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Formwork pressure induced by highly flowable concretes – design approach and transfer into practice

An analytical model for the calculation of the pressure of concrete on vertical formwork has been developed on the basis of experimental tests on highly flowable concretes in the fresh state (see companion paper "Material investigations and large-scale tests" [1]). The model takes into account the time-dependent material parameters of the fresh concrete, the specific properties of the highly flowable vibrated concretes and self-compacting concretes (SCC) as well as operational aspects. A proposal for the design of formwork was developed based on the experimental tests and the semi-probabilistic safety concept. It was found that the design load is often lower than the hydrostatic concrete pressure – even for highly flowable concretes. On construction sites, the pressure can be best controlled by limiting the casting rate. Insufficient experience of personnel in the handling of highly flowable concretes increases the uncertainties with respect to the design values and the safety risk.

Further investigations into construction management-related aspects regarding the use of highly flowable concretes cover the risk assessment during concreting, design of the processes on the construction site and the development of the basis for a documentation system.

Keywords: formwork pressure, friction, fresh concrete properties, setting

1 Introduction

The construction industry is using more and more concretes with a higher workability as well as self-compacting concretes (SCC) in order to build slender and heavily reinforced concrete building elements with sufficient quality. The use of effective superplasticizers and the rheological properties attained have called into question the existing knowledge about the pressure of fresh concrete based on normal vibrated concretes and existing design concepts such as DIN 18218:1980-09 [2] and ACI 347-04 [3]. Furthermore, the reduction in or absence of vibration when using SCC generally invalidates the existing models.

The topic of fresh concrete pressure has been very intensively discussed recently. A number of measurements on SCC in the laboratory and on site (e.g. *Billberg & Österberg* [4], *Assaad & Khayat* [5], *Gregori* et al. [6], *Graubner & Proske* [7]) have revealed new knowledge about the correlation between different influencing factors and the pressure on formwork. Different models [5–13] were developed based on the experimental tests, which often consider the material properties of the concrete merely under static conditions and neglect the load-dependent part of the yield strength (inner friction angle) as well as the construction operations aspects. Moreover, determining the model parameters in practice, e.g. the thixotropy or the friction parameters, is often problematic. Test facilities are not standardized, are comparatively expensive and the personnel of the concrete producer are usually not appropriately qualified.

A state of the art report [14] gives an overview of the existing models for calculating the pressure of fresh concrete in general and identifies five categories of influencing parameters. These are: the fresh concrete properties, the formwork and reinforcement, the interface between concrete and formwork as well as concrete and reinforcement, processing and external influences.

This publication presents the results of the research project "Schalungsbelastung durch Hochleistungsbetone mit fließfähiger Konsistenz" (pressure of fresh concrete asserted by highly flowable concretes) [15]. The studies regarding the design model for pressure of fresh concrete are based on experimental tests, which are presented in the companion paper [1]. The workability of concretes is classified in DIN EN 206-1:2008-08 depending on the spread of the concrete a in the flow-table test. Vibrated concretes with consistency F5 ($560 \le a \le 620$ mm) and F6 ($630 \le a < 700$ mm) as well as SCC ($a \ge 700$ mm) were investigated. By including the results of the large-scale tests and measurements documented in the technical literature, it was possible to develop a proposal for the practical calculation of the pressure of fresh concrete on formwork. It tries to encompass both the reality and practicability to a large extent and considers the requirements for the safety and reliability of temporary structures. The new German standard DIN 18218:2010-01 [16] for the design of formwork was recently issued and includes a simplified concept for the realistic calculation of the pressure on formwork based on the studies presented.

When using highly flowable concretes, the implementation processes of the structural work change considerably compared with the use of concretes of consistency classes F1 to F4. In particular, due to the changed structure of pro-

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cedures and the requirements regarding safety at work, rearrangement of the working systems in the on-site realization becomes clear. Owing to this initial situation, construction management-related aspects were also examined within the scope of the aforementioned research project. The objectives were to develop practical assistance for the creation of a risk assessment during concreting, to draft recommendations for organizing the processes on the construction site, with a focus on the concreting work, to develop the basis for a documentation system for the concreting process and to select criteria for suitable formwork.

2 Modelling the pressure of fresh concrete

The typical development of the pressure of fresh concrete on vertical formwork during the casting of a member is shown in Fig. 1. The casting rate is assumed to be constant and the concrete production continuous. For the design of vertical formwork using two opposite formwork panels, the maximum pressure of fresh concrete is of particular interest. If the formwork panels are supported on only one side of the element without formwork ties, the pressure distribution over the height of the formwork is also of interest.

Initially, hydrostatic pressure $\sigma_{h,hydro}$ must be assumed in section H due to the low inner friction of the fresh concrete plus the dynamic impact during casting. The chemical-physical processes in the fresh concrete increase the internal friction of the concrete. This friction can be characterized by the yield strength of the concrete, which depends on the total vertical stress in addition to the age of the concrete. The material parameters of the inner friction are – in a similar way to soil mechanics – the cohesion and the angle of internal friction. These parameters control the ratio between the horizontal and vertical pressure in the formwork and hence the maximum formwork pressure.

The increase in the pressure slows down as casting progresses and with the concrete height h. The maximum pressure $\sigma_{h,max}$ is located at height h_{max}.

The subsequent decrease in the pressure of fresh concrete is caused by the structural build-up of the concrete as well as the decrease in the pore water content due to the thixotropic build-up at rest and the onset of hydration. A reduction in the inner strain condition (the strain is a result of the elastic deformation of the formwork caused by the maximum pressure) must be realized through shrinkage of the concrete, a horizontal deformation or by releasing the formwork [8]. Once the concrete is in the state of final setting (with setting time t_E), no support by the formwork is necessary anymore. This behaviour was confirmed in the present research project [7], using stiff and soft formwork in the large-scale tests.

