Business from technology

Measuring and Modeling of Formwork Pressure of Self-Consolidating Concrete

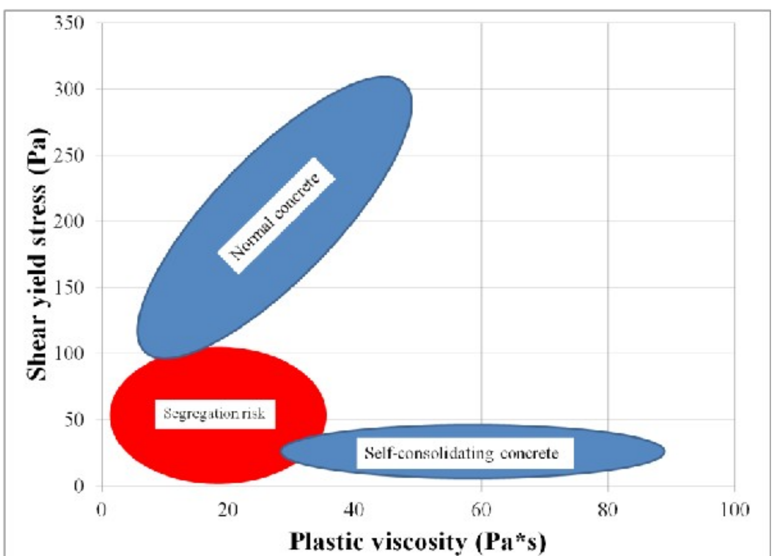
Prof. David Lange and Jacob Henschen
University of Illinois at Urbana-Champaign

Regensburg, Germany – March 12, 2014

Greetings from the University of Illinois

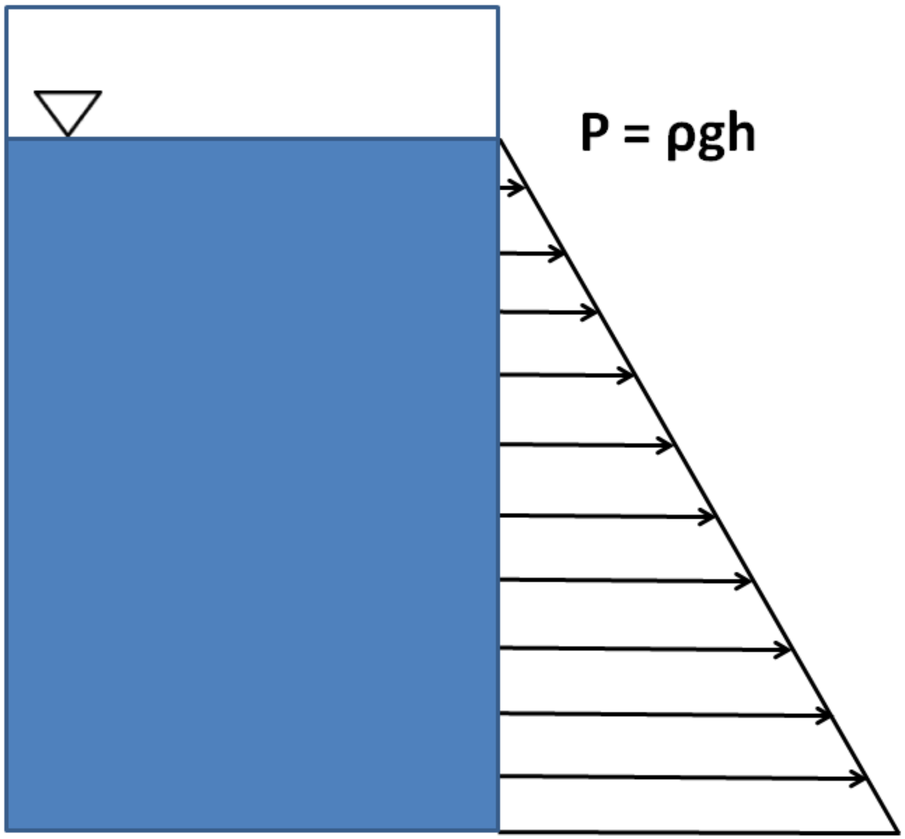
Self-consolidating concrete (SCC)

- Continuous casting
- Higher casting rates
- No vibration necessary
- Casting in dense reinforcement



www.selfconsolidatingconcrete.org

Formwork Pressure



- Higher fluidity leads to higher lateral pressures on the formwork


Over 40ft tall wall
Nominal strength
1600 pcf
One pour.
How fast?

Formwork standards

- ACI 347
  - Forms for highly fluid concrete must withstand full hydrostatic pressure
- DIN 18218:2010-01
  - Recently revised to account for fluidity of SCC

DIN Standard on Formwork Pressures Updated

Standard now addresses pressures exerted by self-consolidating concrete

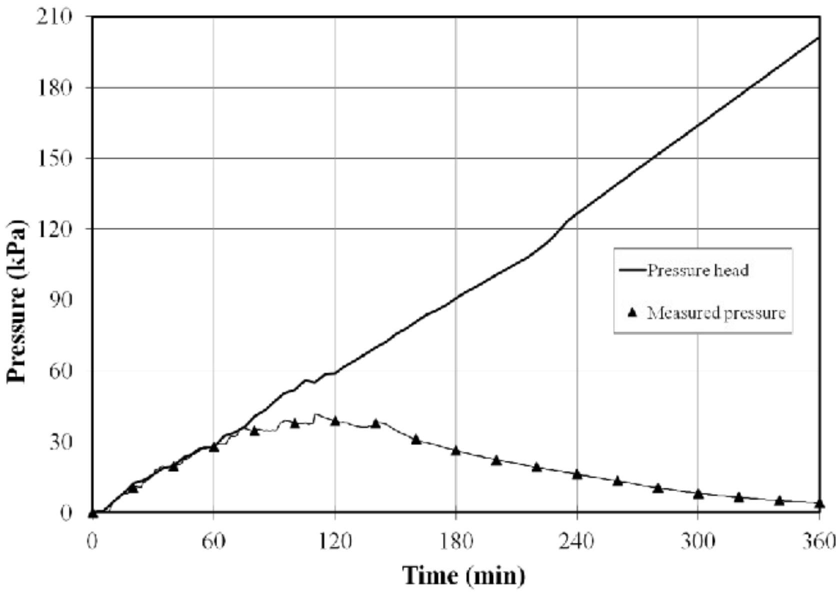
Because overestimation can lead to unnecessary construction cost and underestimation could result in excessive bulging or even collapsed formwork, accurate predictions of formwork pressures are required. Over the past several years, researchers[1-3] have been working to develop methods for predicting pressures exerted by self-consolidating concrete (SCC). While it has been shown that SCC can produce nearly

