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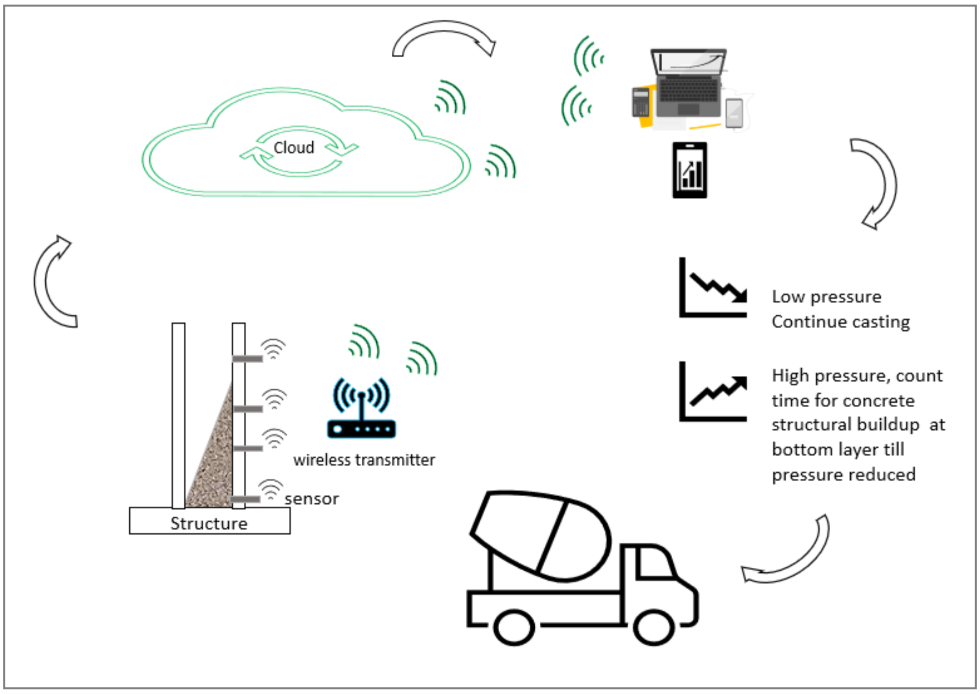
DIGITALISERAT PLATSGJUTET ANLÄGGNINGSBYGGANDE



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FÖRORD

The project participants included NCC and Luleå University of Technology. The report, experimental testing and analysis of the data have been prepared by Yaser Gamil with a support provided by Prof. Mats Emborg, Prof Andrzej Cwirzen and Dr Jonny Nilimaa.

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NCC

Summary

Digital transformation of concrete technology is an important topic tackled by both construction industry and academia. The technology includes novel sensors, virtual reality, or the internet of things. These technologies can be utilized to develop self-learning and automated platforms for concrete technology. It can start from materials characterization, mix design, fresh concrete properties, hardening and hardened properties. Technology can even go further to have self-sensing concrete. The current developments in digital transformation have been studied in this project. Current pathways and directions seen in research and industrial practices were analysed and discussed. Benefits, challenges, and possible opportunities related to the digital transformation of concrete technology were discussed as well.

One of the many challenges that must be still faced is to develop reliable models that could predict various crucial parameters related to concrete. Furthermore, these models must be fed with precise data obtained from possible wireless durable sensors.

The performed study indicated that prediction and monitoring of form work pressure of cast in situ self-compacting (SCC) concrete is one of the areas with evident lacks. The formwork constitutes up to considerable amount of the overall cost of a concrete structure. Common practice of designing the form for SCC is quite often based on full amount of hydrostatic pressure and promoting expensive design and in some cases results to increase of project cost and constraints of casting rate that may cause time overrun. This may outweigh the advantages of using SCC.

What is good to note is that findings from literature reports, SCC exerts form pressure that is less than the hydrostatic pressure due to the development of structural build up and thixotropic behaviour leading to reduction of the pressure., Formwork pressures if 30 % less than hydrostatic has been reported even for high casting rates.

The research performed for this project shows that it is possible to forecast the form pressure during casting more accurately. However, measuring system, input parameters and used models should be further developed. The major findings from the could be summarized as:

- Formwork for SCC is commonly designed assuming a full hydrostatic pressure, while the present project results showed that the actual pressure is lower
- Some of the design models overestimate the formwork pressure leading to increased costs
- Some of the design models underestimate the pressure causing work safety related risks
- There is a lack of studies focusing on form work pressure of ecological SCC
- There is a need for development of a better system for the on-site measurement of the work pressure measurements systems for the cast in place SCC, the current system requires an opening in the form, form friendly system is needed.

The work supporting this project was initiated in April 2020 at the Structural and Fire Engineering division Lulea University of Technology in Sweden. The project is sponsored by The Swedish Construction Industry Development Fund (SBUF), NCC AB, Betongindustri AB and Vema Venturi AB (PERI AB)

Sammanfattning

Digital transformation av betongteknik är ett viktigt ämne som hanteras av både byggbranschen och akademin. Tekniken inkluderar bland annat nya sensorer, VR och sakernas internet. Dessa tekniker kan till exempel användas för att utveckla självlärande och automatiserade plattformar inom betongteknikområdet. Dessa kan exempelvis utgå från materialkarakterisering, betongproportionering, färska betongegenskaper, härdning och härdade egenskaper. Tekniken kan till och med gå längre genom utvecklingen av smart betong med självkännande egenskaper. Den aktuella utvecklingen inom digital transformation har studerats i detta projekt. Nuvarande fokusområden inom forskning och industriella metoder analyseras och diskuteras inom denna rapport. Fördelar, utmaningar och möjliga möjligheter relaterade till den digitala omvandlingen av betongteknikområdet diskuteras också.

En av de många utmaningar som fortfarande måste behandlas är att utveckla tillförlitliga modeller som kan förutsäga utvecklingen och egenskaperna hos olika viktiga parametrar relaterade till betong. Dessutom måste dessa modeller förses med exakta data som samlats med hjälp av tillförlitliga och möjligen trådlösa och hållbara sensorer.

Den aktuella studien indikerade att förutsägelse och övervakning av formtryck vid användning av platsgjuten självkompakterande (SKB) betong är ett område med uppenbara brister. De kostnader som rör betongformar utgör en betydande del av den totala kostnaden för en betongkonstruktion. Vanlig praxis är att dimensionera formarna för SKB utifrån ett maximalt hydrostatiskt tryck och förfarandet leder ofta till en kostsam överdimensionering som i vissa fall resulterar både i ökade projektkostnader och tidsöverskridanden då gjuthastigheten behöver begränsas. Detta kan i värsta fall uppväga fördelarna med att använda SKB.

Ett viktigt resultat från litteraturstudien är att användningen av SKB leder till formtryck som är betydligt lägre än det hydrostatiska trycket, framför allt på grund av att betongen snabbt utvecklar en strukturell uppbyggnad samtidigt som dess tixotropa beteende bidrar till ett minskat tryck. Maximala formtryck som är 30% lägre än det hydrostatiska har rapporterats för SKB även för höga gjuthastigheter.

Forskningen som utförts inom detta projekt visar att det är möjligt att förutsäga formtrycket under gjutning mer exakt. Mätsystem, ingångsparametrar och beräkningsmodeller behöver dock vidareutvecklas. De viktigaste resultaten från denna studie kan sammanfattas som:

- Formar för SKB är vanligtvis dimensionerade utifrån antaganden om ett fullt hydrostatiskt tryck, medan de nuvarande projektresultaten visade att det faktiska trycket är lägre
- Några av dimensioneringsmodellerna överskattar formtrycket vilket leder till ökade kostnader
- Några av dimensioneringsmodellerna underskattar trycket vilket leder till säkerhetsrisker
- Det saknas studier med fokus på formtryck för ekologisk SKB
- Det finns ett behov för utveckling av ett bättre mätsystem för direktmätning av formtryck för SKB. Nuvarande system kräver en öppning i formen och formvänligare system behövs därför.

Arbetet inom detta projekt inleddes i april 2020 vid avdelningen för byggkonstruktion och -brand på Luleå tekniska universitet. Projektet har finansierats av svenska byggindustrins utvecklingsfond (SBUF), NCC AB, Betongindustri AB och Vema Venturi AB (PERI AB)

Content

1 Background

It is known that concrete is the most important building material constituting a basic component in infrastructure structures as well as house frames and industrial facilities. Although the degree of industrialization is already high when using cast-in-place concrete, efforts are being made today to further develop this to enhance the productivity, working environment as well as quality of the end product and durability. One of main developmental directions is digitalization with the latest findings in IT-based production and materials technology, i.e., Lean Construction and BIM. Digitalization can provide further improvements to the cast-in-place construction, especially during casting and hardening. Today, software can forecast and follow-up the concrete construction process like the software tools and wire-less supports, Contest Pro, PPB, Hett22 or BI Distant.

The main challenges when implementing digitalization and automatization in concrete technology are significant lacks fundamental knowledge that is needed to develop various types of physical and mathematical models. These models are bases for development of planning and controlling software, which must be additionally supported by row data collected by reliable sensors.

Several motives and research questions were formulated during planning of this research including:

- Uncertain forecasts are still made regarding early age cracking risk, strength development and form pressure. This leads to oversized measures, cracks, repairs, lower product quality, high costs and unnecessary climate impact.
- Follow-up and management of on-site operations is often deficient.
- How can today's forecast methods for cracks be improved with better models / material data?
- How can calculation models for form pressure be improved?
- How are methods for calculating strength development affected by new, environmentally friendly binders?
- How much information (i.e., measurement data) is needed from casting and hardening to ensure that the optimal construction method is complied with?
- How can the optimal construction method be controlled automatically?

This part of the PhD study enforced the project team to focus on the selected problems of above to achieve the required in-depth knowledge and to produce data that are useful for the Swedish construction sector.

The work started by performing a literature review that were published in two separate journal papers. The first focus was on the general digitalization of concrete technology. The second focus was digitalization, monitoring and modelling of the form work pressure of SCC concretes. (Gamil & Cwirzen, 2022)(Gamil et al., 2021).

Based on these two reviews the experimental and theoretical (modeling work) was limited to the formwork pressure of SCC concrete.

This report presents the main finding from the literature reviews and laboratory experiments related to the formwork pressure measurements with a novel wireless sensor technology.

2 Aim and goals

The main purpose of the entire 4 years PhD project is to gather more knowledge related to the digitalization of concrete technology. The digitalization should thus improve planning and execution of construction, increase efficiency, improve the safety of the working environment and to provide a higher quality of the end-product.

