Abstract

FORMWORK PRESSURE ASSERTED BY HIGHLY WORKABLE CONCRETES

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1 Research objective

The research object of the project was the formwork pressure asserted by highly workable concretes, in order to eliminate the restraints in the application of this innovative material in short-term. Selected questions regarding the main application fields of the highly workable concretes and vertical formwork have been answered.

A simplified model for the calculation of the fresh concrete pressure of concretes with consistency classes F5, F6 and self-compacting concrete should be the final result of the research project. The model was to integrate in the semi-probabilistic safety concept for the design of the formwork.

Different scientists of German research institutions have been united to a group of researchers, in order to concentrate the competence in the area of the fresh concrete pressure. Due to the extent and the complexity of the tasks, the research project was divided into five subprojects (A to E), which were partitioned according to the respective capacity. The research objects of the subprojects are summarized in the following.

Subproject A: Influence of the rheological parameters on the fresh concrete pressure

RWTH Aachen, Institut für Bauforschung (ibac)
Prof. Dr.-Ing. W. Brameshuber, Dipl.-Ing. C. Bohnemann

- developement of mixture proportions for the highly wokable concretes (consistency class F5, F6 and SCC), concretes fullfill defined fresh concrete properties
- determination of the rheological parameters of the refrence mixtures and the time dependent behaviour
- pressure measurements on high walls, analysis of the influence of the rheological parameters and the casting technology on the fresh concrete pressure

Subproject B: Simulation and large scale experiments

(1) Institut für Bauverfahrens- und Umwelttechnik, Trier
(2) Universität Karlsruhe (TH), Institut für Massivbau und Baustofftechnologie
Prof. Dr.-Ing. H. Beitzel[(1)], Prof. Dr.-Ing. H. S. Müller[(2)], Dipl.-Ing. M. Beitzel[(2)]

- analyses of the time dependent development of the fresh concrete pressure on lateral formwork, simulation of the casting process using model formwork and large scale experiments (walls with heigt of 3 m)
- measurement of the fresh concrete pressure, the concrete consistency, the concrete temperature and the formwork deformation in order to provide a scientific basis from which a grounded design model can be established
- investigation of the influence of the casting rate, the formwork geometry and the concrete temperature on the formwork pressure

Subproject C: Friction and deformation behaviour of the fresh concrete and modelling of the lateral formwork pressure

Technische Universität Darmstadt, Fachgebiet Massivbau
Prof. Dr.-Ing. C.-A. Graubner, Dr.-Ing. T. Proske

- friction between fresh concrete with highly workable consistency (F5, F6 and SVB) and the formwork surface as well as the friction resistance between fresh concrete and the reinforcement through experimental studies.
- influence of the inner friction of the fresh concrete on the formwork pressure through experimental studies
- development of an analytical model to be used in practice to calculate the concrete pressure on vertical formwork

Subproject D: Influence of vibration on fresh and young self-consolidating concrete and the resulting lateral pressure on rotational symmetric formwork systems

Technische Universität München, Department of Concrete Structures
Prof. Dr.-Ing. Dr.-Ing. E.h. K. Zilch, Dipl.-Ing. J. Lingemann, Dipl.-Ing. Ch. Stettner

University of Leipzig, Institute for Mineralogy, Crystallography and Material Science
Jun.-Prof. Dr.-Ing. F. Dehn, Dipl.-Ing. K. Pistol, Dipl.-Ing. A. König

- theoretical studies to the stability of rotationally symmetric formwork systems
- examination of the influence of vibrations on the material properties and the structure of fresh and young self-consolidating concrete
- quantification of the influence of vibrations on the lateral pressure as well as the wave propagation of the vibration inside the concrete (using wall with length of 9 m)
- influence of the deformability of formwork on the development of lateral pressure (the formwork elements with different stiffness)

Subproject E: Subproject E - Issues in the area of “Construction Management and Technology”

Technische Universität Darmstadt, Institut für Baubetrieb
Prof. Dr.-Ing. Christoph Motzko, Dipl.-Ing. Erik Boska

- development of supporting tools for the preparation of a risk assessment during concreting,
- recommendations for the design of processes on the construction site with the main emphasis on the field of concreting,
- development of a basis for a documentation system for the concreting process,
- selection criteria for suitable formworks.