Their tests showed that the major factors affecting the maximum formwork pressure are setting time (corresponding to initial setting time by ASTM C403/C403M)[4] and placement rate. Specifically, the maximum pressure was found to increase with an increasing water-cementitious material ratio (*w/cm*), due to the correlation between *w/cm* and setting time. The pressure was also significantly influenced by the type of

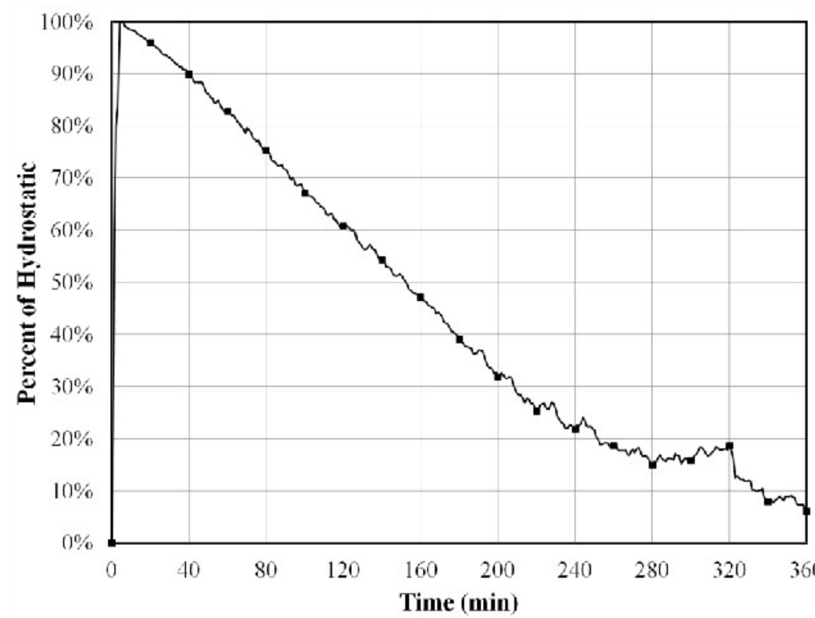
$$\sigma_{hk,max} = (1.0\ \mathrm{m} + 0.26\ v \cdot t_E) \cdot \gamma_C \geq 30\ \mathrm{kPa} \qquad (1)$$

where $\sigma_{hk,max}$ represents the 95th percentile value of the maximum pressure exerted by the fresh concrete, γ_C is the unit weight of fresh concrete = 25 kN/m^3 (159 lb/ft^3), t_E is the setting time of the concrete (using the Vicat needle test per Reference 9), and v is the mean rate of concrete placement. Equation (1) is valid for t_E from 5 to

