stiffness in order to be able to follow the deformation without the localization of cracks. After the deformation of the mould the concrete itself has to stay in shape. In [10], the stiffness parameter E is defined, which has to be exceeded during 3DCP in order to obtain a stable structure dependent of the boundary conditions of the structure. The critical strain related to the peak shear stress / yield stress is of the order of a few % and about 2% [4]. This value is comparable with the results on the maximum strain capacity shown by Figure 6. The maximum strain capacity is for the FMP an upper bound and a complementing criterion with the yield strength.

4 Conclusions

This paper discusses the flexible mould process and compares it with regard to production boundary conditions with 3D concrete printing. Based on the discussion the following conclusions can be drawn:

- Both production processes are examples of optimized combinations of material design, execution method and structural performance.
- 3DCP and the flexible mould process are production processes with significant differences. However, the discussion of the time-dependent transition and magni-

tude of and strain at shear stress indicates similarities with regard to basic production requirements.

- The reliable measurement of material properties for both processes is challenging, due to the quick change of the material properties during the first hour and the time and handling required for various measurements.

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