The main goal of this first part of the PhD project was focused on form pressure i.e., to measure and predict the form pressure for a typically used in Sweden SCC. Detailed objectives and present status are listed in Table 1.

Table 1. Detailed objectives of the entire PhD study and their status at the time of writing this Part 1 report.

Objective	Status
To explore the current trends and developments in digital support and digital transformation in concrete technology	Achieved in state-of-the-art review, (Gamil & Cwirzen, 2022)
To study the development, modelling and technologies related to form pressure when casting in place with SCC	Achieved in article review, (Gamil et al., 2021)
To develop a laboratory instrumented setup simulating casting process, considering varying input parameters needed for design model assessment	Finalised and soon to be published
To assess the current design models and identify limitations and possible extension of the models	Finalised and soon to be published
To incorporate monitoring pressure for ecological SCC concretes containing slag	Planned in the second phase of the project
Develop a unified form pressure design model addressing the effect of slags and other SCMs	Planned in the second phase of the project
To verify the model in a full-scale test on a building site	Planned in the second phase of the project

3 Work plan

The project has been organized on 5 work packages as shown in Figure 1 where main findings and result are described in the relevant work packages.

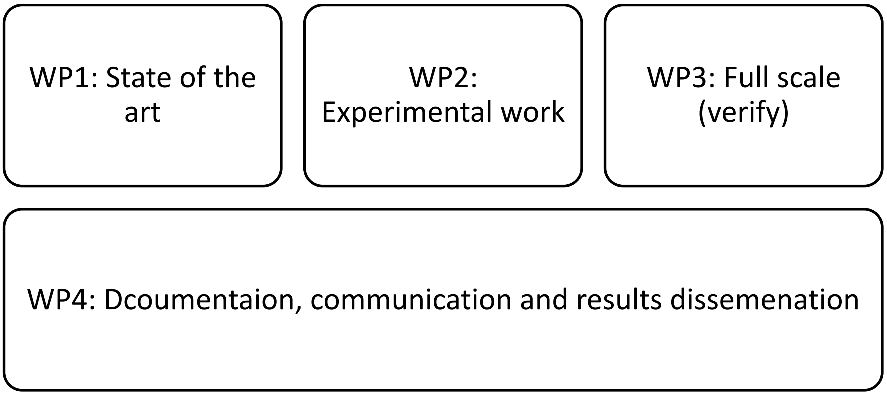

Figure 1. Work packages

3.1 State of the art on Digitalization of Concrete Technology (WP1)

In the first state of the art review, a comprehensive general study on the digital transformation in concrete technology was established, (Gamil & Cwirzen, 2022), Figure 2. The benefit of digital transformation is not only limited to saving time but also helps to make accurate decision on concrete, perhaps greater technological integration will operate effectively to create a system to collect and transmit the concrete information. What makes digital transformation even more important is their need during casting process. This includes monitoring of the concrete temperature, workability, casting rate, formwork pressure, form pressure reduction, maturity of the concrete. These data enable to determine (predict) the formwork removal time, expected mechanical properties, and cracks risk monitoring. Future development will integrate the current technologies and applications into one fully integrated system for possible information acquisitions and instant communication.

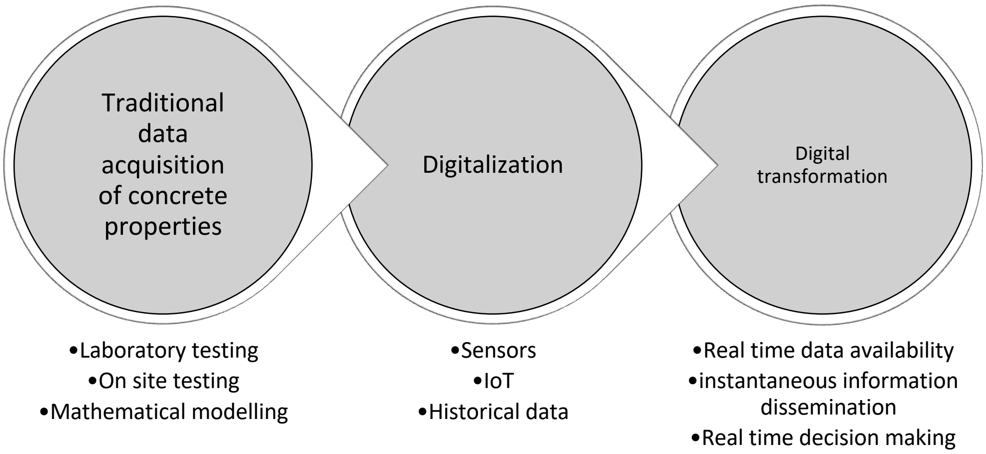

Figure 2. Elements of digital transformation of Concrete technology *(Gamil & Cwirzen, 2022)*

Digitalization of the concrete mix design has been recently significantly developed. The process includes application of various tools and model to establish several key parameters. This includes water to cement ratio, automated dosage of cements and admixtures, or coarse aggregate to cement ratio.

Table 2. Digitalization of the mix design, data adapted from (Gamil & Cwirzen, 2022)

Targeted parameters	Technology/method	Tool (s)	Key findings
Water-to-cement ratio and cure-state This is known at the concrete plant. A key parameter in QA control	Near-field microwave techniques	Open-ended rectangular waveguide probe radiating into OPC materials at 5 GHz (G-band) and 10 GHz (X-band).	The near field sensing technique of hydration state and w/c ratio
High performance concrete	Neural Networks	Nonlinear Programming	The model developed based on the workability and strength as outcome indicators of the mix.
Dosage of materials, cement grade and the effect of admixtures	ANNs	Knowledge-acquisition system, Visual C++	The developed system produces effective mix design and save time.
Coarse aggregate-to-cement (ca/c) ratio	Non-destructive testing technique	Microwave near-field reflection property analysis, open-ended rectangular waveguide probes	It is possible to measure coarse aggregate to cement ratio.
Water to cement ratio	Real time and on-site Microwave non-destructive testing	Monopole antenna probe, the probe, the probe operates with 3GHz with a reflectometer to determine the w/c ratio.	The reflectometer with the probe helps to quickly determine the w/c ratio onsite.
Nominal and equivalent w/c	ANNs	Design algorithm	The algorithm developed is an effective tool to produce

ration, FA to binder ration, aggregate size			mix design with less trials and errors.
OPC, water, fine and coarse aggregate	Simplex and modified regression theories	Visual basic Language, computer-aided design	The model developed predicts the compressive strength for any arbitrary mix.
Optimizing concrete mix design	3D printing	Laboratory based optimization	Optimization of mortar mixed design is controlled by extrudability, buildability, workability, and open time in 3D printed concrete.

The cement hydration can be characterized by several measurable parameters which then can be utilized in digitalized systems. The key parameters are summarized in Figure 3.

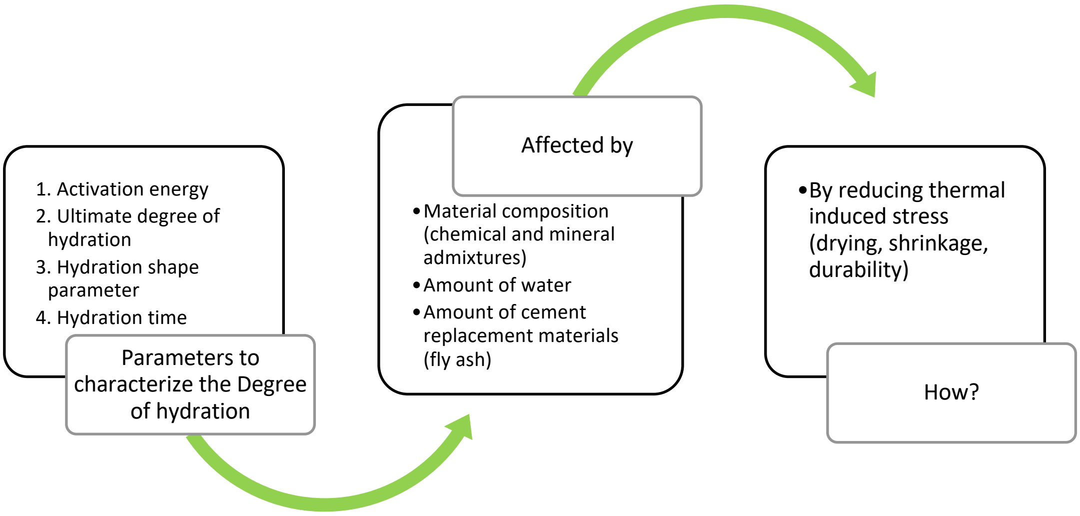

Figure 3. Parameters and process used to characterize cement hydration, data adapted from (Gamil & Cwirzen, 2022).

Monitoring of concrete temperature is crucial for following the hydration process and thus are fundamental for prediction of the compressive strength development. These data are important for planning of the concrete work including the casting speed, demolding, or the applied curing procedure. The overview of used methods is shown in Table 3

Table 3. Digitalization of the concrete temperature and humidity monitoring, data adapted from (Gamil & Cwirzen, 2022).

Parameters	**Technology/ method**	**Tool (s)**	**Limitations/key findings**
Temperature and moisture monitoring	Sensors	Embedded nanotechnology /Microelectromechanical systems (MEMS) sensors	The MEMS displayed repeatability and signal processing issues
Temperature	Thermography	Embedded thermal sensors	Thermography technique must be in visual contact with the concrete and that is difficult to achieve due to form covers.
Temperature and humidity	Radio Frequency Integrated Circuit (RFIC) and sensor technology	Pt-100 resistance thermometer and RFIC transmitter	The signal instability of the sensors, and lack of electronic protection cause deterioration of devices.
Temperature and humidity	Automatic wireless sensor	Negative temperature coefficient (NTC) thermistor and an IRIS mote to create IEEE 802.15.4 network.	The sensor measurements present a 5 °C standard deviation between actual and experimental values.
Temperature	Sensors	Passive wireless surface acoustic wave (SAW) sensor and Orthogonal frequency coding (OFC)	The results provided non-destructive method to detect internal temperature. But there were constraints by effect of propagation loss in concrete and isotropic radiation loss was detected
Temperature	Sensors	A passive RFID sensor tag	Short range remote sensing is achieved, and the sensors enabled detection withing 0.25°C resolution.
Temperature	Sensors	Embedded passive radio frequency identification (RFID) sensor tag	Both lab experiment and onsite testing show that sensor tag in concrete can provide accurate data.