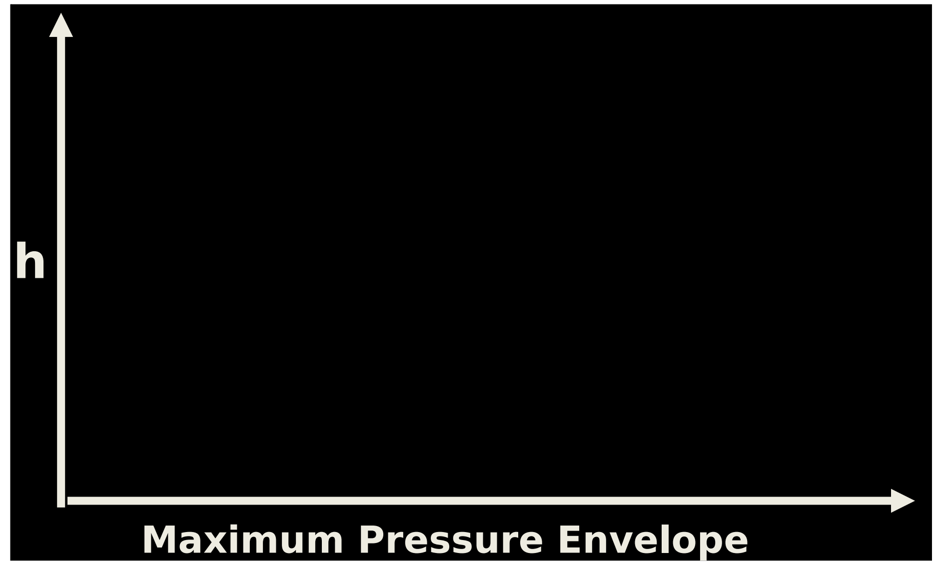
Measured pressures

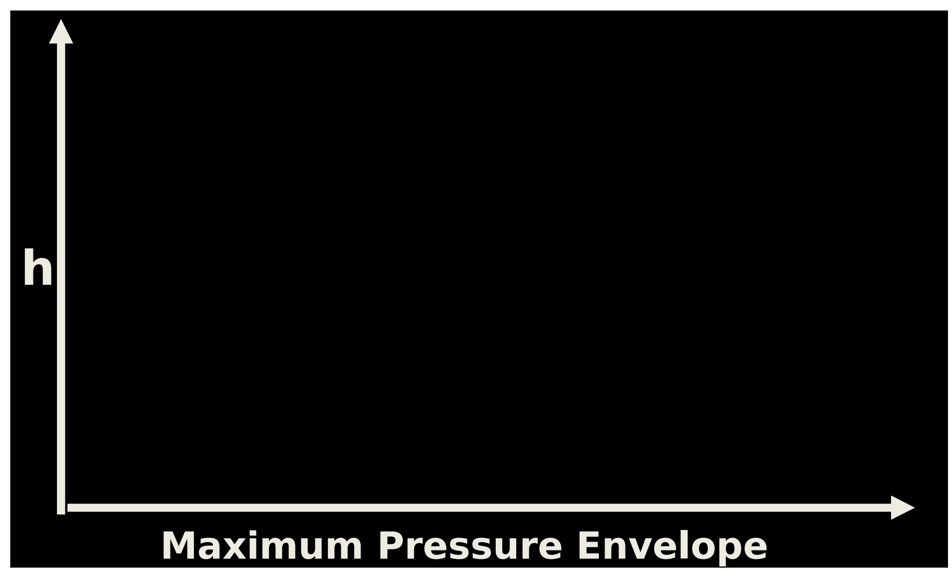


- Maximum pressures typically lower than hydrostatic



Field measurements have shown that…





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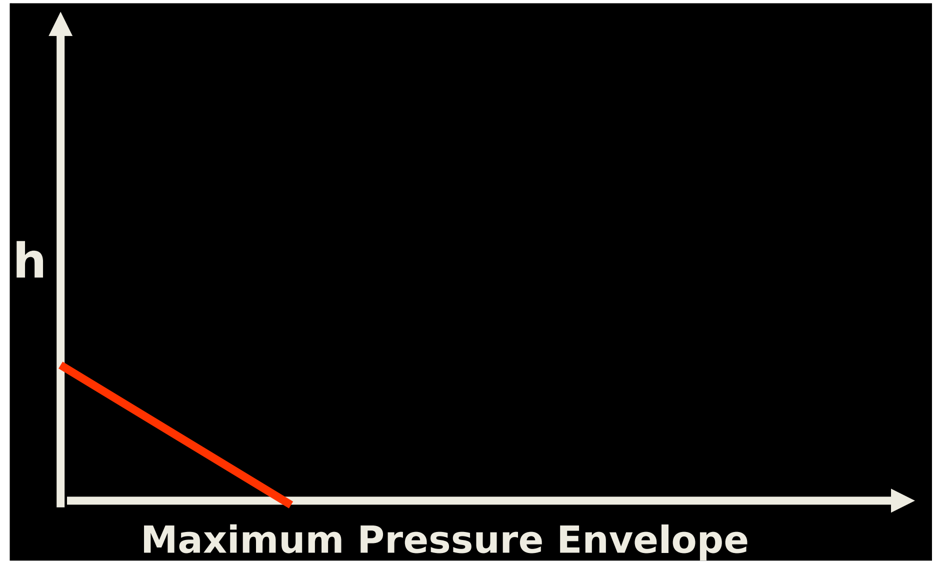

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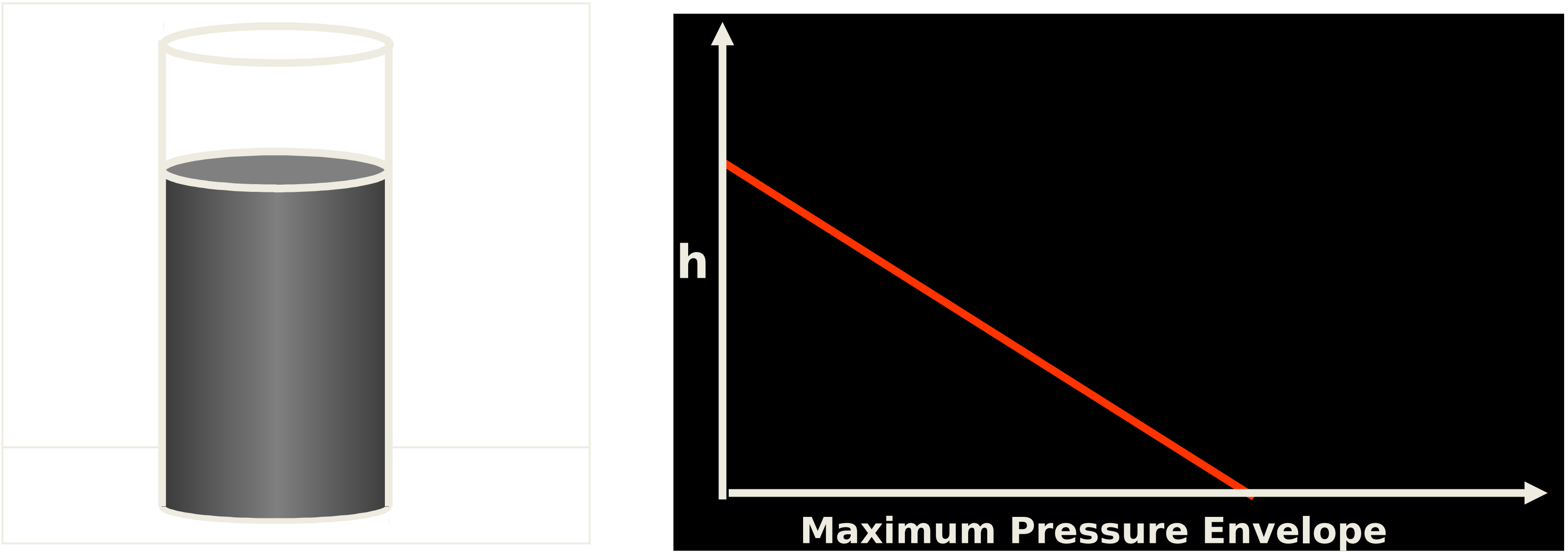