In general, for the design of formwork and falsework, only the loads in the section $h_E = v \cdot t_E$ need to be considered because of the ductile behaviour of the construction. The development of the concrete level during the concreting implies different load cases. However, the maximum pressure $\sigma_{h,max}$ is of primary importance.

In the following, a new analytical model for the calculation of the maximum pressure of fresh concrete $\sigma_{h,max}$ asserted by highly flowable concretes will be presented. Assuming a constant casting rate v, the normalized maximum pressure of fresh concrete $\bar{\sigma}_{h,E,max}$ is:

$$\bar{\sigma}_{h,E,max} = \frac{\sigma_{h,max}}{v \cdot t_E \cdot \rho_c \cdot g} = \frac{\sigma_{h,max}}{v \cdot t_E \cdot \gamma_c} = \frac{\sigma_{h,max}}{h_E \cdot \gamma_c} = \frac{\sigma_{h,max}}{\sigma_{h,E,hydro}} \quad (1)$$

The value $\bar{\sigma}_{h,E,max}$ represents the maximal horizontal pressure of fresh concrete $\sigma_{h,max}$ divided by the maximum hydrostatic pressure at height $h_E = v \cdot t_E$ using the specific concrete weight $\gamma_c = \rho_c \cdot g$, with density ρ_c and gravity constant g. The setting time t_E is based on the Vicat penetration test according to DIN EN 480-2:2006-11 and is equal to the initial setting time according to ASTM C403/C403M-05. A more practical alternative is the setting time $t_{E,KB}$ according to the setting-bag test in DIN 18218:2010-01 [16]. The final setting state occurs when the indentation of a thumb in the concrete is < 1.0 mm (with a force of 50 N), which corresponds to a compressive strength < 50 kPa. The correlation between $t_{E,KB}$ and t_E is:

$$t_E \approx 1.25 \cdot t_{E,KB} \quad (2)$$

If the value $\bar{\sigma}_{h,E,max}$ is given, the maximum pressure of fresh concrete can be calculated according to Eq. (3), with the casting rate v and the setting time t_E:

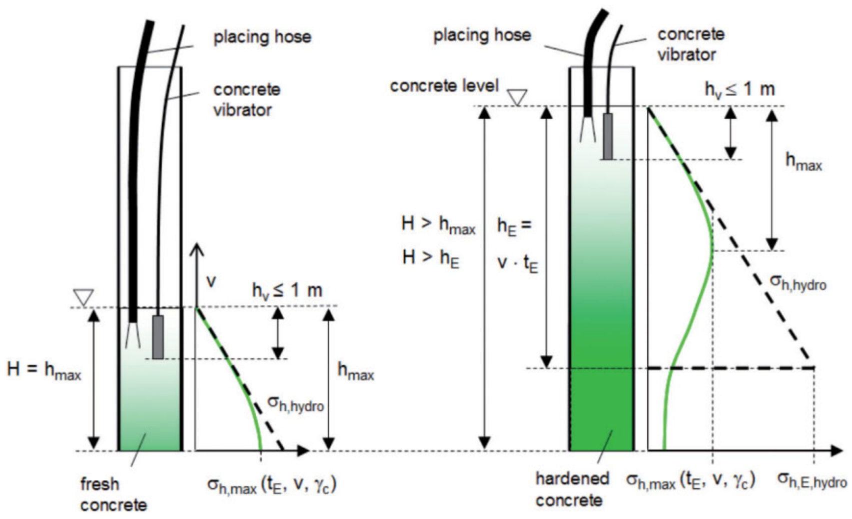

Fig. 1. Typical distribution of pressure of fresh concrete during casting

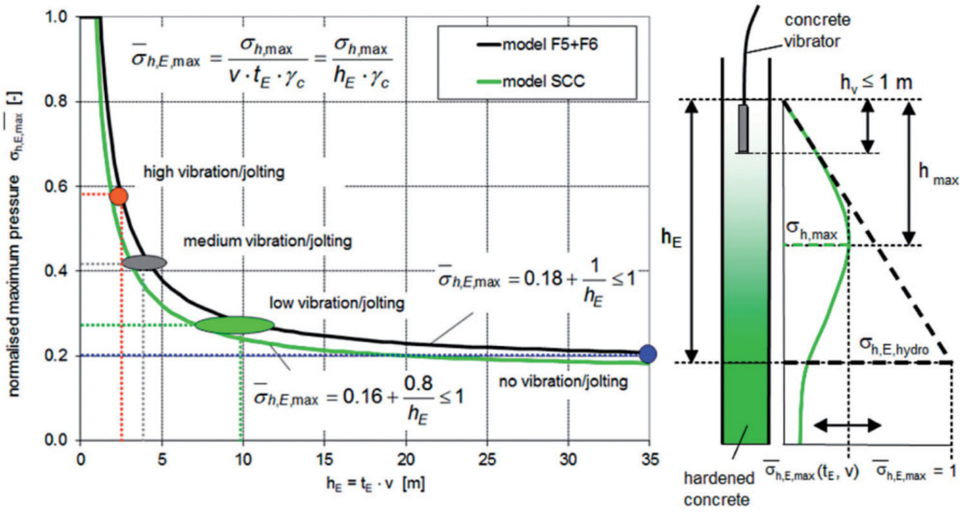

Fig. 2. Development of the normalized maximum pressure $\bar{\sigma}_{h,E,max}$ asserted by highly flowable concretes

$$\sigma_{h,max} = \bar{\sigma}_{h,E,max} \cdot v \cdot t_E \cdot \gamma_c \tag{3}$$