Cracking of concrete is still one of main problems related to application of concrete. Despite all developments in limiting crack risk and crack width, the cracking still occurs. Thus, efficient methods integrated with digitalized systems are needed to enable early detection of cracks to e. g. lower the repair costs and enhance durability. Several efforts have been made and examples are summarized in Table 4.

Table 4. Example of digitalized crack detection and crack characterization methods, data adapted from (Gamil & Cwirzen, 2022).

Targeted properties	Type of cracks	Technology/method	Tool (s)	Key findings
Crack detection	Extrinsic	Automated image processing techniques using multi-temporal crack measurements	Automatic crack detection and algorithms (the route-finder and the fly-fisher)	The finding shows that the automatic crack detection technique accurately delineates the crack even with poor quality image.
Crack width + Expansion	Extrinsic and intrinsic	Multitemporal image processing where photos are taken every 2 weeks. A high-resolution scanner AGFA DUOSCAN T2500 used to scan the digital images	Automatic crack tracing using Using analog camera Rolleiflex 6008 Integral and film Kodak Ektachrome 64	The finding shows the consistency of the width between automatic estimation and the manual measurement is between 0.05 mm.
Crack pattern	Extrinsic	Digital camera embedded into calibrated cylindrical attachment	Digitales Rissmess-System German Digital Crack monitoring System	The crack width can be estimated reliably but the drawback of the device is that it gives an estimation of crack width and varies depends on the operator without being reproducible.
Defect Detection	Extrinsic and intrinsic	Thermography	Thermal imaging/infrared thermography (IRT)	Direct access to concrete layers is not required when using infrared thermography to detect damage
Crack width	Extrinsic	Image digitalizing and digital image processing methods (DIP)	Digital microscope, digital image processing	The tortuosity of cracks can be mapped by DIP. DIP can also provide the

				possibility of pixel depth analyses of the digital image
Crack detection and orientation	Extrinsic and intrinsic	Combined acoustic emission (ear) and digital image correlation techniques (eye)	Digital image correlation	The finding shows that combining ear aided (acoustic emission) and eye aided techniques (digital image) can help to estimate the concrete crack behaviour.
Crack detection	Extrinsic	Local binarization algorithm	Gray-scale images	The method can detect the surface and cross-sectional area of cracks.
Microcracks detections	Intrinsic	Ultrasound-excited thermography	thermal imager	Cracks with 0.01–0.09 mm width were effectively detected by ultrasound-excited thermography.

Note: intrinsic cracks are deformations caused by the characteristic of concrete such as shrinkage, extrinsic cracks caused by external factors such as thermal expansion, differential movements

The form work pressure is one area where digitalization is crucial from economical and safety reasons. The literature study showed several problems which need to be solved. They are related to several basic phenomena, e.g., hydration of cement but also to full-scale real-life applications with number of factors not being present in laboratory settings. The main factors affecting the formwork pressure are summarized in Table 5 including concrete mix design, fresh concrete properties and placement technology, (Gamil et al., 2021).

Several design models have been introduced to determine the maximum form pressure while casting with SCC, but these models are not generally accepted by the construction industry yet. Consequently, the design of the form is performed with the assumption of full hydrostatic pressure which is not cost-effective.

More studies are also needed to ecological SCC incorporating various types of supplementary cementitious materials (SCMs) that affect the fresh concrete properties and early strength development. The reliability of most sensors currently used to monitor the formwork pressure is strongly affected by the build-up of a solid binder matrix or thixotropy of the concrete mix and it is therefore important that used sensors can capture the true pressure level also during the hardening phase.

In summary, determination and prediction of the lateral formwork pressure exerted by SCC require further research, including on the effects related to material properties, mix design, placement techniques and casting rates, rheology, temperature, setting times, hydration rate, stiffness build-up and sensors and their installation and data interpretation, and modelling.

These issues are planned to be addressed in the second part of this PhD study which is planned.

Table 5. Factors Affecting Form Pressure Exerted by SCC

Category	Parameters
Concrete Mix design	Gradation, shape, texture, and amount of fine and coarse aggregate
	Water to cement ratio
	Amount and type of SCMs (if used), Amount and type of additives
	Cement type and amount
Fresh concrete properties	Concrete temperature
	Setting time (rate of hardening)
	Concrete density
	Initial shear stress
	Slump flow and T50 (consistency class)
	Thixotropy and viscosity
Placement technology	Casting rate and casting method
	Humidity and ambient temperature
	Reinforcement
	Pumping location, i.e., pipe location in the form
	Size of structure (what is meant?), casting height
	Type of formwork and its geometry, surface friction
	, equipment and materials, possible external loads created, e.g., pressure sensor location

3.2 Experimental Laboratory Works (WP2)

The objective was to develop an instrumented setup simulating casting process with state-of-the-art pressure sensors, considering varying input parameters needed for design model assessment and to use the laboratory data to assess the current design models and identify limitations and possible extension of the models.

In this work package, a laboratory plan was established including the instrumented setup is used to monitor the pressure. Then, the final mix design was developed based on mix suggested by

Betongindustri AB and data required for the model were obtained simultaneously to be used in the assessment of the design model.

3.2.1 Methodology

The approach used in the experimental part of this project consisted of the following:

a) Application of new formwork pressure measuring system developed by Vema Venturi AB, PERI company

b) Usage of in house developed experimental system that can simulate the actual concrete casting process using controllable laboratory setup while obtaining the input parameters

c) Collecting data from the laboratory

d) Evaluation of existing theoretical models by using the collected data.

The new system developed is based on the cutting-edge wireless sensors where collected data are sent to the cloud and can be accessed instantaneously using smartphone or computer anywhere.

3.2.2 Concrete mixes and test plan

The objective of the testing plan, Table 6, was to establish effect of each single parameter on the measured formwork pressure. The workability was adjusted by variation of the superplasticizer (SP) content. Two cements with different setting time were used Bascement (BAS) CEM II/A-V 52.5 N, Anläggningscement FA (ANLFA) a Portland-fly ash cement type CEM II/A-V 42,5 N MH/LA/NSR. Cementa AB.

Table 6. Laboratory tests plan

Test code	Initial slump flow (mm)	Casting rate (m/h)	Cement type	Variations
BAS1	700-750	0.25	CEM II/A-V 52.5 N (BAS)	Casting rate
BAS2		0.5		
BAS3		1		
BAS4		4		
BAS2	700–750	0.5		Slump flow
BAS5	600–650			
BAS6	500–550			
BAS7	400–450			
ANLFA1	700-750	0.25	CEM II/A-V 42,5 N (ANLFA)	Cement type, casting rate
ANLFA2		0.5		
ANLFA3		4		
ANLFA1	700–750	0.5		Cement type, the slump flow
ANLFA4	600–650			
ANLFA5	500–550			

3.2.3 Fresh concrete testing

The fresh concrete properties were determined by measuring slump flow, T50 time, density, air content, and static yield stress using a portable vane. The slump flow and T50 were recorded every 30 minutes until reaching 400 mm flow diameter because it is an input for the model developed by (Gardner et al., 2012). It is thus an indication knowing the time where concrete losses its flowability and starts to build its own skeleton in the bottom layers of the structure and the time used by the theoretical models. Ambient and concrete temperature were also documented.

The setting bag test was performed. as test was needed as an input parameter for verification of the model according to DIN 18218. The procedure was followed according to the DIN standard where about 8 liters of concrete is filled in a polyethylene plastic bag and placed in a bucket. Every 30 minutes the consistency is evaluated by manual press of thumb of approximate 50 N on the bag surface and checking the impression on the concrete. The depth of the impression indicates the setting condition. Setting time is defined as 1.25 times the time taken to have less than 1 mm impression. For example, the setting time is recorded as of $t_{e,kb}$=5 h, then the final setting time is t_e=1.25*5=6.25 h. This means that concrete cast later than 6.25 h from the mixing is assumed to be self-carrying according to DIN18218. Achieving 50 N of thumb pressure on concrete was made possible by a load pressure cell mounted on a rig, an “artificial thumb” as described in (Nilimaa, 2022).

The portable vane test was performed immediately after mixing for each concrete recipe to measure the static yield stress after 15 min of rest (PVτ0rest@15min@Ti). It was performed for the fresh concrete to be used as an input for the theoretical models as described in (Khayat & Omran, 2009) Figure 4. Portable vane test

The used procedure was as follows, see Figure 4: after mixing, cubes are filled with fresh concrete into specific immersion height, which is noted, the container then is covered at the time of rest, a torque meter is attached to the vane, the vane is rotated slowly about 10 to 15 seconds for quarter turn, the maximum torque value is then recorded and converted into static shear stress using the following formula as prescribed in (Khayat & Omran, 2009) : $PV_{\tau_{orest}} = \frac{T}{G}$ where: $G = 2\pi r^2 \left(h + \frac{1}{3} r\right)$ and T is the torque value, r is the vane radius (37 mm), h is the immersion depth of the vane into the concrete (180mm), then, G is calculated for this test as 1653,6 cm^3.