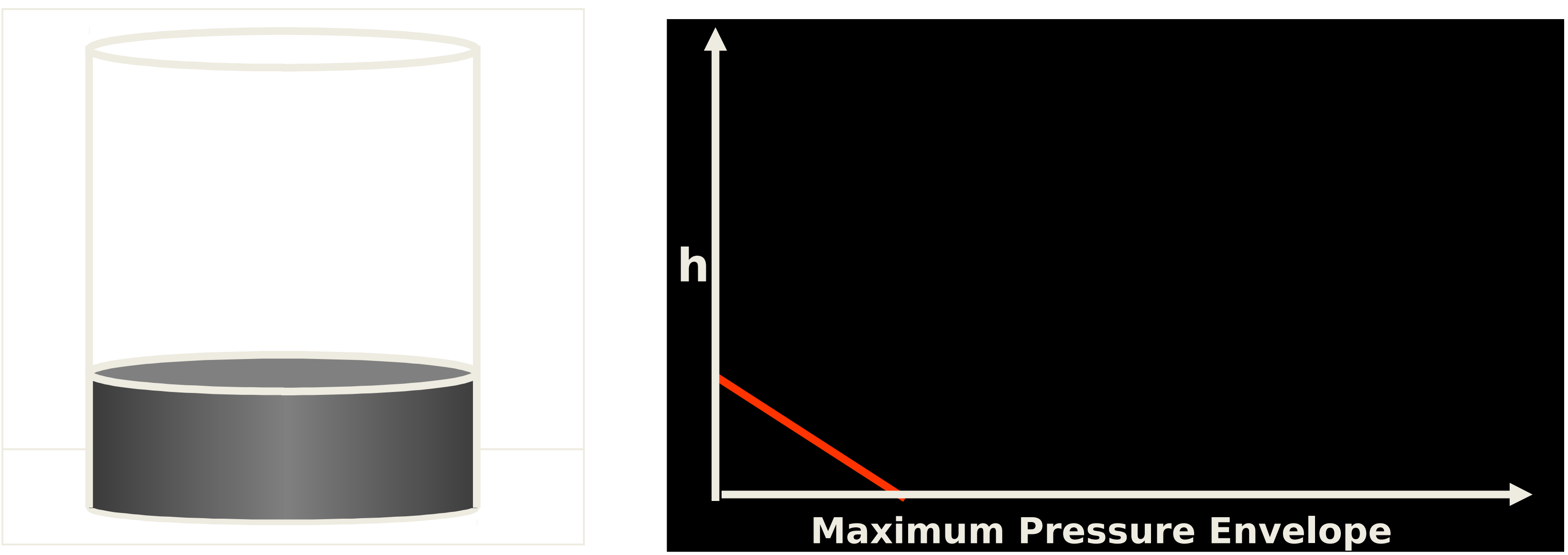

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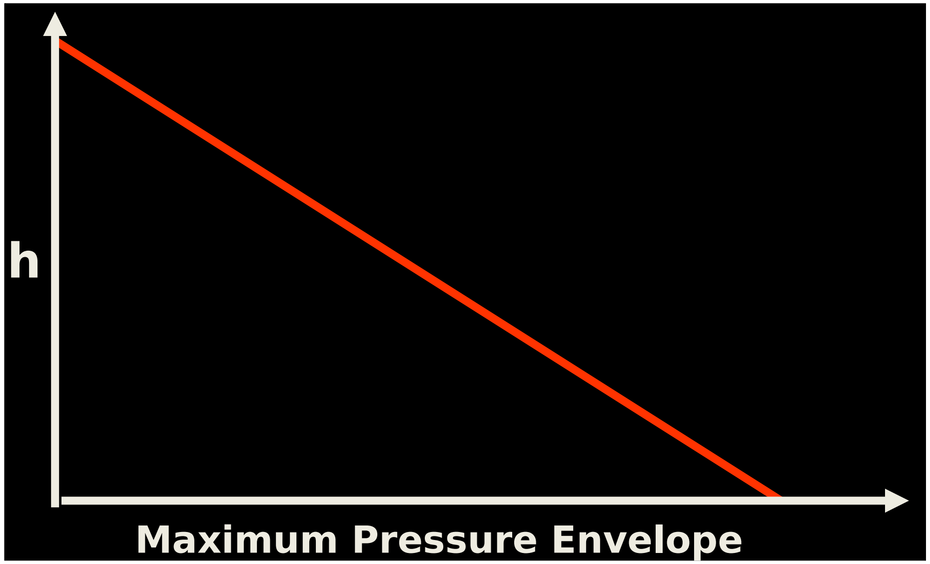

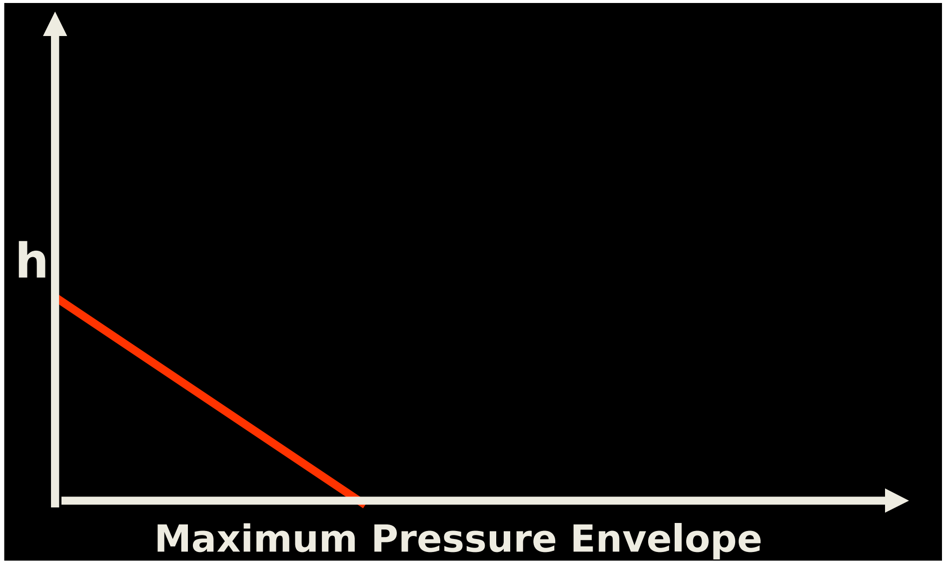

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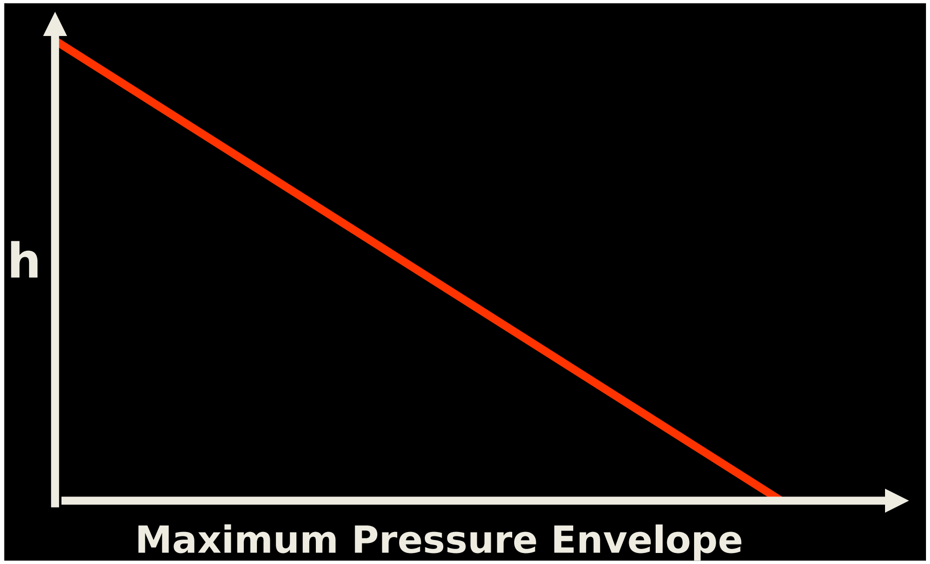