A proposal for $\bar{\sigma}_{h,E,max}$ was developed based on experimental tests on small concrete samples and full-scale tests (see [1]). For each consistency class, the small-scale tests showed that the value $\bar{\sigma}_{h,E,max}$ is to a large extent independent of the concrete design, assuming the same boundary conditions such as formwork stiffness and vibration [1]. Frequent vibrations have a significant influence on $\bar{\sigma}_{h,E,max}$. Therefore, for each consistency, the value $\bar{\sigma}_{h,E,max}$ is not assumed to be constant in the model (if concreting from the top), but depends on the height $h_E = v \cdot t_E$ and consequently considers the influence of the compacting technology and external vibrations on the pressure of fresh concrete – see Fig. 2 and Eqs. (4) and (5):

Consistency classes F5 and F6:

$$\bar{\sigma}_{h,E,max} = 0.18 + \frac{1}{h_E} \leq 1 \quad (h_E \text{ in [m]}) \tag{4}$$

SCC:

$$\bar{\sigma}_{h,E,max} = 0.16 + \frac{0.8}{h_E} \leq 1 \quad (h_E \text{ in [m]}) \tag{5}$$

The lower the value h_E, the lower the distance between the position of the dynamic impact caused by the compacting technology (h_v) and the position of the maximum pressure of fresh concrete (h_{max}), provided the vibration depth h_v does not exceed 1 m. Because of the reduction in the inner friction resistance close to the maximum pressure, the normalized pressure of concrete $\bar{\sigma}_{h,E,max}$ increases as h_E decreases. By contrast, a larger h_E value will decrease the influence of vibration and hence reduce the value $\bar{\sigma}_{h,E,max}$.

For consistency classes F5 and F6, no significant differences between $\bar{\sigma}_{h,E,max}$ values were measured in the material test. Hence, the model was chosen similarly. If height h_E is approx. 2.5 m, vibration must be assumed to exert a significant influence. In this case the value $\bar{\sigma}_{h,E,max}$ = 0.58, measured in the material test with direct vibration, is implemented in the model. If $h_E \approx 4$ m, a high influence is still expected and $\bar{\sigma}_{h,E,max}$ = 0.41 is assumed in the model. The influence of compaction can be neglected if h_E = 10 m. If the age of the concrete exceeds t_E, the pressure of fresh concrete cannot be increased, even with strong and constant vibration. Therefore, the upper limit of the normalized pressure is $\bar{\sigma}_{h,E,max}$ = 1.0.

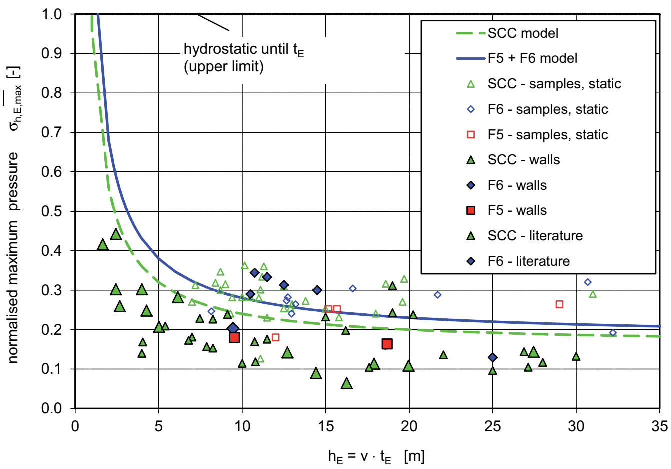

Fig. 3. Proposed normalized pressure and measured normalized pressure asserted by highly flowable concrete

For SCC, the influence of vibration – as a result of the casting process – on the pressure of fresh concrete is much lower compared with the vibrated concretes. Hence, the $\bar{\sigma}_{h,E,max}$ values of SCC were found to be lower – see Eq. (5).

The friction between concrete and formwork or reinforcement can be reduced significantly by vibration. As concretes with consistencies F5 and F6 are compacted with intense vibration, the pressure-reducing influence of the silo effect is not considered explicitly in the analytical model. Moreover, for SCC, the risk of vibrations resulting from construction operations cannot be excluded. However, positive effects can be introduced in the calculation of the model (un)certainties, which are used for calibrating the design values. In Fig. 3, calculated $\bar{\sigma}_{h,E,max}$ values are compared with the results of different measurements based on the maximum pressure of concrete; in general,

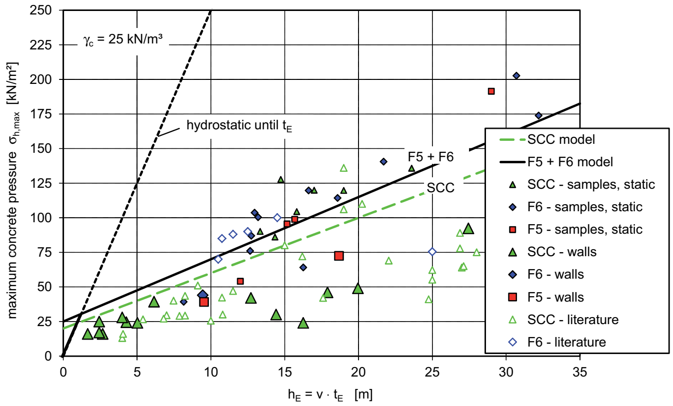

Fig. 4. Pressure of fresh concrete $\sigma_{h,max}$ according to the analytical models and measured pressure

there is a good fit. However, the test results are often considerably lower than the calculated values, especially if the loss of workability of the concretes was high (not appropriate for practical applications). It must be considered that some test results would be higher if the concrete level had increased further. That the model results were exceeded can be explained by unusually high vibration during the casting process.