Figure 4. Portable vane test

3.2.3.1 Form pressure setup

An in house designed set up was used to simulate the full-scale casting process. A circular column having 2 m high and with diameter of d= 0.15 m was used, Figure 5. The pipe was transparent. The fours sensors were placed at 0.1 m, at 0.5 m, 1 m and at 1.5 m heights from the bottom. The sensors were fixed on a 3D printed plastic adapter to grip the sensors at the specified locations. Openings for the sensors, d= 50 mm were drilled in the formwork providing a direct contact between the diaphragm of sensor and the concrete. The pressure was monitored instantaneously, and data from the main unit was transferred to the cloud at one-minute intervals. The form was filled in from the top, and the casting rate was kept as shown in Table 6.

a) The formwork b) The setup c) During casting d) After casting

Figure 5. Form work pressure measurement setup

3.2.4 Tests results

The pressure reading from sensor 1 at the bottom of the form increases in the first three hours and then it decreases, see example from one of the tests, Figure 6. The concrete at the bottom thus starts to form structural build-up and the concrete while the second sensor placed at 0.5 m from the bottom shows a pressure increase when fresh concrete reaches its level. The pressure reduction displayed from sensor 1, and the overall pressure decays after time and that gives a time for more casting and that would result to speed up the construction process. Figure 7 shows the response for each sensor over the height of the form for selected measurements. From the data, the overall maximum recorded pressure is at sensor 1 is 13.9 kPa, while the maximum recorded pressure for sensors 2, 3 and 4 are 12.3 kPa, 9.3 kPa, and 6.6 kPa respectively. It is shown the pressure increases with height. With this low casting rate, the pressure starts to decrease at the bottom layers. It is interesting to compare the actual recorded lateral pressure with the hydrostatic pressure $P_{hydro}=\varrho gh$. with a fresh concrete density of 2331 kg/m^3. The actual pressure is evidently less than the hydrostatic pressure giving a room to speed up the casting

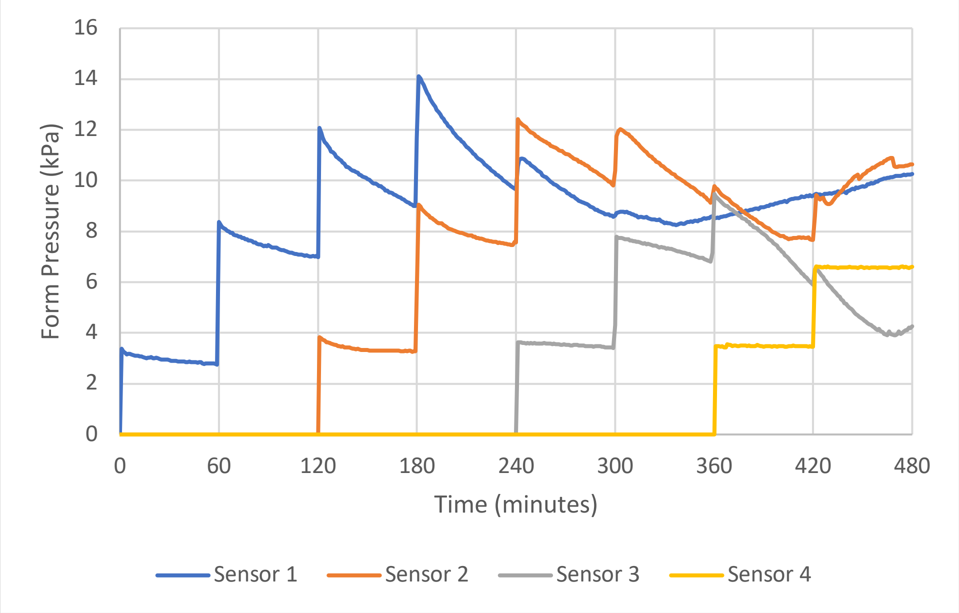

Figure 6. Real time pressure monitoring for 0.25 m/h casting rate BAS1

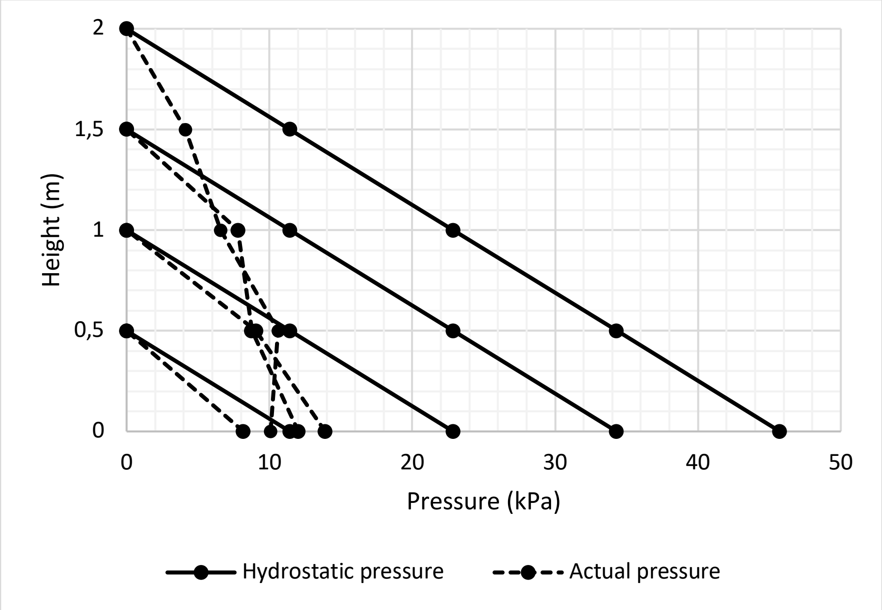

Figure 7. Pressure vs height of casting for 0.25 m/h, test BAS1, see Figure 6

Figure 8 shows the monitoring for the second column where 0.5 m/h was maintained as casting rate. The results display four batches in four hours. This higher casting rate did not allow the concrete in the bottom layers to build its own structural bonds as observed for the lower rate of Figure 6.and that was indicated by the reduction pattern. Figure 9 shows pressure versus height of casting and it is clearly observed the higher pressure as compared to Figure 7.

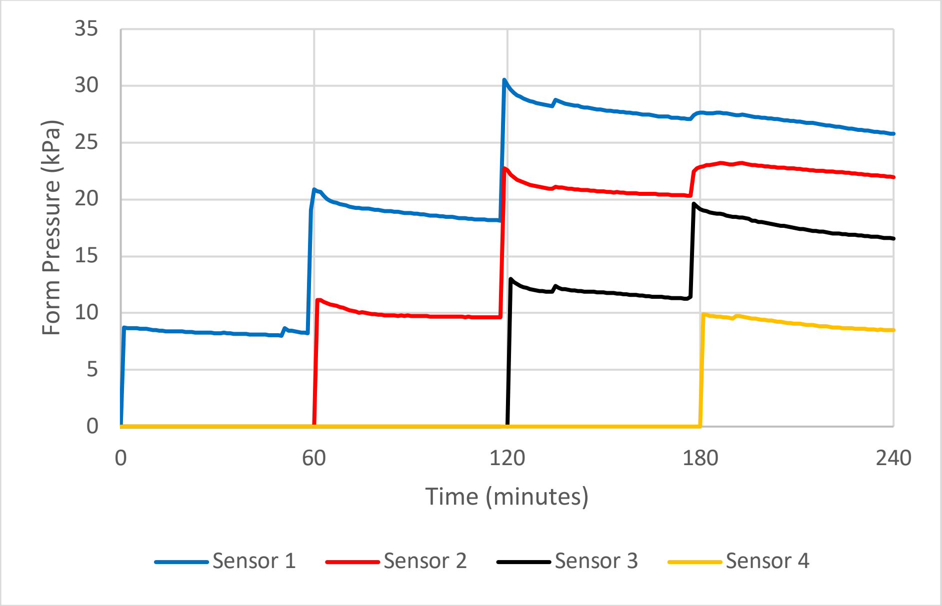

Figure 8. Real time form pressure monitoring, at casting rate 0.5 m/h, test BAS2

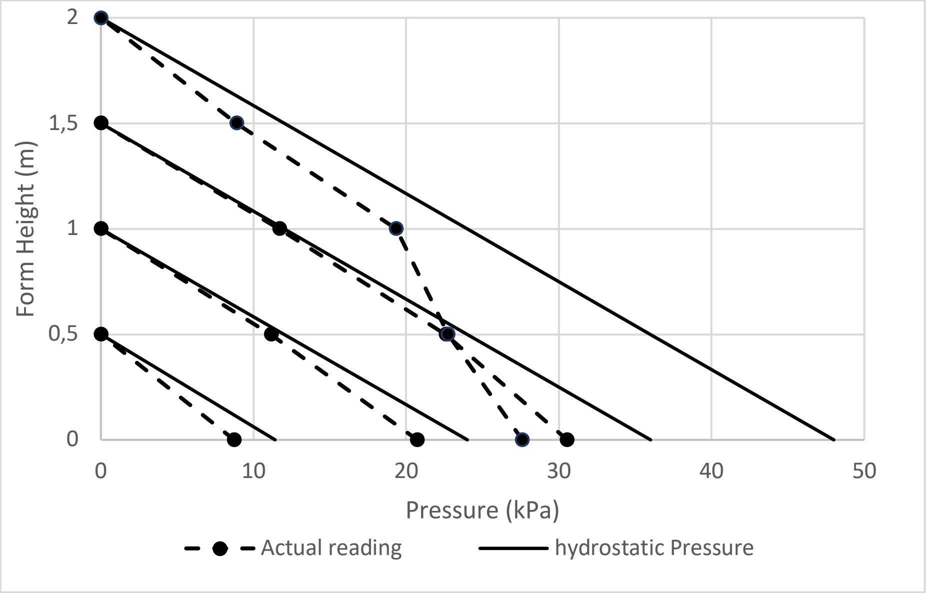

Figure 9. Pressure vs height at 0.5 m/h casting rate, see Figure 8.

Figure 10 demonstrates the maximum pressure vs. form height for different casting rates. It is observed when the concrete is freshly cast it behaves like hydrostatic but after some time the form pressure starts to decrease. Comparing to casting with 0.25 m/h the pressure is slowly reduced at the bottom layer.

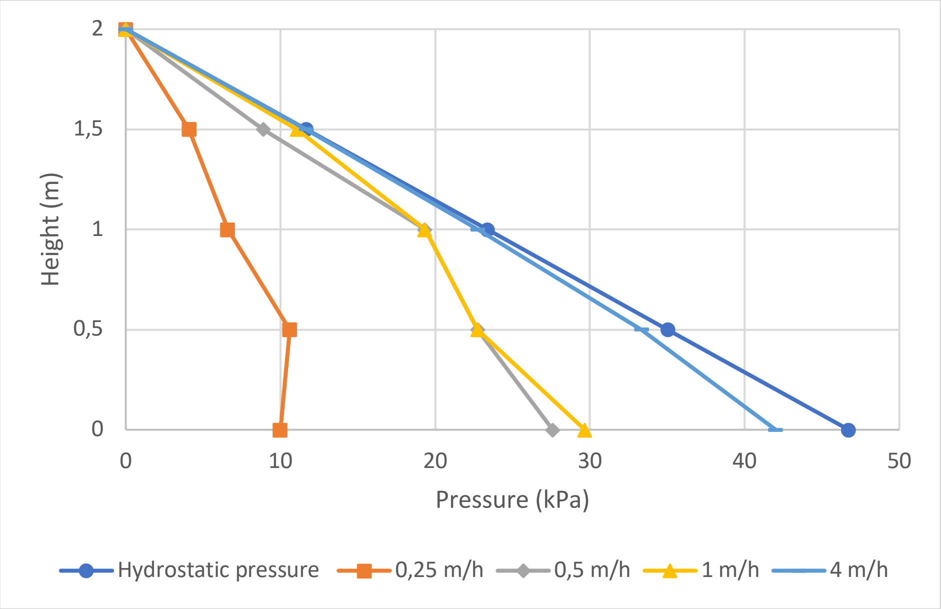

Figure 10. The maximum pressure by form height of the form for different casting rates and same cement type

Figure 10 shows the maximum values obtained by taking the average of all sensors reading at specified height for different casting rate 0.25, 0.5, 1, and 4 m/h. It is clearly the pressure is highly affected by casting rate where higher casting rate leads to higher form pressure. A variation of slump flow was also performed by controlling the amount of added superplasticizer, see corresponding results in Figure 11.