Fig. 1 shows the shematic procedure of the reseach project.

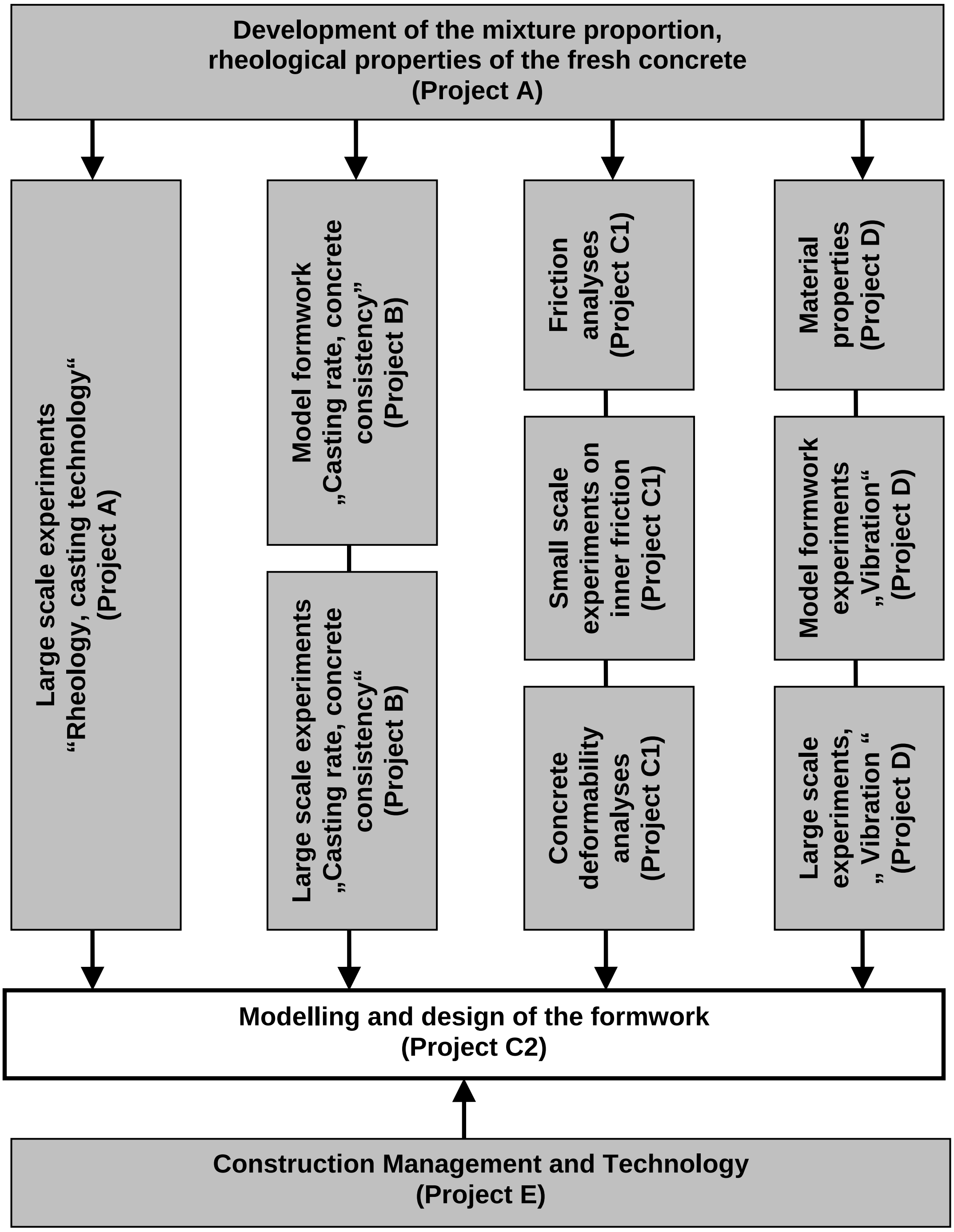

Fig. 1: Procedure of the research project

The project was coordinated by the Technische Universität Darmstadt, Fachgebiet Massivbau, Dr.-Ing. Tilo Proske.