Fig. 4 presents the maximum horizontal pressure $\sigma_{h,max}$, inserting Eqs. (4) and (5) in Eq. (3). The pressure of fresh concrete varies linearly with the casting rate v and the setting time t_E. Assuming γ_c = 25 kN/m³ leads to Eqs. (6) and (7):

consistency classes F5 and F6:

$$\sigma_{h,max} = 25 \text{ kN/m}^2 + 4.5 \cdot v \cdot t_E \leq \sigma_{h,E,hydro} \quad (6)$$

SCC:

$$\sigma_{h,max} = 20 \text{ kN/m}^2 + 4.0 \cdot v \cdot t_E \leq \sigma_{h,E,hydro} \quad (7)$$

The hydrostatic concrete pressure $\sigma_{h,E,hydro} = v \cdot t_E \cdot \gamma_c$ is a theoretical upper limit value. However, for practical applications it should be considered as a minimum value, allowing variation in the operational process, e.g. a high local casting rate v_{local} compared with the calculated mean casting rate v. This minimum value should be considered with 25 kN/m² for concrete consistencies F5 and F6 and 20 kN/m² for SCC, assuming for the latter a local impact down to a depth of 0.8 m. If vibration is excluded, Fig. 4 shows good correlation between the analytical model and the test results. The model is verified for a casting rate of up to 8 m/h, a casting height of up to 20 m and a setting time of between 5 and 20 h. Assuming, for example, a casting rate of 2 m/h and a setting time of 7 h, the calculated maximum formwork pressure for SCC is 76 kN/m².

The actual pressure on the formwork for narrower walls and columns containing dense reinforcement could be significantly lower than the model values due to the silo effect. An analytical model explicitly incorporating the friction between concrete, formwork and reinforcement is presented by *Graubner & Proske* [8, 11, 17]. Based on this model, a higher casting rate would be possible in some cases.

3 Proposed formwork design approach

The bilinear pressure distribution in line with DIN 18218:1980-09 (applicable with DIN EN 12812:2004-09) was chosen for the design of the formwork and is presented in Fig. 5. Accordingly, the pressure of fresh concrete must be assumed to be hydrostatic until the maximum horizontal pressure $\sigma_{h,max}$ and the respective height h_s is reached. Further, the horizontal pressure is constant in the remaining section of $h_E = v \cdot t_E$. Once the concrete reaches an age of t_E, no pressure need be considered anymore. This simplified distribution has the advantage of applying the maximum pressure over a large distance. In reality, the position of the maximum pressure of fresh concrete h_{max} is influenced by a number of parameters, e.g. formwork stiffness or early shrinkage, and cannot be predicted exactly. A significantly lower pressure than $\sigma_{h,max}$ occurs below the section of h_{max}. However, for the design of formwork, the "safe" bilinear distribution is advantageous, considering the variation in setting time t_E, casting rate v and height h_E (see Fig. 5). Assuming hydrostatic pressure up to h_s, un-

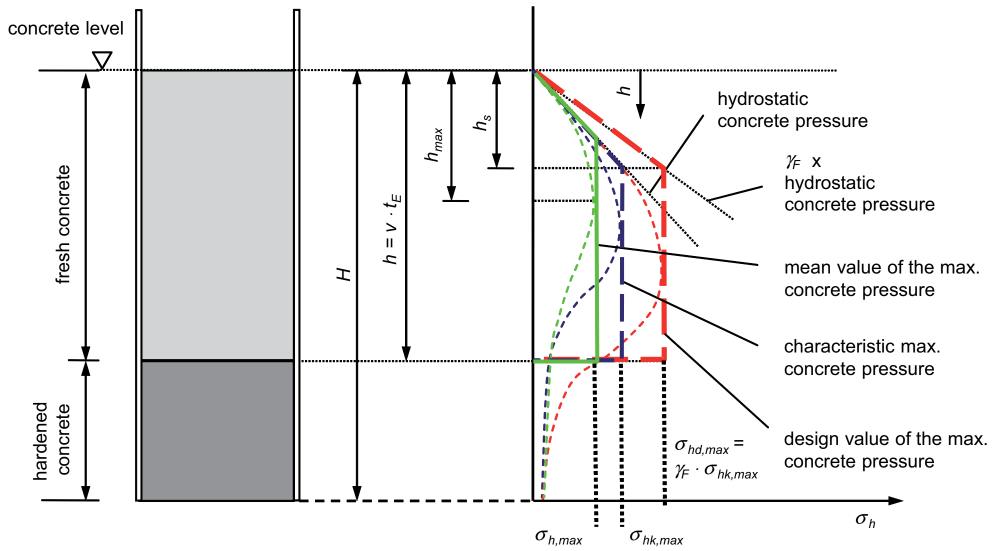

Fig. 5. Distribution of the horizontal pressure of fresh concrete on formwork

certainties due to discontinuous casting rate and vibrations can be considered.

The calculated pressure of concrete $\sigma_{h,max}$ based on the bilinear distribution and Eqs. (6) and (7) is compared with measured values in Fig. 6. The good correlation between the test results and the calculations can be seen.

The design of formwork and falsework must also fulfil requirements regarding the safety and reliability of the construction. According to the semi-probabilistic safety concept, the design value of the pressure of fresh concrete σ_{hd} can be calculated with Eq. (8). The characteristic value σ_{hk} must be multiplied by the partial safety coefficient γ_F:

$$\sigma_{hd} = \sigma_{hk} \cdot \gamma_F \tag{8}$$

The characteristic value and the partial safety factor take into account the variation in the model parameters (e.g. casting rate v) and uncertainties in the calculation model and hence limit the probability of failure of the construction. Like the analytical model (approx. mean value), the distribution of the characteristic pressure σ_{hk} and the design value σ_{hd} is chosen to be bilinear (see Fig. 5).