It is also of significance to observe the effect of cement type on the form and that is proven by different research (Assaad, 2016; Billberg, 2006; Omran et al., 2012; Omran & Khayat, 2014). It is of interest to check the extent of using different cement on the pressure. A comparison between the data acquitted from the bottom sensor for 0.25 m/h casting with BAS and ANLFA cement giving slightly different concrete densities, 2331 kg/m^3 with BAS and 2382 kg/m^3 ANLFA. According to the cement supplier the setting time for BAS cement is 150 minutes while for ANLFA is 170 minutes. Logically it was observed a slightly faster structural built up and a faster pressure decay for; BAS; 12.0 kPa as compared with ANLFA 13.14 kPa at the bottom of the form. The cement type appeared thus to have a limited effect on the maximum developed pressure, but it affects more the pressure decay.

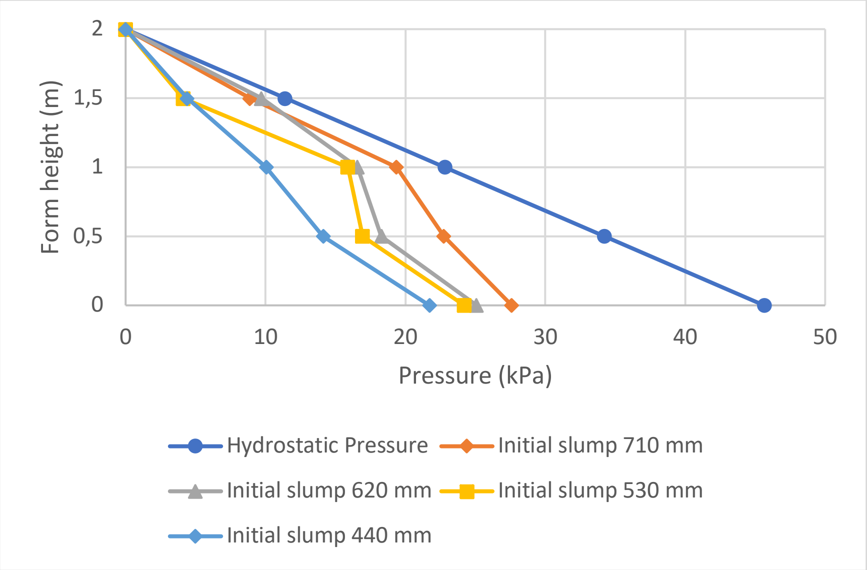

Figure 11. Pressure vs height for different initial slump flow and casting rate 0,5 m/h and same cement type (BAS)

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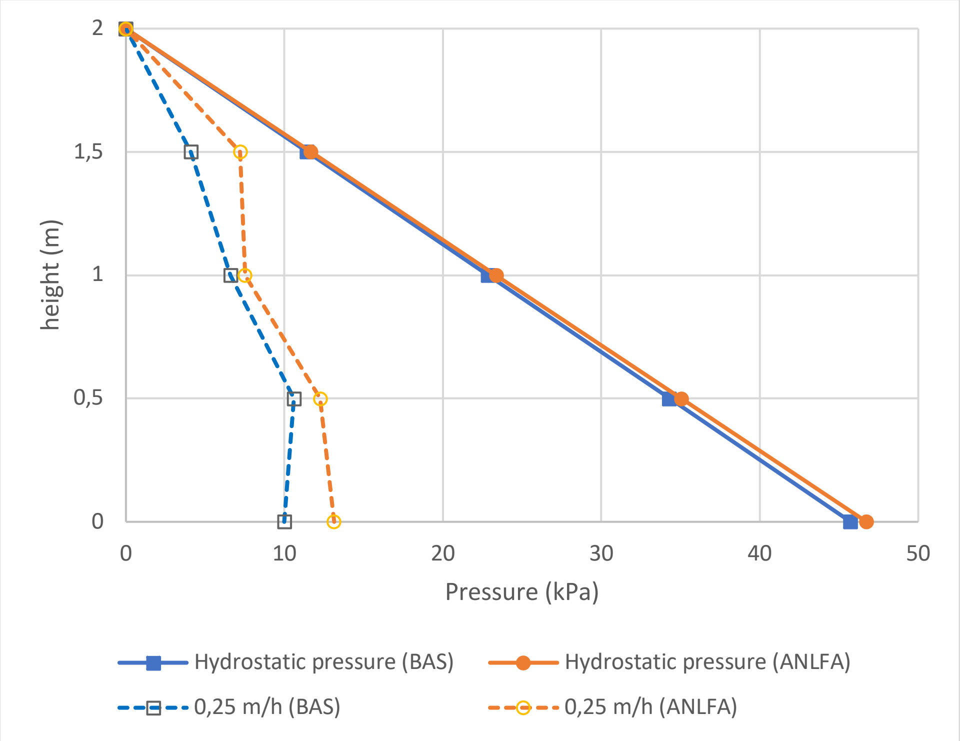

Figure 12. Pressure by height for concrete with two cement type, same casting rate slump flow range

3.3 Models

Several theoretical models related to the form pressure for SCC have been developed where researchers have focused on different input parameters to estimate pressure. In this section, selected models are assessed where the theoretical prognoses are compared with the sensor data obtained

The idea was to observe of and how the models could consider changes in casting rate, slump flow and cement type. For example, the DIN18218 model, says that hydrostatic pressure will result up to a maximum level, thereafter constant pressure. If it is over a certain height, there is a region with zero pressure. That corresponds to a total casting height of he=te*v=6,25*0,7=4,375 m.

DIN18218 model worked well if the casting rate was low, but gave almost hydrostatic pressure when larger than 1 m/h. This lack of accuracy could be related to the fact that the casting time was less than the maximum setting time obtained from bag test.

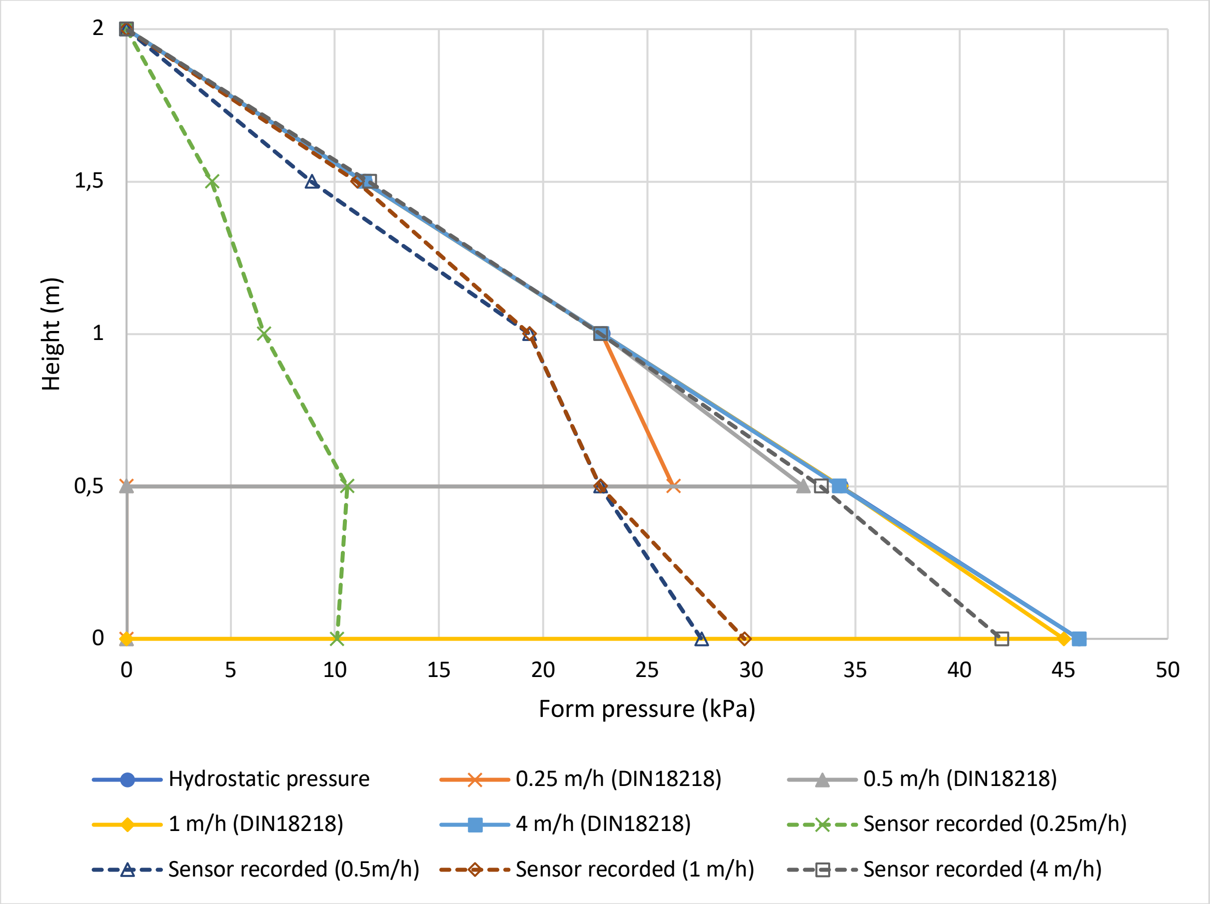

Figure 13. Pressure estimations by height using model according to DIN18218 (2010) vs. recorded data.