2 Procedure

The realisation procedure of the subprojects is stated as follows.

Subproject A:

The investigations of the influence of the rheological properties on the fresh concrete pressure were carried out on model walls with the dimensions 3.30x2.56x0.24 m³. The fresh concrete pressure was determined as a function of the velocity of placing and the method of pouring of SCC compared with VC. The pressure was determined using load cells. The load cells were attached to the medium formwork element in a distance of 0.15 m, 0.75 m, 1.35 m and 2.55 m above the formwork bottom edge. The concrete was placed either with a concrete bucket from above or with a pump by using a special connection in the lower formwork area. The medium rates of the velocity of placing amount to 2 m/h and 10 m/h. At each first filling of the walls in the pre-casting plant the fresh concrete characteristics were determined. Additionally the solidification behaviour was investigated by Knead-Bag tests.

Subproject B:

The research project’s experiments formed the scientific foundation for deriving a general calculation method to describe the formwork pressure behaviour of fresh flowable concrete. At the same time, the link between the predominant concrete pressure and the related influencing parameters was recorded and scientifically settled.

The behaviour of fresh concrete pressure on vertical formwork was recorded and analysed through the simulation of a casting process on a medium sized wall component. At the same time, the absolute fresh concrete pressure, the consistency, the fresh concrete temperature as well as the resulting formwork deformations, inter alia, were all registered. Furthermore a precise examination of the influencing parameters, which are the casting rate, the formwork geometry and the fresh concrete temperature, was sought. As a last step, the results should be reviewed within the context of large scale experiments with a panel wall formwork.

Subproject C:

A testing apparatus was developed to analyse the friction and deformability of the fresh concrete. Using a fresh concrete sample 250x250x250 mm³, various levels of vertical stress were applied to determine the corresponding horizontal pressure and the surface friction. In the experimental studies, the influence of the concrete consistency, the rheological parameter, the casting rate and the formwork stiffness and vibration on the material properties as well as the formwork pressure was analysed systematically.

Simplified analytical models to calculate formwork pressure were developed from the experimental results. Subsequently, characteristic pressure values for the design of formwork constructions were derived using probabilistic methods. The statistical parameters of the basic variables were determined from the pressure measurements on high walls found in the experiments of all project partners and in literature.

Subproject D:

Considering the given basic formulations four mixtures have been prepared which differ in their viscosity (low / high viscosity) and in their type of concept (Powder Type/ Viscosity-Agent-Type). Using a vibrating table a velocity of 20 to 30 mm/sec was applied for one hour on a fresh concrete sample (500x250x250 mm³). After this, the determination of the rheological properties (flowability, viscosity) followed. They were compared to the values of an unexcited sample taken at the same time.

According to the results of the material experiments one mixture was chosen to examine the influence of vibration on formwork pressure. Several scaled walls (l=0,66 m, h=1,35 m) and one full scale wall (l=9,20 m, h =2,70m) have been casted with the chosen mixture. The influence of deformability on the development of formwork pressure was demonstrated by a single formwork element of the full scale wall, which had flexible bearing conditions. During the tests a pendulum (m=14,6 kg) was taken as source of impact excitation. Field measurements of accelerations on a conical formwork system caused by working process have been done to estimate the order of the magnitude of energy to be chosen in the experiment. So, the relationship between experiment and practice was established.

Subproject E:

The issues were dealt with on the background of empiric studies on building sites but also within the large scale experiment of the research group Subproject D in Leipzig, on theoretical considerations on the basis of own research results and theoretical considerations on the basis of scientific literature.