The characteristic value of the maximum pressure $\sigma_{hk,max}$ was calculated using the full probabilistic method (level III) according to DIN 1055-100:2001-03, Appendix B, and the Monte Carlo method. The calculation of $\sigma_{hk,max}$ was based on the analytical models (see companion paper [1]) as well as the large-scale tests. The partial safety factor for the load in the ultimate limit state was defined as $\gamma_F = 1.5$. The limit state function for the calibration of the characteristic pressure of fresh concrete was developed from the relation between impact E and resistance R.

Compared with the collapse of a multi-storey building or a nuclear power plant, the negative effects of a formwork collapse for persons and property are relatively moderate. Hence, the failure probability in the ultimate limit state was defined as $P_f = 10^{-4}$. The basic variables of the load are summarized in Table 1. The statistical parameters were derived from the experimental tests and values found in the literature. The casting rate v has the biggest influence on the variation, with a variation coefficient of $V = 0.25$, assuming a low casting rate of 1 m/h and a standard derivation of 0.25 m/h. The reason for this is mainly insufficient control of the casting process. The variation coefficient will decrease at higher casting rates. For $v = 2$ m/h, a variation coefficient of $V = 0.20$ was assumed and gives a standard derivation of 0.4 m/h. A high variation is seen in the setting time t_E. In particular, the variation of the mix constituents using high-performance additives increases the variation coefficient of t_E. Furthermore, the uncertainties caused by the setting tests cannot be neglected. The variation coefficient for SCC is higher than

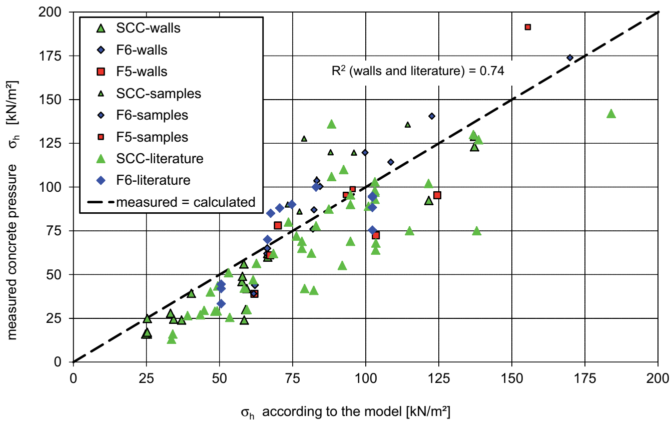

Fig. 6. Correlation between the pressure of fresh concrete according to the analytical model and measured pressure

Table 1. Basic variables for calibrating the characteristic pressure of fresh concrete

Basic variable SCC, consistencies F6 and F5			**Mean value** m	**Standard deviation** S	**Variation coefficient** V
					[–]
Specific concrete weight	γ_c	[kN/m³]	23.5	0.5	0.021
Casting rate	v	[m/h]	1.0	0.25	0.25
			2.0	0.40	0.20
Internal force variable	c	[–]	1.0	0.10	0.10
SCC					
Setting time of the concrete	t_E	[h]	7.0	1.75	0.25
Model uncertainties	θ_E	[–]	0.77	0.21	0.27
Additional factor	u	[–]	1.15	0	0
Consistency F6					
Setting time of the concrete	t_E	[h]	7.0	1.4	0.20
Model uncertainties	θ_E	[–]	0.96	0.19	0.20
Additional factor	u	[–]	1.00	0	0
Consistency F5					
Setting time of the concrete	t_E	[h]	7.0	1.4	0.20
Model uncertainties	θ_E	[–]	0.75	0.10	0.14
Additional factor	u	[–]	1.10	0	0

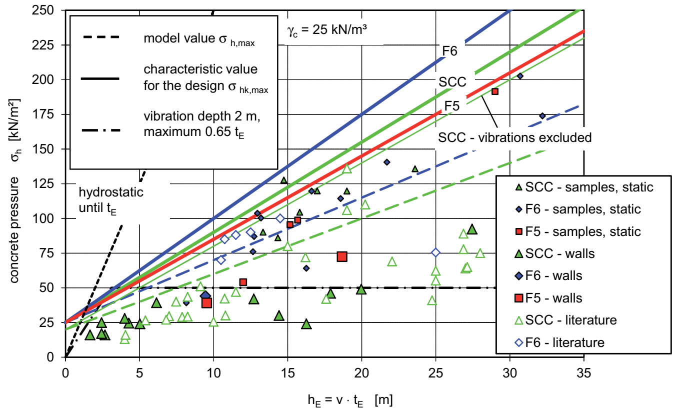

Fig. 7. Characteristic pressure of fresh concrete for the design $\sigma_{hk,max}$, measured values and analytical model

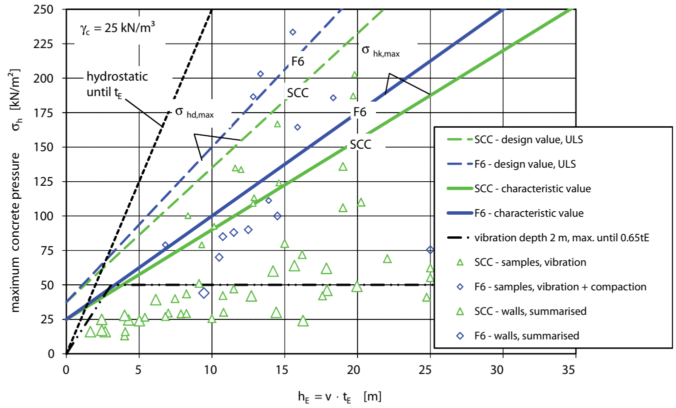

Fig. 8. Design values of pressure of fresh concrete $\sigma_{hd,max}$ and characteristic values $\sigma_{hk,max}$

for consistencies F5 and F6 because of the higher sensitivity of SCC.