The model developed by Khayat et al (2009) gave a good approximation of the pressure especially for the higher casting rates as it considers quite many parameters, i.e., casting height, structural build-up, dimension of the structure and casting rate. However, it overestimated the pressure when the casting rate was low, i.e., 0.25 m/h. A more thorough observation of the Khayat et al (2009) model revealed that the form pressure was lower in comparison to the hydrostatic pressure, Figure 14. When the pressure reached the maximum values, the model produced form pressure that decreased to zero, with the increasing from height. When the form height was as low as 0.5 m for the low casting rate, the thixotropic effect on the form pressure appeared to have too little of impact on the results obtained by the model. The effect of thixotropy on the form work pressure appeared to be less than the hydrostatic pressure when casting with SCC.

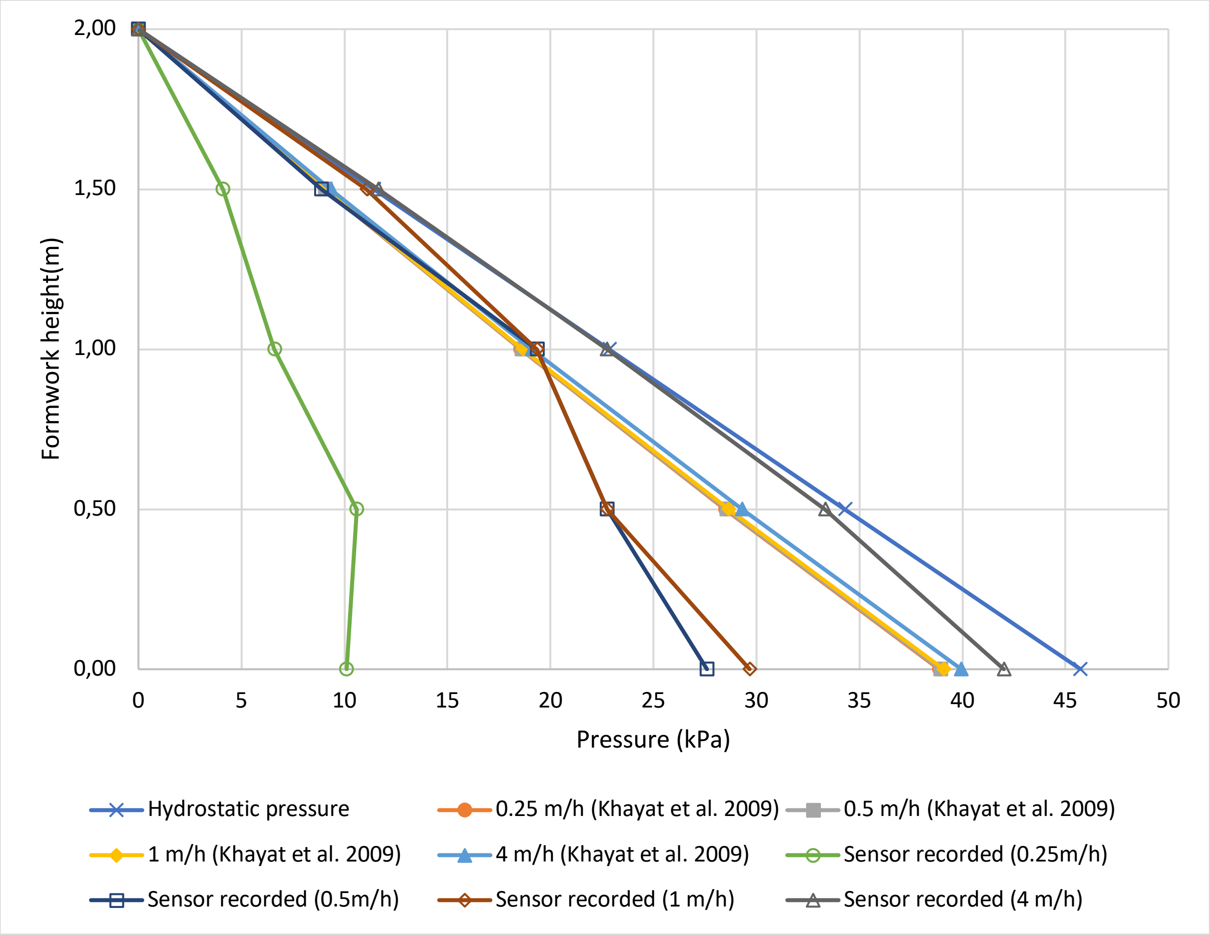

Figure 14. Pressure by form height using Khayat et al (2009) model with. recorded data

The model developed by Gardner et al (2012) considered the casting rate, and the loss of workability measured by the time when the slump drops to 400 mm. This corresponds to the time when the concrete starts to harden and loses its fluidity. The model produced a better estimation than DIN 18218 of the form pressure for both low and high casting rate, Figure 15, because it considers the time for the workability reduction when it reaches 400 mm of the slump flow. It also considers the casting rate, which is considered the most significant impact parameter. It describes better the impact of thixotropy's on the form pressure than the models developed by Ovarlez and Roussel (2006) and (Beitzel, 2010). It further demonstrates that even small differences in the casting rate can cause the from pressure to upsurge suddenly when the concrete does not build a solid structure quickly enough relative to how quickly the form fills with concrete.

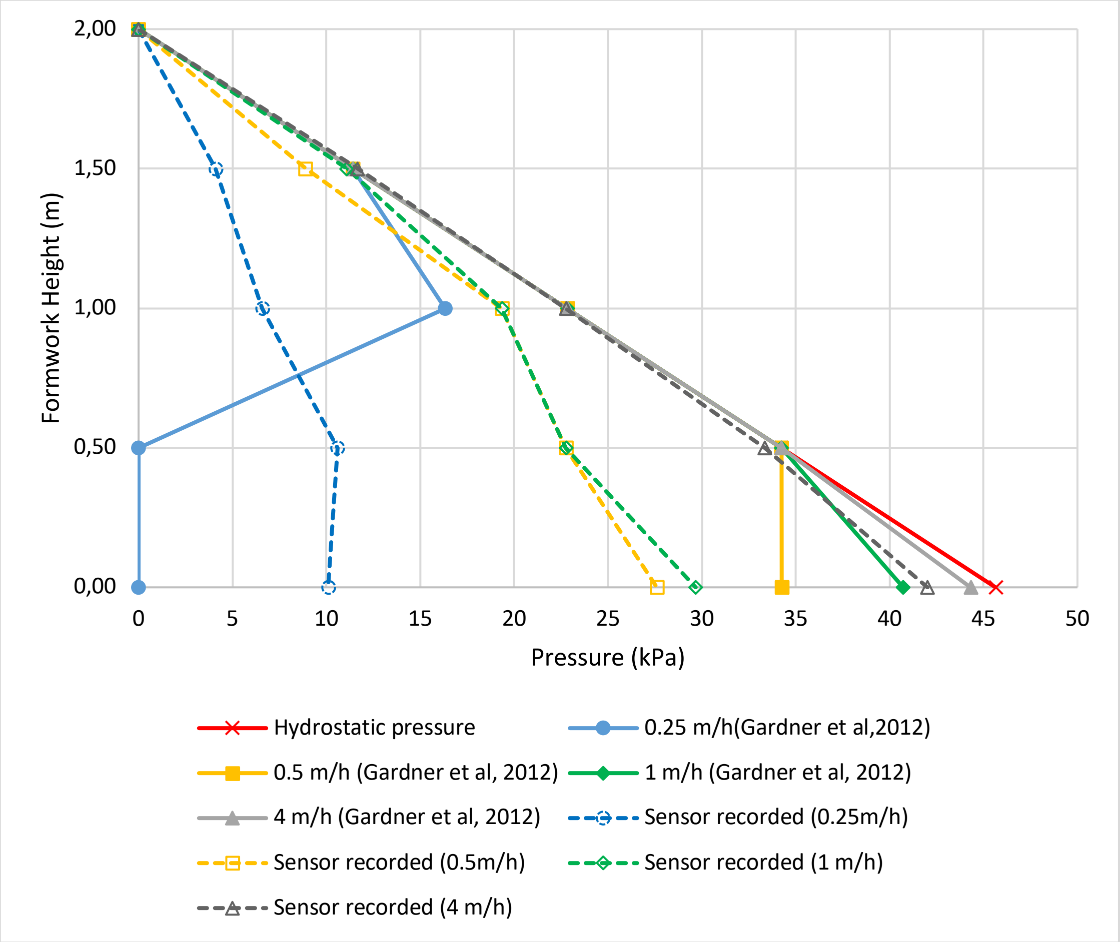

Figure 15. Pressure calculations using Gardner et al, (2012) model as compared to. recorded pressure

The model developed by Teixeira et al. (2017) using regression analysis, the model addresses several form pressure parameters and emphasizes that the estimation of form pressure is thereby ensured to never be greater than the hydrostatic distribution of a liquid with concrete density. Figure 16 shows the comparison between the form pressure estimation using the regression model developed by Teixeira et al. (2017) and the recordings from the sensors. The results shows that the mathematical model underestimate the pressure for different casting rates. This might be the reason why model didn't give more consideration on the casting rate and workability. It also didn't show pressure decay because the model didn't consider the build-up phenomenon that occurs after casting.