The research project „Recommendations for the design of processes on the construction site with the main emphasis on the field of concreting” was carried out on the basis of an analysis of critical points (SWOT Analysis). The required cognitions and the basis for the assessment of the endangering factors during the concreting were achieved by time studies in form of group work studies after REFA on the aforesaid building sites.

3 Results

Die Ergebnisse des Forschungsvorhabens sind aufgeschlüsselt nach Teilprojekten nachfolgend zusammengefasst. Die Ergebnisse zur Modellbildung und zum Bemessungskonzept (Projektteil C) wurden aufgrund der Folgerichtigkeit ans Ende gestellt.

Subproject A:

At the beginning of placing the SCC into the formwork the slump flow was amounted to 705 to 740 mm. The spread of the VC was averaged between 620 and 680 mm. The fresh concrete densities amounted to 2181 to 2328 kg/m³. The solidification times of the SCC were determined between 8.0 and 10.0 h and of the VB between 5.5 h and 6.5 h. The fresh concrete temperatures of these measurements were amounted to 22.1 to 28.6 °C.

In Fig. 2 the fresh concrete pressures at the lowest measuring point are represented for the investigations using the concrete bucket from above and a velocity of placing of 2 m/h.

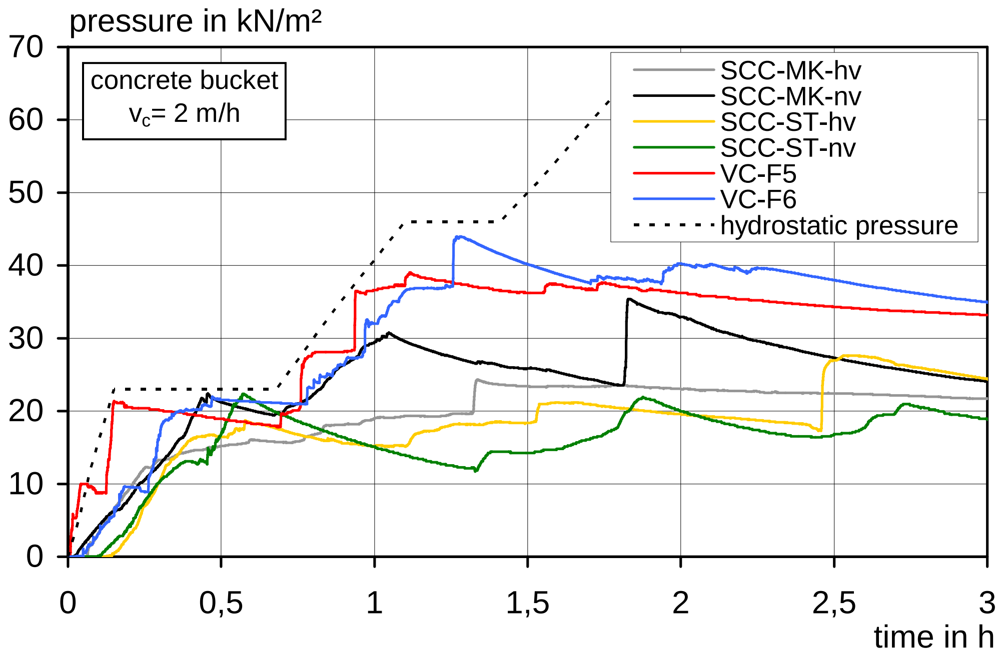

Fig. 2: Temporal development of the fresh concrete pressures at the lowest measuring point of the walls 1 to 6 for a velocity of placing of 2 m/h

The VC exhibit due to the compaction the highest fresh concrete pressures and lie within the range of the hydrostatic fresh concrete pressure. The fresh concrete pressures of the SCC types with a lower viscosity (nv) are larger than those of the SCC types with a higher viscosity (hv). An influence of the SCC type on the fresh concrete pressure cannot be ascertained since the pressures of the lower and higher viscosity mixes are nearly identical. In the time frame / time period between finishing the placing and solidification end t_E the fresh concrete pressure at the lowest measuring point declined to approximately 66 % of its maximum pressure.