The model uncertainties θ_E were calculated based on the measured and calculated pressures and depending on the consistency class. Besides the basic variables, e.g. specific concrete weight γ_c and the calculation of the internal force variables, an additional factor u was introduced. This factor considers other uncertainties such as unintentional vibrations during casting, the geometry of the member or the mix design. The impact of strong and constant vibration is an exceptional load and not considered in the calibration initially.

Eqs. (9) to (11) were determined for calculating the maximum characteristic pressure:

SCC:

$$\sigma_{hk,max} = h_s \cdot \gamma_c = \left(1m + 0.26 \cdot v \cdot t_E\right) \cdot \gamma_c \tag{9}$$

consistency F6:

$$\sigma_{hk,max} = h_s \cdot \gamma_c = \left(1m + 0.30 \cdot v \cdot t_E\right) \cdot \gamma_c \tag{10}$$

consistency F5:

$$\sigma_{hk,max} = h_s \cdot \gamma_c = \left(1m + 0.24 \cdot v \cdot t_E\right) \cdot \gamma_c \tag{11}$$

Assuming $\gamma_c = 25$ kN/m³ leads to Eqs. (12), (13) and (14):

SCC:

$$\sigma_{hk,max} = 25\ \mathrm{kN/m^2} + 6.5 \cdot v \cdot t_E \tag{12}$$

consistency F6:

$$\sigma_{hk,max} = 25\ \mathrm{kN/m^2} + 7.5 \cdot v \cdot t_E \tag{13}$$

consistency F5:

$$\sigma_{hk,max} = 25\ \mathrm{kN/m^2} + 6.0 \cdot v \cdot t_E \tag{14}$$

According to the analytical model, the characteristic values for SCC are lower than for consistency F6. The values for consistency F5 are lower than those of both SCC and F6 because of the lower model uncertainties of F5 and the lower spread of t_E. Using SCC and neglecting the influence of unintended vibrations, the pressure of SCC is lower than the load of the vibrated concrete. In this case the higher workability of SCC has less influence on the pressure of fresh concrete than the mechanical compaction.

The experience on construction sites shows that a vibration depth of 2 m cannot be excluded. However, the material tests showed that a change in the concrete consistency due to vibration can be achieved up to a concrete age of approx. $0.65 \cdot t_E$ and a depth of $0.65 \cdot h_E$. Fig. 7 shows that the pressures accounting for this additional requirement are mostly included in the characteristic equation. Further, how the pressure of fresh concrete is influenced by any impacts of the concrete skip or the pump hoses or continuous external vibration can be seen as special loads. Assuming a maximum failure probability of $P_f = 10^{-2}$ in this situation, an additional factor u according to the probabilistic calculation is 1.65 for SCC (replacing u = 1.15). Hence, in case of a special load, a pressure increase of 45 % can be accepted. For consistencies F6 and F5, an increase of 40 and 50 % respectively is acceptable.

For SCC and consistency F6, the design values of the maximum pressure $\sigma_{hd,max}$ (calculated with $\gamma_F = 1.5$ and the mean values of the input parameters) are presented in Fig. 8. The test results with intense vibration do not exceed the design vales significantly. A formwork collapse is also unlikely in this case because the actual load must be compared with the formwork resistance, which is enhanced by the corresponding partial safety factor. Therefore, such special loads are considered adequately in the design model.

4 Construction management-related aspects

The construction management-related aspects were selectively directed at the subject of the cost-effectiveness regarding the execution of the construction work as well as towards the matter of safety at work.

The obligations of employer and employee with regard to safety at work have changed decisively as a result of Directive 89/391/EEC [18], issued by the Council of the European Community, coming into force. Regarding the creation of a risk assessment, which in Germany is compulsory for all employers in accordance with cl. 5 of the Labour Protection Act (Arbeitsschutzgesetz, ArbSchG [19]) and which must be available on every construction