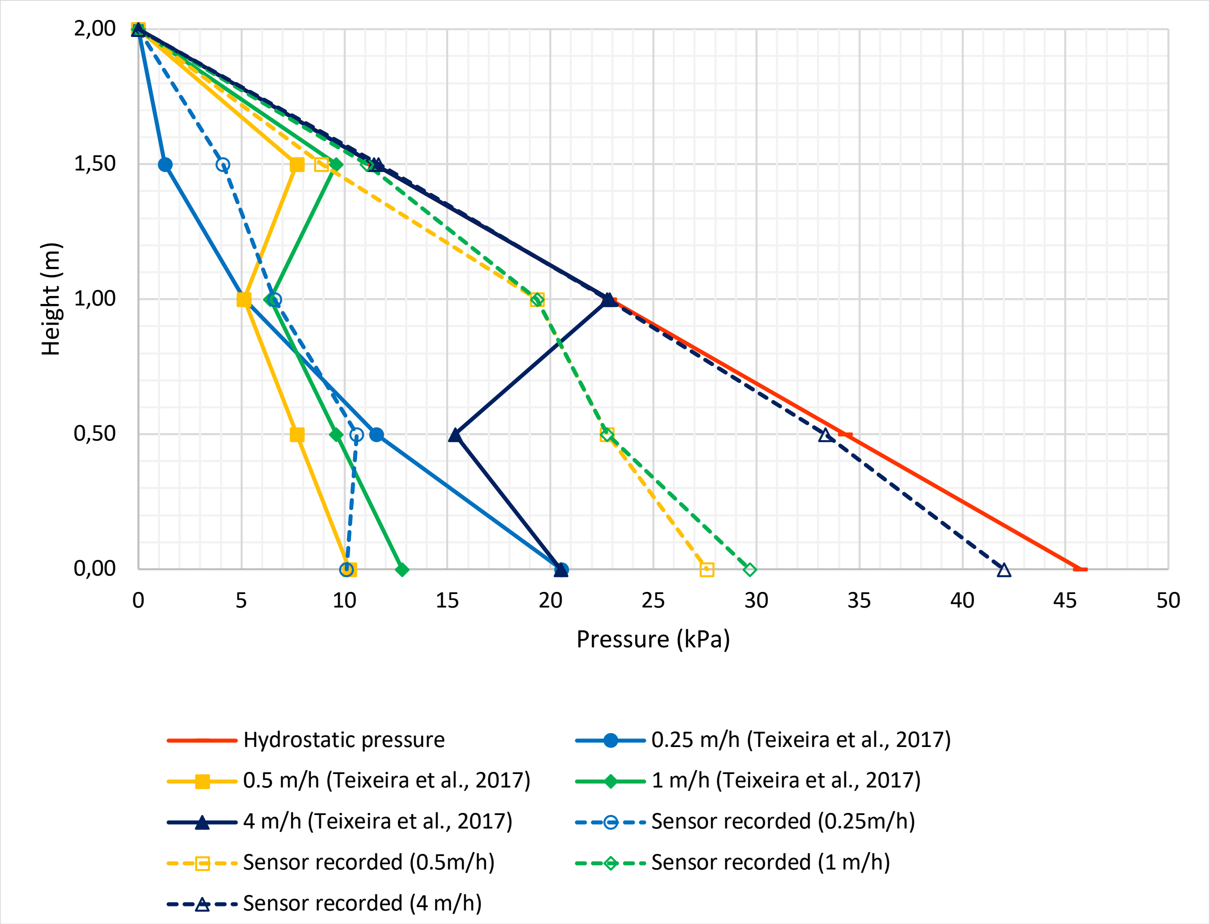

Figure 16. Pressure estimation using Teixeira et al. (2017) model compared to. recorded data

The model developed by (Beitzel, 2010) gives good approximation for higher casting rates for example 4 m/h. However, the model underestimates the pressure for low casting rate; 0.25 m/h, Figure 17. Hence, the extension of the model needs to address the effect of the structural build-up.

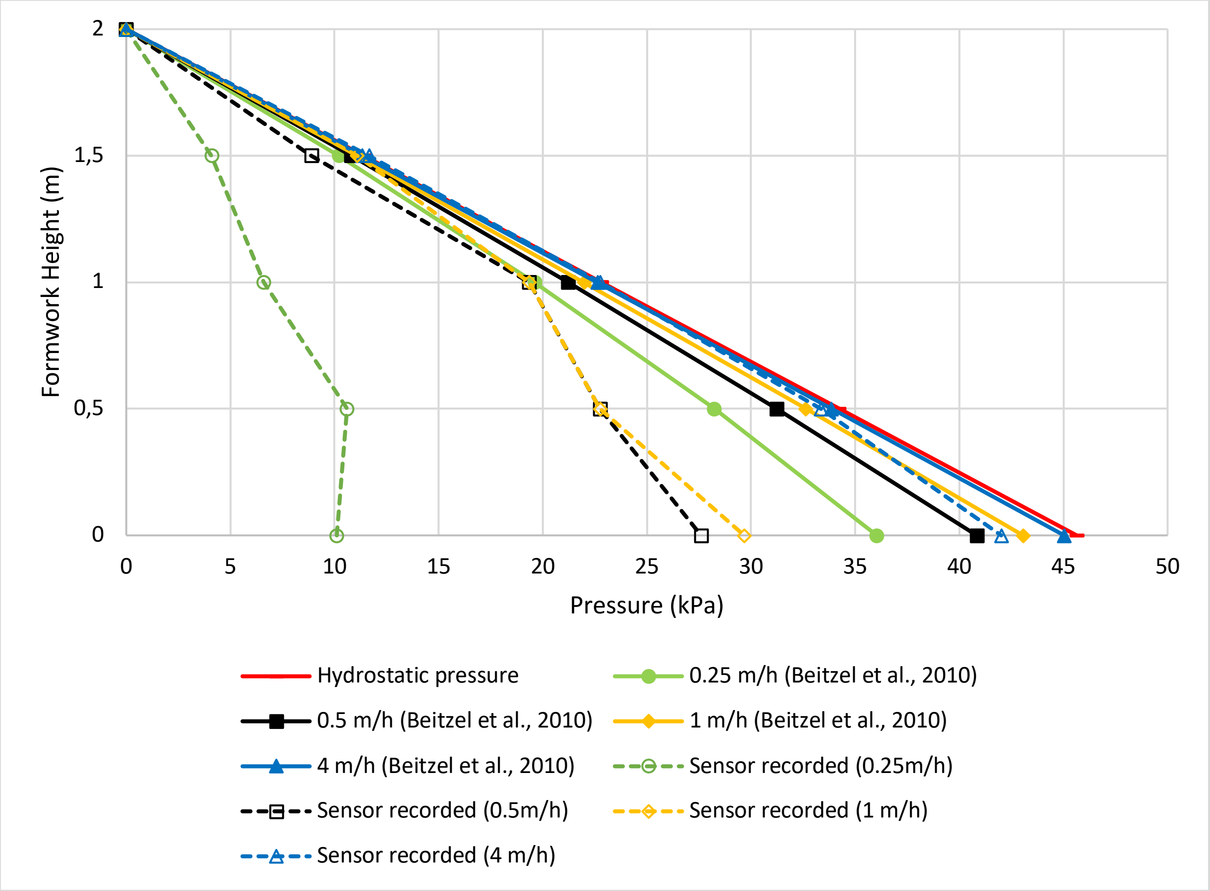

Figure 17. Pressure estimation using Beitzel (2010) model as compared. to recorded data

The pressure prediction using Ovarlez and Roussel (2006) model is shown in Figure 18. It is observed that the theoretical model is like the Beitzel (2010) model. Both models were developed based on the silo theory of Janssen (Beitzel, 2010). Parameters A_{thix} and C_{thix} in both the models of Ovarlez & Roussel and Betizel have a little effect on the pressure. It is observed that when the concrete has a slower structural development, the formwork pressure decay is slower.

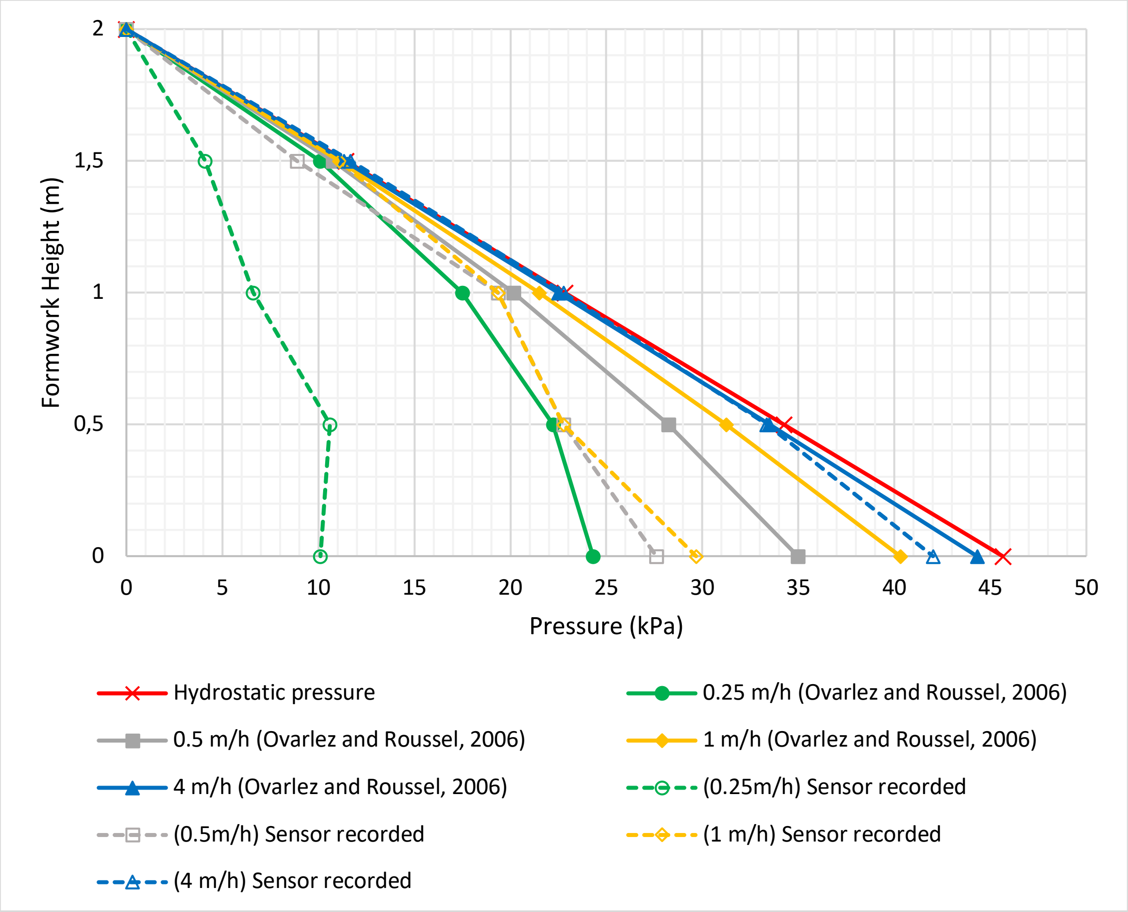

Figure 18. Pressure estimation using Ovarlez and Roussel (2006) model compared to. recorded data

3.4 Full scale trial testing (WP3)

A full-scale trial test was performed on a 7 m wall in connection to commercial pilot casting of a civil engineering structure, The same system used in the laboratory tests was used to monitor the form pressure. Sensors were installed at various distance intervals, Figure 19.

The concrete was delivered in multiple batches and was pumped from the bottom by a vertical pipe with drilled holes every 50 cm letting the concrete flowing out, filling the form. The casting rate was between 0.5 and 0.7 m/h. The pressure was monitored in real time. Data was stored in the cloud from the main unit. Engineers on the site were able to see the level of concrete as well as the pressure sensor readings. To possibly shorten the casting time, communication between the supervisors and the concrete pump operator was established.