Similar results show the pouring of SCC using a velocity of placing of 10 m/h. But the values of the fresh concrete pressures lie within the range of the hydrostatic fresh concrete pressure. By pouring the concrete using a pump from the bottom of the formwork and a velocity of placing of 2 m/h the fresh concrete pressures of both SCC types are almost identical for different viscosities. The values were determined within the range of the hydrostatic fresh concrete pressure. Even if the hydrostatic pressure is not achieved for the application of SCC with a pressure-free pouring using the concrete bucket from above and a velocity of placing of 2 m/h, nevertheless the calculation of formworks for concreting with pourable concretes should be proceeded for the hydrostatic pressure to ensure a sufficient security of the formwork for all pouring methods and velocities of placing.

Subproject B:

During an analysis of the influence of the casting rate on the formwork pressure, a significant difference could be established between 3.5 m/h and 7 m/h. This can primarily be attributed to the fact that at a casting rate of v = 3.5 m/h it was not possible, due to the formwork dimensions, to have a continual increase in the poured amount. Therefore, at the lower casting rates no significant vertical pressure, in terms of concrete being poured per time unit, was exerted on the formwork’s concrete. Furthermore it was confirmed that lower casting rates lead to longer time periods, during which the concrete can, due to a corresponding build up within the structure, develop a high shear resistance, which leads to lower formwork pressure readings. This effect is strengthened by the fact that the missing structural build up prevents an increase in the concrete’s yield stress with higher casting rates. However, the relationship between formwork pressure and casting rate cannot be solely derived from the behaviour of the pure physical matter. Mechanical phenomena, such as the impulses during the casting period must also be considered as they can lead to a further strain on the concrete within the formwork.

With regard to the influence of the formwork geometry, the large scale experiments revealed that the width did not have an effect on the behaviour of the fresh concrete pressure. In principle and as expected, the formwork pressure of the tested concrete increased in relation to the casting height. However, with regards to the behaviour of the vertical formwork pressure distribution, two different characteristics could be recognised. Dependant on particular heights, these resulted from an interplay between the concrete’s rheological properties, the casting rate and the hydration behaviour. A vertically linear formwork pressure pattern usually results from a concrete with lower thixotropy or high casting rates. However, a break in the results curve can sometimes be detected in concrete’s with higher thixotropy grades, or reduced casting rates.

During the testing period the fresh concrete’s temperature did not have any noticeable influence on the formwork pressure.

In relation to the chronological analysis of flowable concrete’s formwork pressure, the results demonstrated that the formwork pressure steadily increased during the initial casting period. At the end of the pouring period a variably pronounced decrease in the formwork pressure was observed. The primary cause of this is the concrete’s thixotropic properties as well as its hydration behaviour. Concretes with a lower thixotropy tend to have a slower pressure decrease compared to highly thixotropic concretes. This difference can be explained by the chronological development of the concrete’s yield stress. At the same time, chemical and physical processes are occurring during the hydration process, which also significantly influence the formwork pressure of flowable concrete.

Thixotropy must be considered first when assessing the value of the respective influences on the definitive pressure of fresh concrete. The concrete’s setting behaviour has a secondary role in this regard.

The development of a model formwork system was not necessary within the framework of the research mandate. In fact, one had already been constructed during a separate research project. Therefore, there was no such research requirement at the start of the research project.

Subproject D:

Based on the results of slump-flow and v-funnel test of all four samples a recurrence of liquefaction could be determined for each mixture. The viscosity (characterized by the v-funnel time) has changed considerably more than the flowability (characterized by the slump-flow). The recurrence of liquefaction could be determined until the samples gained plastic consistency.

The results of the small scale test have shown that an increase of formwork pressure until about 90% of initial pressure is possible with 15 pendulum impacts (E=13,3 Joule/ impact) before the concrete gets plastic consistency. By choosing a lower impact energy (E=3,3 Joule/ impact) the increase of formwork pressure was reduced to 60 % of the initial pressure. The sensitivity for an increase of pressure due to vibration decreases generally with the progression of setting.