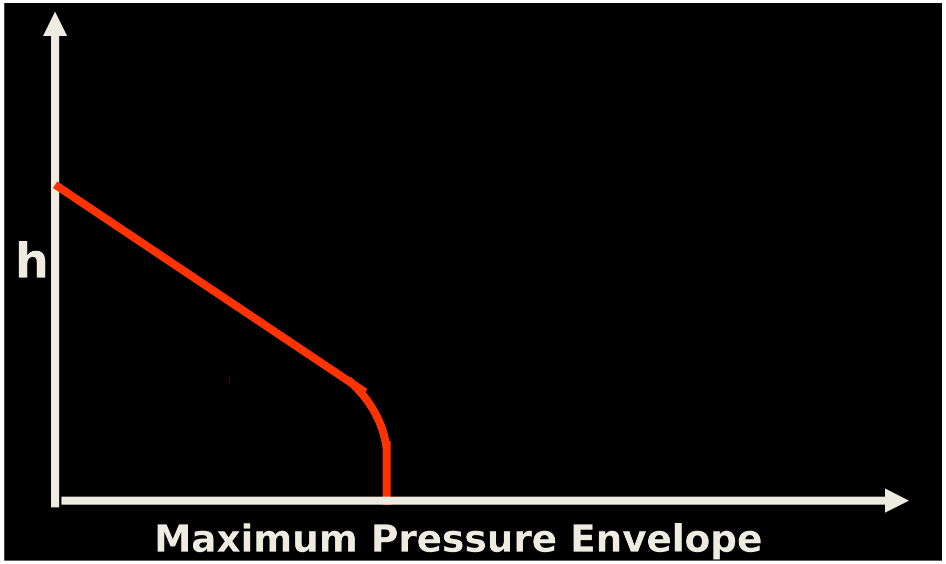

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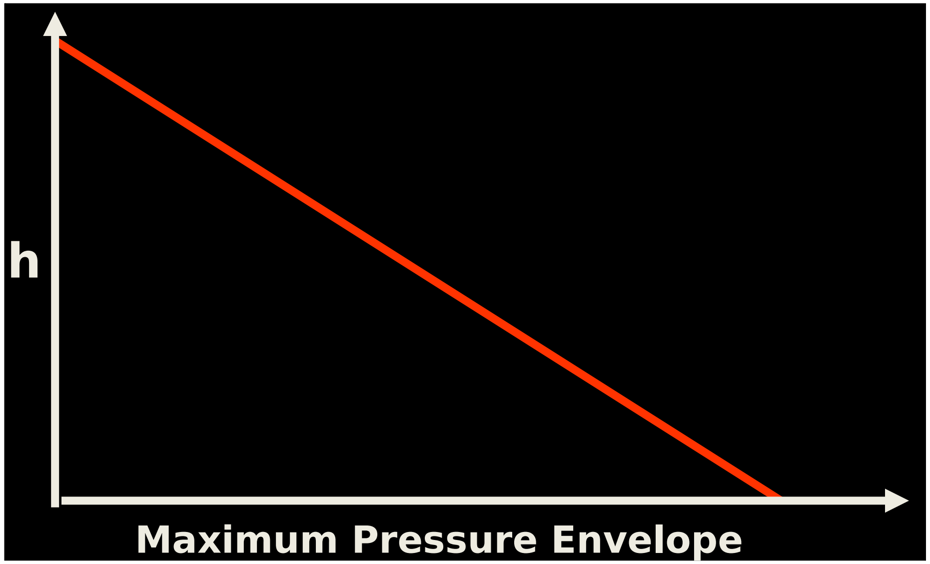

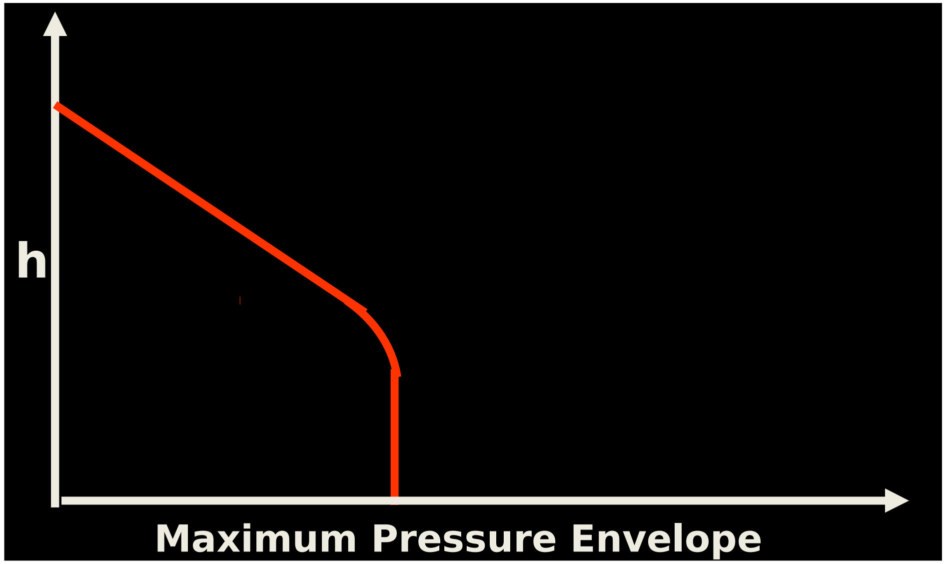

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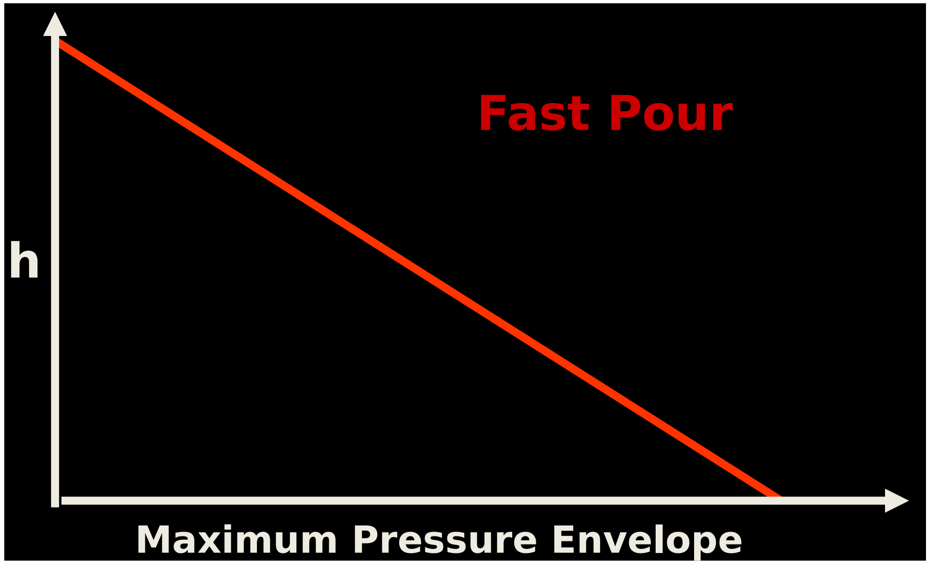
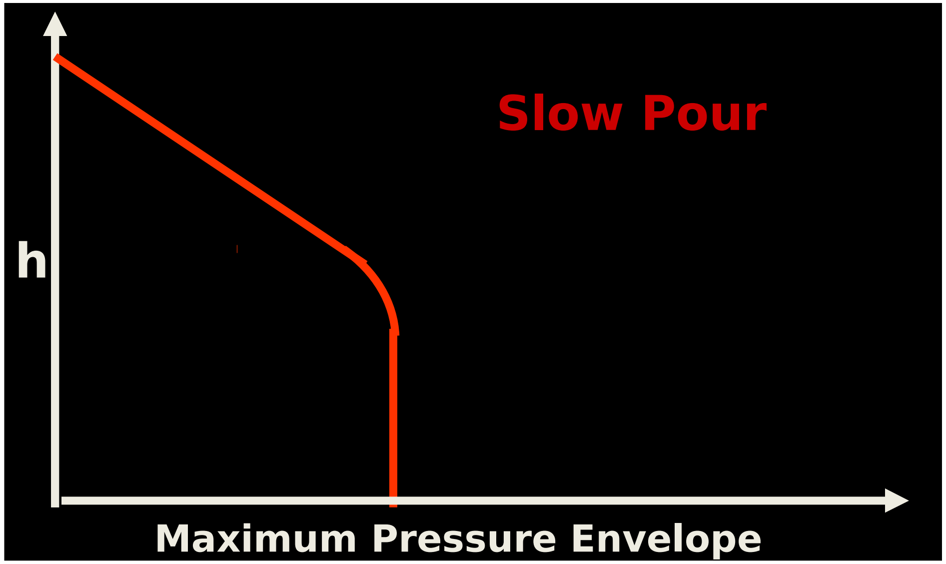