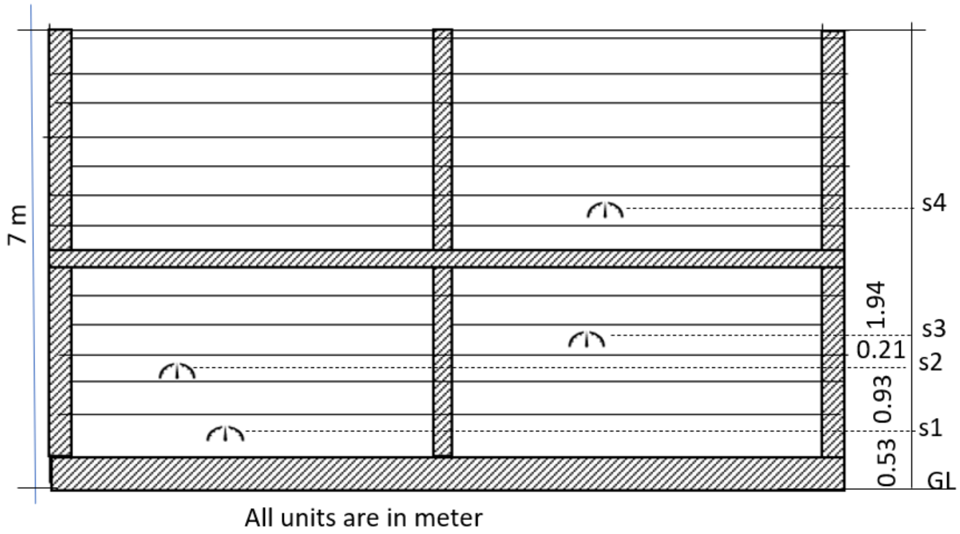

*Figure 19. Full scale test, l*ocations of sensors

Recorded pressure is shown in Figure 20. The pressure peaks at each truck unloading the concrete then drops before next truck delivery. It is seen that the pressure rises at the top layers because the bottom layers have achieved a sufficient structural build up. This is possible due to the slow casting rate of 0.5 m/h. The pressure begins to fall after the fifth hour and the maximum pressure recorded is 37 kPa which is about 20 % of the hydrostatic pressure for the 7 m wall.

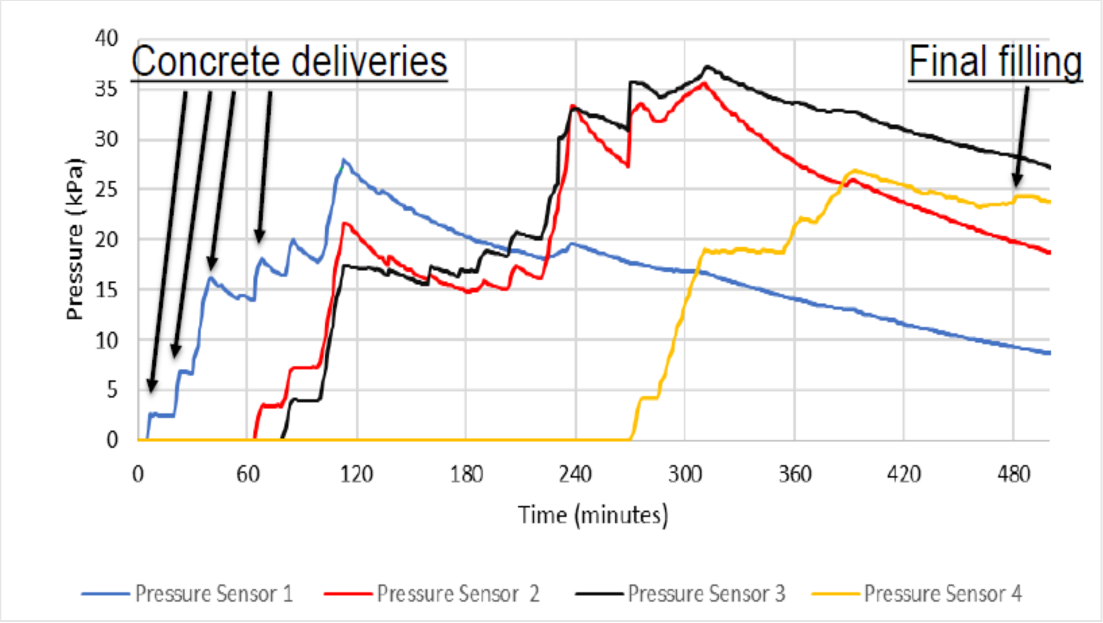

Figure 20. Pressure monitoring over time for 7 m wall at full scale recording

4 Publications

The results of the project were published in two state-of-the-art review papers, two peer-revied scientific journal papers. Details and links to the publications are listed below.

Table 7. Publications produced or to be produced within this PhD study.

Type	Title	Status
Journal	Lateral Formwork Pressure for Self-Compacting Concrete—A Review of Prediction Models and Monitoring Technologies." Materials 14.16 (2021): 4767.Yaser Gamil, Jonny Nilimaa, Mats Emborg, Andrzej Cwirzen https://doi.org/10.3390/ma14164767	Published
Journal	Digital Transformation of Concrete Technology—A Review. Frontiers in Built Environment, 8. (2022). Yaser Gamil, Andrzej Cwirzen, https://www.frontiersin.org/articles/10.3389/fbuil.2022.835236/full	Published
Journal	Deep Learning Prediction Model of Form Pressure for Cast in Place Self-Compacting Concrete (Submitted to automation in construction), Yaser Gamil, Jonny Nilimaa,Taoufik Najeh, Andrzej Cwirzen, Mats Emborg	Submitted
Journal	Assessment of Form Pressure Models for Self-Compacting Concrete (Final draft) Yaser Gamil, Jonny Nilimaa, Mats Emborg, Andrzej Cwirzen	Final draft
Conference	Modelling pressure decay for SCC	Planned
Journal	Modelling form pressure for ecological concrete	Planned
Conference	Form pressure monitoring of full scale in-situ wall cast with SCC	Planned

5 Summary and recommendations for the continuation

The report shows results obtained from the first part of the ongoing PhD study of which focus is digital transformation in construction industry and more specifically, the modelling and monitoring of lateral form pressure for cast in place self-compacting concrete.

The project was funded by Development Fund of the Swedish Construction Industry (SBUF) and NCC AB.

The following initial conclusion and recommendations were formulated based on the performed study:

1. The form pressure is affected by different input parameters, but the degree of each parameter is not yet well established
2. The actual formwork pressure is lower than the hydrostatic pressure even for a very high used casting rate.
3. The mathematical design models show some deviation on pressure estimation and distribution
4. It is possible to model the maximum pressure and pressure reduction making better decision for next day casting.
5. Designing based on the assumption of the hydrostatic pressure does not guarantee cost effective form, and fast construction time same economical and leads to overdesigned formworks.
6. The theoretical design models need to be extended to accurately estimate the maximum form pressure.
7. It is possible to digitalize form pressure with real-time monitoring and that provides accurate monitoring, the accuracy measured by comparing the reading with other materials i.e., water

The main activities of the second part of the project will include:

- Testing of ecological SCC, for example containing blast furnace slag (up to 50 % of the total binder)
- Development a unified model for maximum pressure, pressure distribution and pressure reduction.
- Performing more full-scale test to calibrate model developed,
- Updating and expanding the contractor-oriented guidelines for form pressure when casting with SCC with a special emphasis on ecological SCC.

6 References

Assaad. (2016). Correlating thixotropy of self-consolidating concrete to stability, formwork pressure, and multilayer casting. Journal of materials in civil engineering, 28(10), 04016107. doi:10.1061/(ASCE)MT.1943-5533.0001624

Gamil, Y., & Cwirzen, A. (2022). Digital Transformation of Concrete Technology—A Review. In Frontiers in Built Environment (Vol. 8). https://doi.org/10.3389/fbuil.2022.835236

Gamil, Y., Nilimaa, J., Emborg, M., & Cwirzen, A. (2021). Lateral formwork pressure for self-compacting concrete—a review of prediction models and monitoring technologies. In Materials (Vol. 14, Issue 16). https://doi.org/10.3390/ma14164767

Beitzel, M. (2010). Modeling fresh concrete pressure of normal and self-compacting concrete Design, Production and Placement of Self-Consolidating Concrete (pp. 243-254): Springer.

Billberg, P. (2006). Form pressure generated by self-compacting concrete: influence of thixotropy and structural behaviour at rest. Byggvetenskap.

Gamil, Y., & Cwirzen, A. (2022). Digital Transformation of concrete technology – a review. Front. Built Environ. - Sustainable Design and Construction, 8.

Gamil, Y., Nilimaa, J., Emborg, M., & Cwirzen, A. (2021). Lateral Formwork Pressure for Self-Compacting Concrete—A Review of Prediction Models and Monitoring Technologies. Materials, 14(16), 4767.

Khayat, & Omran, A. (2009). State-of-the-art review of form pressure exerted by self-consolidating concrete. Université de Sherbrooke, Canada.

Khayat, & Omran, A. (2010). Evaluation of SCC formwork pressure. Concrete international, 32(6), 30-34. doi: https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/51663748

Khayat, K. H., & Assaad, J. J. (2008). Measurement systems for determining formwork pressure of highly-flowable concrete. Materials and Structures, 41(1), 37-46.

Leemann, A., Hoffmann, C., & Winnefeld, F. (2006). Pressure of self-consolidating concrete on formwork. Concrete international, 28(2), 28-31.

Nilimaa, J. (2022). Lateral form pressure induced by SCC. Paper presented at the Nordic Concrete Research XXIV NCR Symposium 2022.

Omran, Khayat, & Elaguab. (2012). Effect of SCC mixture composition on thixotropy and formwork pressure. Journal of materials in civil engineering, 24(7), 876-888. doi:https://doi.org/10.1061/(ASCE)MT.1943-5533.0000463

Omran, & Khayat, K. (2014). Choice of thixotropic index to evaluate formwork pressure characteristics of self-consolidating concrete. Cement and concrete research, 63, 89-97. doi:10.1016/j.cemconres.2014.05.005

Vanhove, Y., & Djelal, C. (2002). Formwork pressures with self-compacting concrete. Concrete-London-Concrete Society-, 36(6), 22-23.