During the procedure of the full scale test (Fig. 3) an increase of the formwork pressure was measurable until a distance of L = 3,10 m from the position of the pendulum impact executed with an energy of 12 Joule. Under given conditions the increase of pressure was possible until the time of t=0,44 * $t_{E,KB}$ ($t_{E,KB}$ = final setting time measured by kneading).

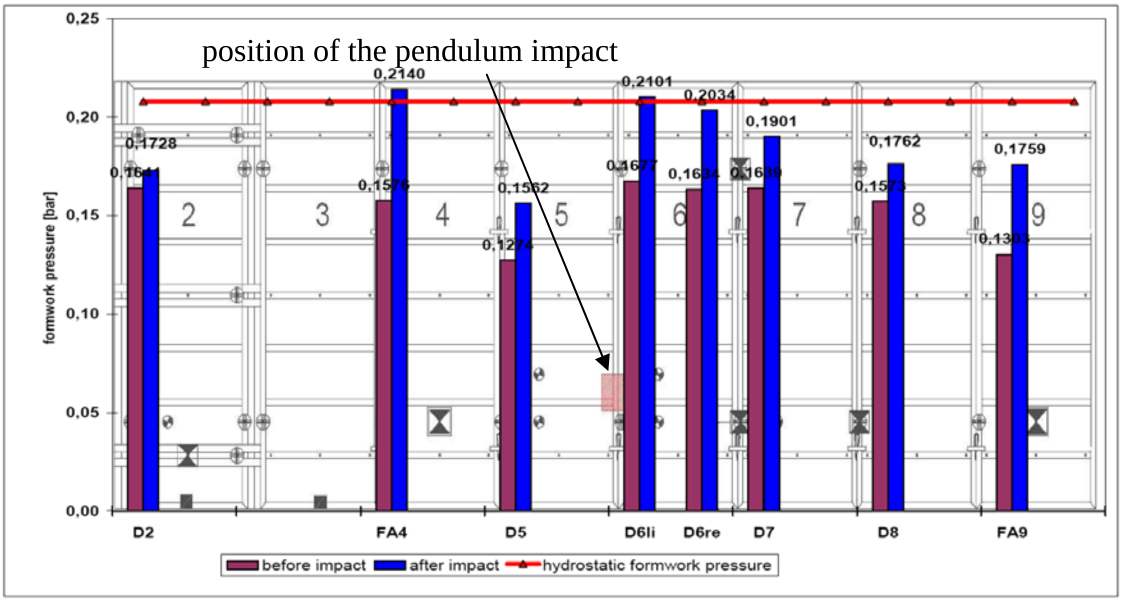

Fig. 3: Lateral pressure at the sensors before and after pendulum-impact

The measured pressure at the sensors and the forces at the formwork ties displayed the influence of the deformability. Because of the higher deformation at the flexible formwork element, resulting from concreting after a break of five hours in the upper half of the wall, a significant reduction of the pressure was measured in parts of the section of the wall which was cast first. The pressure at the sensors implemented at the elements with stiff bearing increased.

Subproject E:

In the context of the research project a quantification of the endangering factors was achieved. Fig. 4 shows the result of this quantification after NOHL in comparison to working systems in the filed of the common jolted kinds of concrete (F1 to F4) and the F5-, F6- concrete sorts as well as Self Compacting Concrete (SCC).

Particularly the mental / psychogenic factors show a distinctive difference between F1 – F4 -concrete and F5, F6-concrete and Self Compacting Concrete due to the lack of knowledge in the handling of high performance kinds of concrete.