Mechanisms of form pressure decay

- The main factors:
  - Internal friction
  - Aggregate contact and tendency to settle/consolidate
  - “Skeleton” structure
  - Higher agg content leads to rapid pressure decay
  - Thixotropy
  - *Tendency of concrete to gel when at rest*
  - Shear strength increases even before “set” occurs
  - Greater thixotropy leads to rapid pressure decay

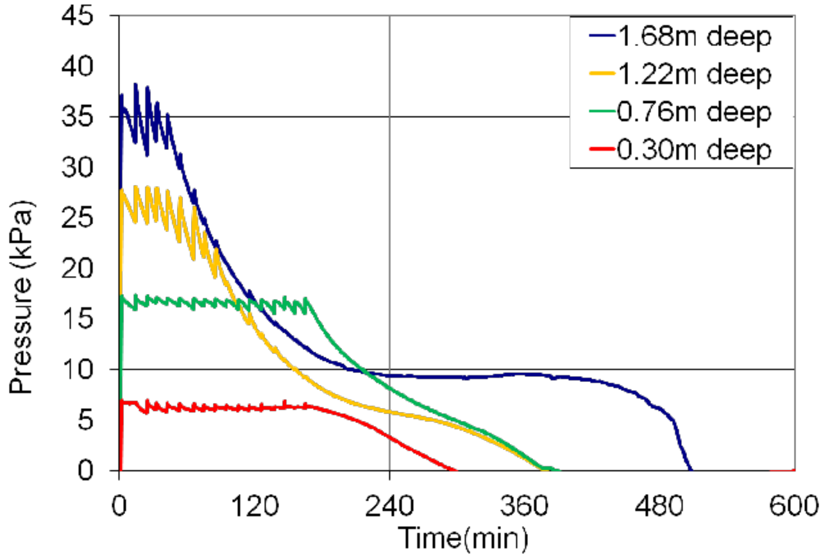
Can we accurately model formwork pressure?

- Minimize testing
- Accurate and robust
- Field deployment

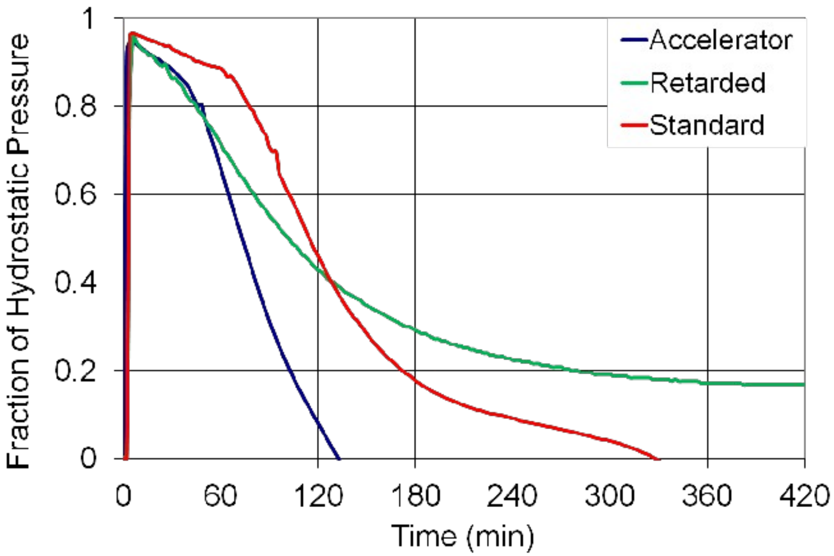
First step, measuring formwork pressure

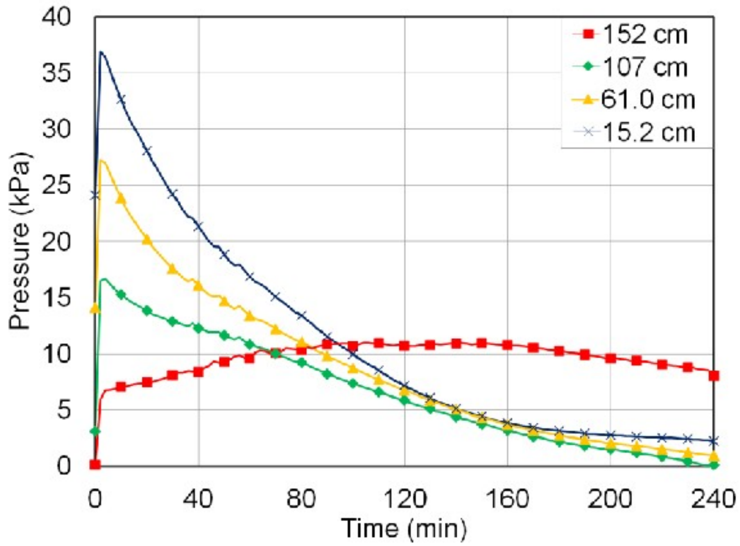
- Honeywell full bridge pressure transducer
- Sensor brackets hold sensor face flush to formwork surface

Lab testing



- Pressure decay rate consistent at varying depths
- Vibration and admixtures alter pressure decay