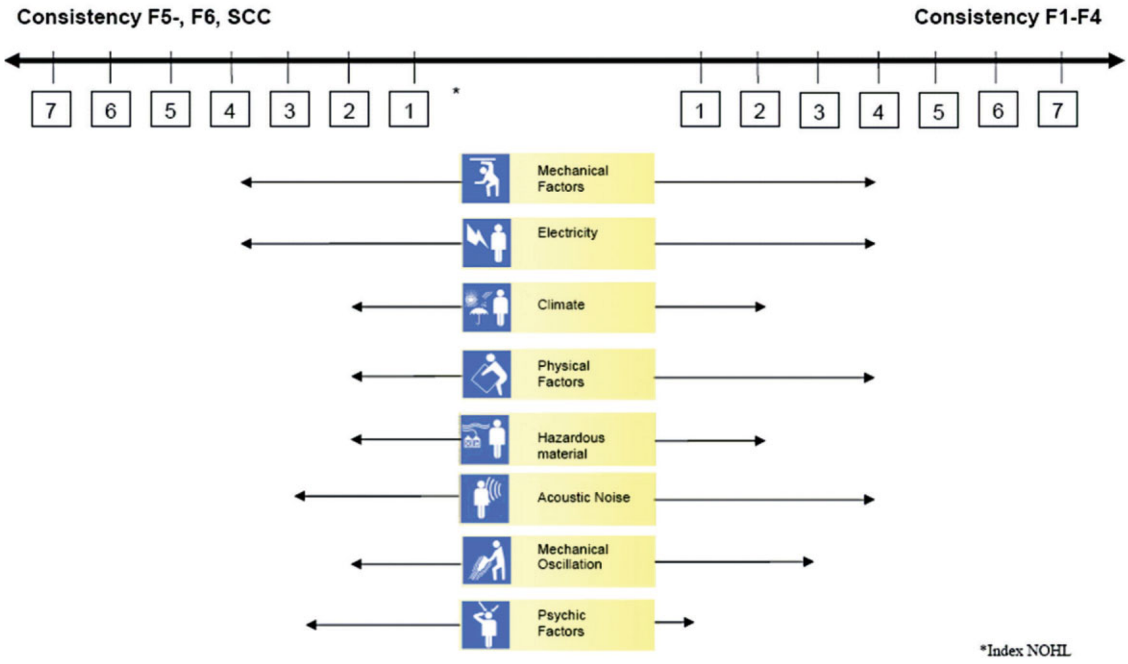

Fig. 9. Basic measured values for risk assessment during casting process

site, risk factors within the scope of building site investigations during the concreting process were recorded and assessed by the Institut für Baubetrieb (Institute of Construction Technologies & Management). The use of standard concretes with consistencies F1 to F4 and the use of highly flowable concretes were examined. The risk assessment was carried out in accordance with the proven procedure according to *Nohl* which is recommended by BG Bau (Employers' Liability Insurance Association for the Construction Industry).

Based on the results of building site investigations, integrated basic measured values of the risk evaluation for concreting were developed in a comparison of work systems in the area of standard concretes with consistencies F1 to F4 and highly flowable concretes, which are shown in Fig. 9.

The arrows in Fig. 9 show the level of risk using workable concretes compared with conventional concretes. The results form a valuable basis for the creation of a risk assessment for construction sites whose individual steps can be taken from "Recommendations for the compilation of a risk assessment with the use of formwork" [20].

Apart from the aspects relevant to safety at work, the processes were examined in great detail with regard to their cost-effectiveness. The working time study for this purpose was carried out according to REFA [21] methods. Regarding the use of highly flowable concretes, it can be said that for actual concreting procedures, many construction companies currently have little or no data available from post-calculation analyses or working time studies [22].

Evaluation of the working time studies carried out allows a weak-point analysis of the concreting procedures to be made. What is particularly interesting here is the result when using SCC. The following weak points were determined:

– Too many workers in the construction crew: for the concreting procedure, the building contractor used the same amount of personnel required for vibrated concrete. The potential for reductions was not exploited.
– Inadequate monitoring of the mean casting rate: for regulating the pressure of fresh concrete, the mean casting rate was not monitored. Casting breaks that might have been required during concreting were not heeded.
– Unsatisfactory coordination of the so-called supply and consumption rhythm: the call-off order of the fresh concrete and the entire delivery structure were insufficiently coordinated with the concrete suppliers and there was also poor coordination during concreting itself.
– Unsatisfactory formwork construction: in one case, the formwork construction (door block-out) was not designed to withstand the higher concrete pressure. This resulted in fresh concrete escaping from the formwork, which caused substantial damage (see Fig. 10).

Fig. 10. Damage on a construction site: the formwork was inadequately designed and constructed and so did not bear up to the pressure of fresh concrete!

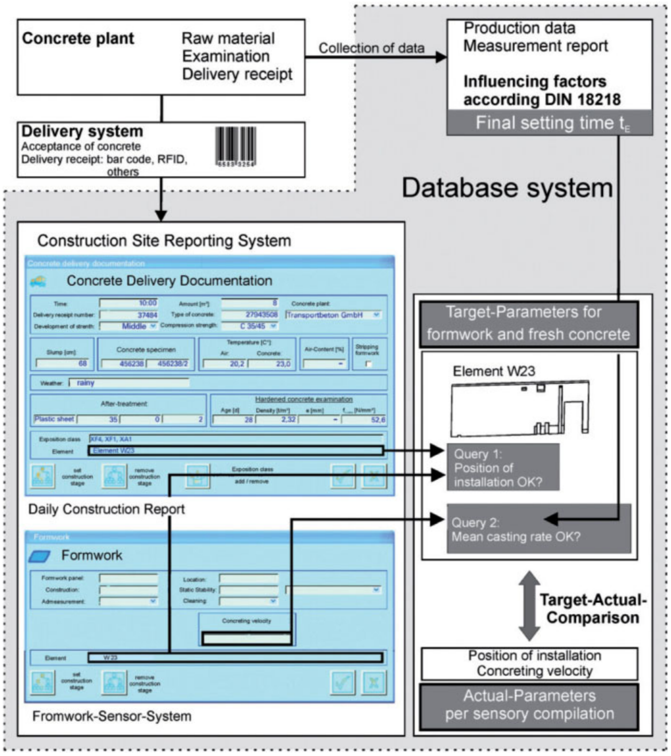

Fig. 11. Basic structure of a database system for documenting the casting process

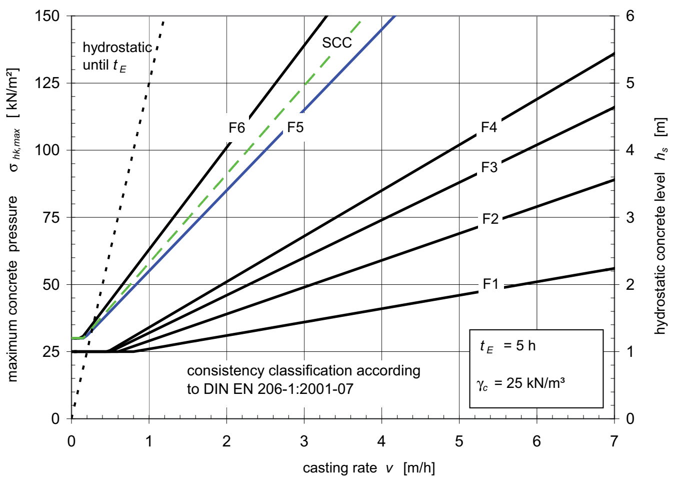

Fig. 12. Maximum lateral pressure of fresh concrete $\sigma_{hk,max}$ according to DIN 18218:2010-01; setting time of concrete: 5 h

Furthermore, in the context of the research project [15], the basic structure of a database system was developed for documenting the concreting procedure. A permanent target–actual comparison of different parameters should be possible here (see Fig. 11). The "mean casting rate" as well as "position of installation" values were revealed. The poly-sensory systems, e.g. image processing systems, already developed and currently being developed at the Institut für Baubetrieb show the potential for supplying the relevant actual data both reliably and promptly. The controlling elements implemented should send immediate corresponding warning messages to the construction site management in the case of any inadmissible deviations so that process control takes place in time.