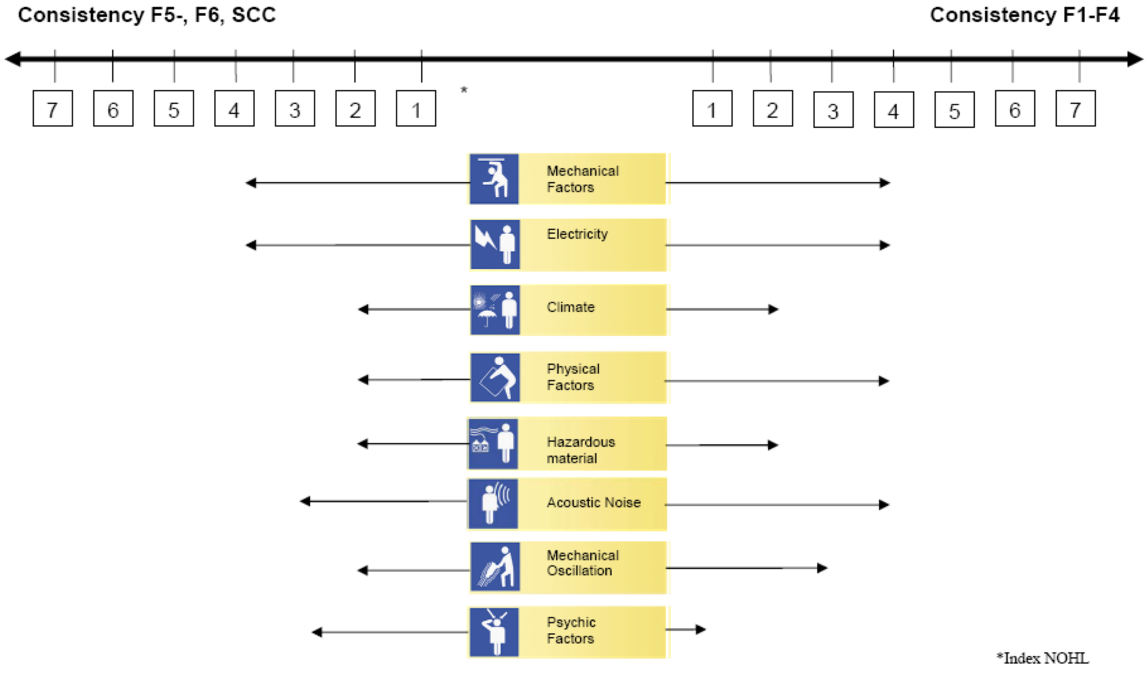

Fig. 4: Integrated base-indexes for risk assessment during concreting

The evaluation of the SWOT Analysis of the process design of concrete works shows that the demanding requirements in casting Self Compacting Concrete were not considered. Therefore it turned out that the amount of manpower in the crew was oversized. The assembly elements of the framework construction (door block out) were built deficiently and did not bear up against the fresh concrete pressure. An insufficient coordination of delivery- and consumption frequency of the concrete was also noticed.

Furthermore in the context of the research project a basis structure of a database system was developed. A permanent target-performance comparison of different variables can be realised with the database system. The data of the concreting velocity as well as casting location were particularly considered. The polysensoral systems that have been generated at the Institut für Baubetrieb and which are still under continuing development (e.g. image processing system) show the potential to provide the relevant actual data reliably and contemporarily. Implemented Controlling-Elements should transfer warning calls about incorrect deviations to the building site executives, in order that the task management can be carried out in time.

Based on the experienced data of building site research as well as on the basis of further considerations a check list has been developed (see final report table E-4) in which criteria and processes during the selection of appropriate formwork are summed up. These specifications can be used as an input parameter within the scope of standardised comparison systems.

A consolidated view of all these factors indicates that the targets of the subproject E “Issues on the side of construction management and technology” have been hit.