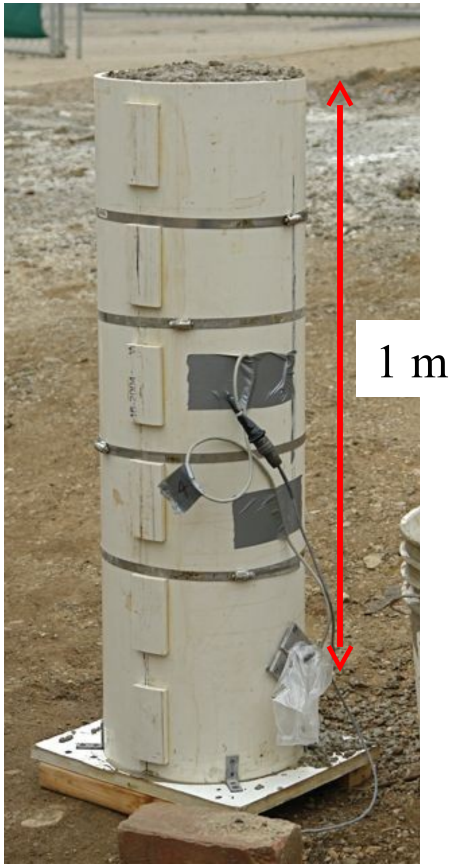




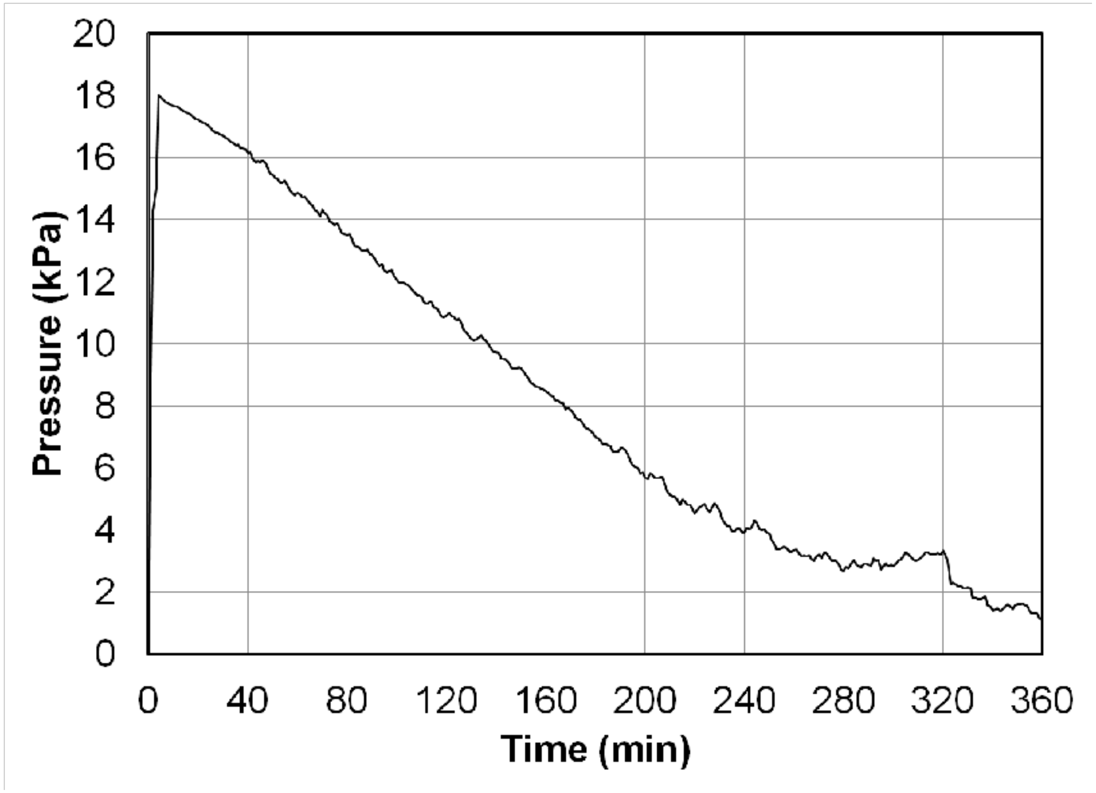
Our approach

- **Step 1:** Characterize the characteristic pressure decay of the material
  - Measure decay curve from a column
  - Calculate pressure as a function of height of concrete over time, C(t)
- **Step 2:** Impose variable pressure head on the material that is undergoing gelation, stiffening
  - Generate filling rate curve
  - Multiply filling rate curve by C(t) from column to generate predicted pressure over time