The construction management-related investigations have revealed a lack of data on construction site experience concerning the use of highly workable concrete. Among other things, this is the reason for the scatter of the basic variables for the calibration of the characteristic pressure of fresh concrete (see Table 1). In particular, the casting rate during the casting process is subject to high fluctuations.

A precise control and regulation system (see Fig. 11) has the potential to minimize the scatter of the basic variables. These construction management measures contribute to reducing the rather high design value for fresh concrete pressure (see Fig. 8).

5 Pressure of fresh concrete to DIN 18218:2010-01

At the request of the construction industry, the standard DIN 18218 "Pressure of fresh concrete on vertical formwork" was improved by DIN committee NA 005-07-11 AA. The intention was to integrate concrete with consistencies F5, F6 and SCC into the standard. The provisions for consistency classes F1 to F4 were not modified significantly, compared with the former standard. The proposal presented here for the calculation of the pressure of fresh concrete was implemented in DIN 18218:2010-01 [16] mostly unchanged.

In Fig. 12 the maximum pressure $\sigma_{hk,max}$ according to DIN 18218:2010-01 is plotted against the mean casting rate for the final setting time t_E = 5 h, γ_c = 25 kN/m^3 and concrete placed from the top. The absolute minimum pressure is defined as 30 kN/m^2.

To determine the final setting time t_E, the concrete must include all chemical additives. The temperature of the concrete sample may not exceed the expected concrete temperature on a construction site. For practical applications, determining the setting time with the setting-bag test according to DIN 18218:2010-01 is recommended.

Compared with the pressure for concretes with consistencies F1 to F4, the pressure for highly flowable concretes is considerably higher. In addition to the different rheological behaviour connected with the development of the inner friction, the higher sensitivity of the concrete and the consideration of higher uncertainties are responsible for this difference. If SCC is placed from below by pumping, the design pressure of fresh concrete must be assumed to fully hydrostatic, multiplied by γ_F = 1.5 according to DIN 18218:2010-01. The material tests showed at most 15 % higher values compared with the hydrostatic pressure. However, the committee decided to apply the relatively high factor γ_F = 1.5 to the hydrostatic pressure in order to consider all casting situations and processes with the same safety factor.

6 Concluding remarks

The pressure of highly flowable concretes is mainly influenced by the casting rate, the setting behaviour of the concrete, the specific concrete weight and the member height. In addition, the pressure of fresh concrete can be increased significantly by the dynamic impact of the concreting plant and external vibration as a result of the construction work. The friction between the concrete, the formwork surface and reinforcement can reduce the pressure of fresh concrete. According to the proposal for the calculations, there is generally no need to calculate using the hydrostatic pressure, especially if the building element is comparatively tall. Vibrated concrete with consistency F6 applies the highest maximum pressure $\sigma_{hk,max}$ of all consistencies.

The most important parameter controlling the pressure of fresh concrete on construction sites is the casting rate. Furthermore, a reduction in the pressure of fresh concrete can be achieved by reducing the setting time. Considering the concrete technology, this parameter is mainly influenced by type of cement, water-cement ratio and chemical admixtures. It should be noted that the setting time cannot capture the development of the inner friction exactly and hence the pressure of fresh concrete.

From the point of view of construction practice, it must be further said that the complex theme of risk assessment regarding the use of F1 to F6 consistencies and SCC has to be carried out more intensively, both by construction companies and on building sites. In the context of the research projects, new insights were gained concerning the risk factors during concreting work in the differentiation between standard concretes with consistencies F1 to F4 and highly flowable concretes. In particular, it was determined that due to insufficient experience in handling highly flowable concretes, the psychological strain on construction site personnel rose considerably. Furthermore, clear deficits have been determined with regard to structural and procedural organization in construction practice when using highly flowable concretes. For this reason, careful working processes are necessary in the context of the planning procedures for the construction projects.

A more exact statement about the spread of different influencing variables on the pressure of fresh concrete regarding existing uncertainties on construction sites, e.g. mean casting rate, can be made with continuing investigations in the process configuration of working time studies.

For a defined failure probability, the design value of the pressure of fresh concrete is primarily influenced by the variation of the model parameters casting rate and setting time. The insufficient experience of the personnel in the handling of highly flowable concretes significantly increases the uncertainties, too. Further research into this subject is necessary.

The results of this research project were incorporated in the improved standard DIN 18218:2010-01.

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Notation

a	spread in flow-table test [mm]
g	gravity constant [m/s^2]
h	distance from the concrete level to a certain location [m]
h_E	distance from the concrete level to the location where the concrete has achieved the final setting [m]
h_S	hydrostatic height corresponding to the maximum pressure [m]
H	height of casting section [m]
t_E	final setting time of the concrete [h]
v	mean casting rate [m/h]
V	variation coefficient [–]
γ_F	partial safety factor [–]
ρ_c	concrete density [g/cm^3]
σ_h	horizontal (lateral) pressure of fresh concrete [kN/m^2]
$\sigma_{h,max}$	maximum horizontal pressure of fresh concrete [kN/m^2]
$\sigma_{h,max}$	maximum horizontal pressure of fresh concrete [kN/m^2]
$\bar{\sigma}_{h,E,max}$	normalized maximum pressure of fresh concrete [–]

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