Subproject C:

As a result of the investigations regarding the analytical model and the design (Project part C2), Fig. 5 shows the maximum formwork pressure, for concrete poured from the top, against the casting rate *v* and the final setting time t_E (according to the Vicat penetration test for mortar). The figure presents the results of the small scale experiments (Project part C1 - inner friction measurements) as well as the wall experiments in addition to published values. The simplified models, also presented in the figure, show a linear increase of the formwork pressure according to $h_E = v \cdot t_E$ and the minimum values 20 kN/m² (SCC) and 25 kN/m² (consistency F5 and F6). The minimum values are a result of vibration and change of position during the casting considering an unplanned vibration depth up to 2 m in the unset concrete. As an alternative to the Vicat setting time $t_{E,}$, the setting time $t_{E,KB}$ determined according to E DIN 18218:2008-01 (Knead bag test) can be used, considering $t_E = 1.25 \cdot t_{E,KB,}$.

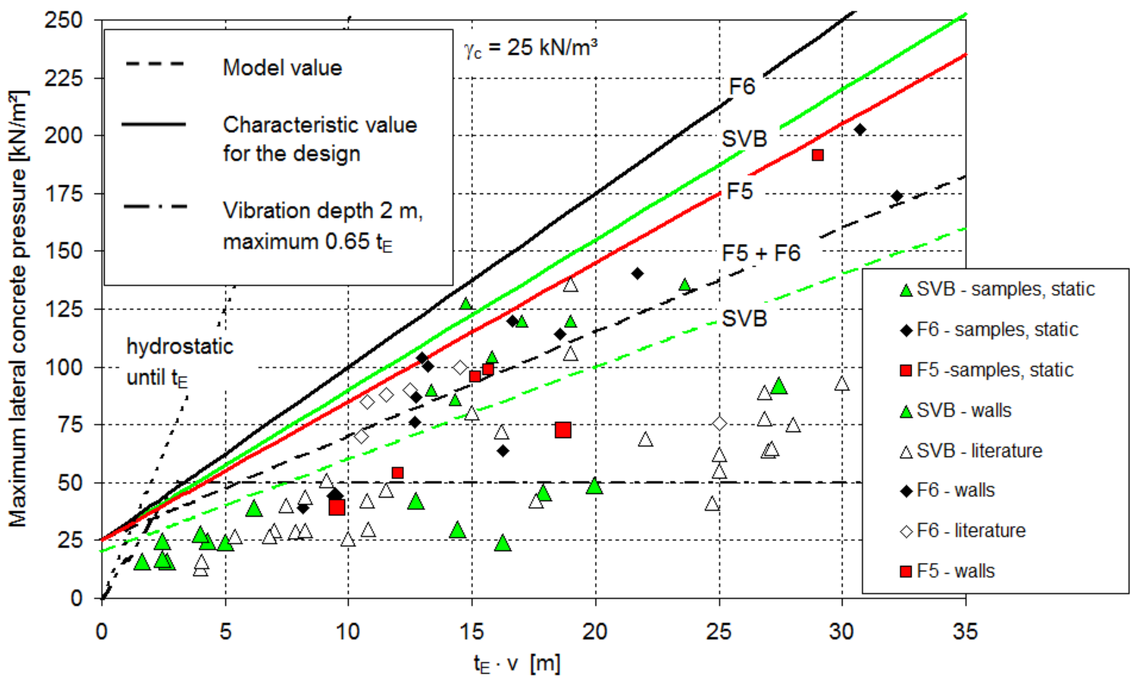

Fig. 5: Measured maximum lateral pressure, the values of the analytic model and the design values versus casting rate *v* and Vicat setting time t_E

The friction between the concrete and the formwork surface as well as the reinforcement is not included as an explicit parameter in the calculation models due to the high sensitivity of the friction to vibration. This explains the significant variations between measured and calculated values. In particular, significantly lower fresh concrete pressures are to be expected for highly reinforced elements than for unreinforced or minimally reinforced elements.

The characteristic values of the formwork pressure for the ultimate limit state design were calibrated and must be multiplied by a partial load safety factor of $\gamma_F = 1.5$. The difference between the characteristic values for the consistency classes F5 and F6 is the result of the corresponding spread of the basic variables such as setting time and model uncertainties. Furthermore, due to the effects of the compaction process (vibration) the formwork pressure is greater for F6-concrete than for SCC.