Step 1

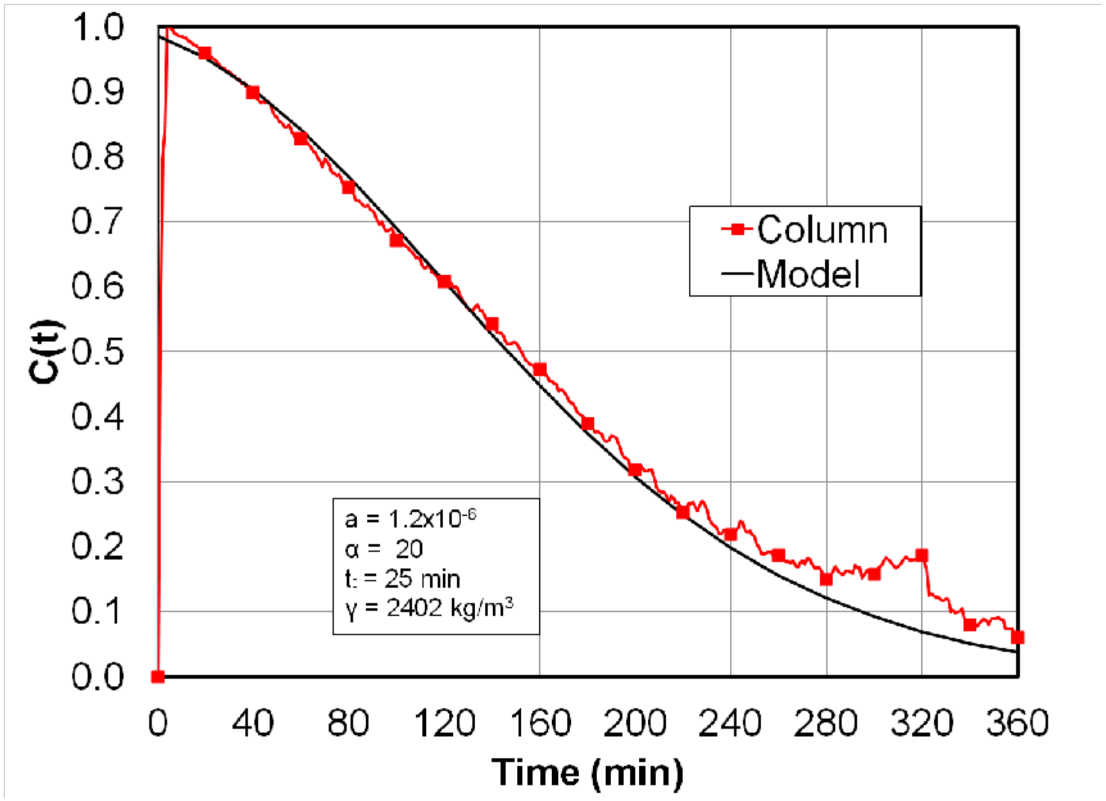


Filled quickly to generate maximum pressure



Pressure measured while material is at rest

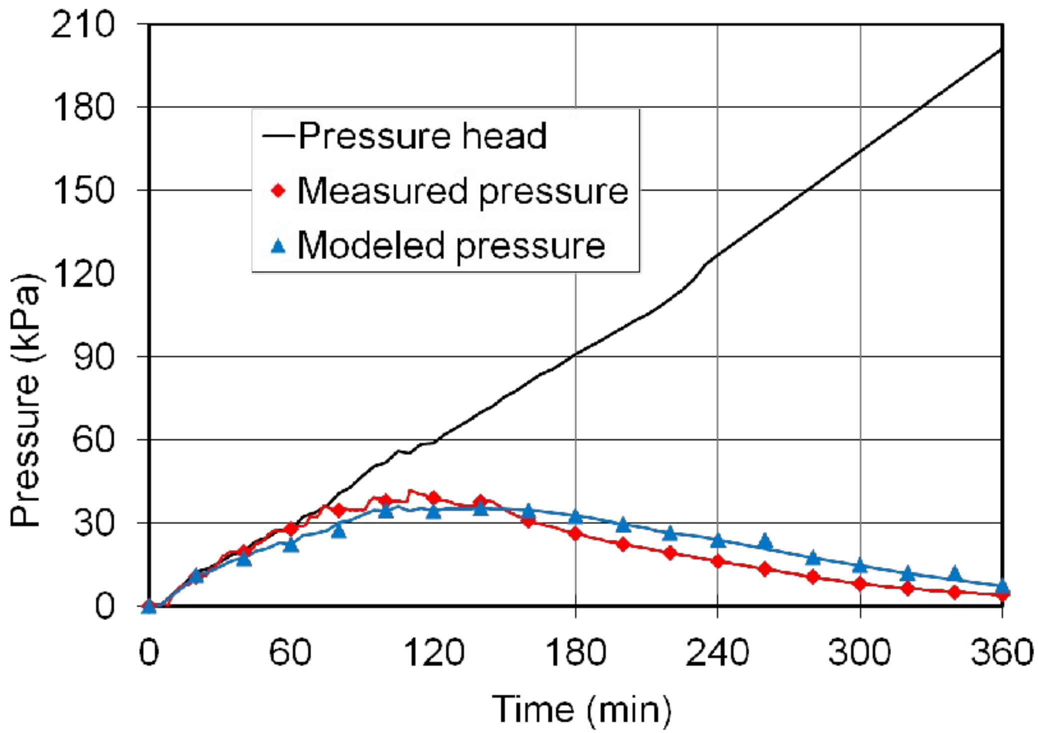
“decay signature”



- Normalize pressure
- Apply numerical approximation of curve

$$C(t)_{\mathrm{mod}} = \frac{C_0}{\left(at^2+1\right)^{\alpha}}$$

Step 2



- Apply overburden pressure head
- Use unit weight of concrete

$$P(t) = C(t) \times \gamma \times h(t)$$

Pressure = Model x Unit weight x Casting rate

Field Validations

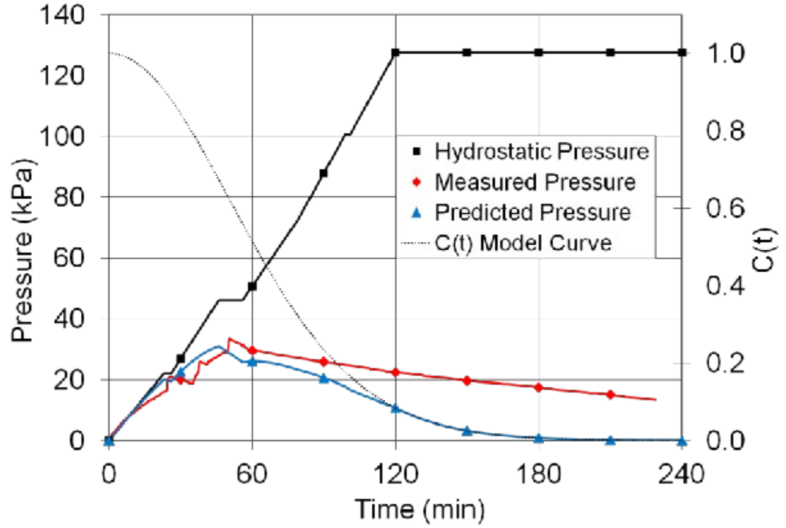
- Illinois DOT I-74 retaining walls
- OSF Hospital Milestone Project
- Stockholm Round Robin Tests

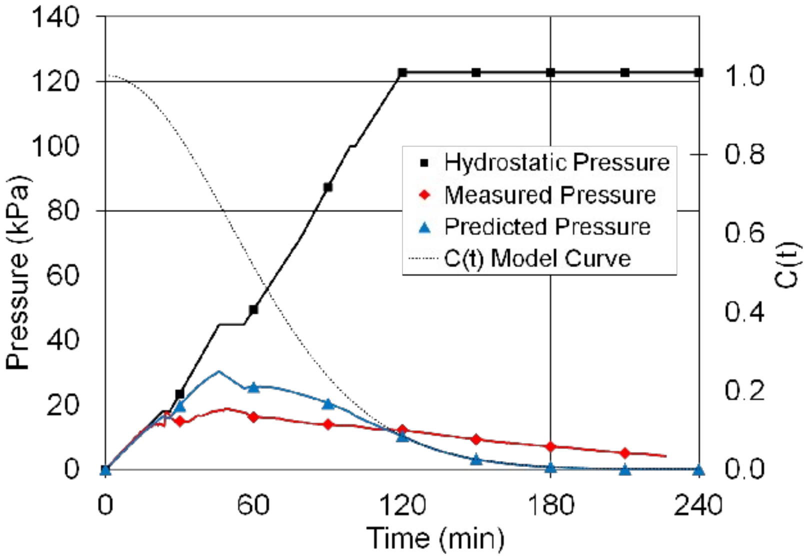
Field Validation #1
Illinois DOT I-74 retaining walls

I-74 Retaining wall

- SCC used for aesthetics
- Slump flow: 71 cm
- Wall height: ~7 m
- Placed with tremie or pump

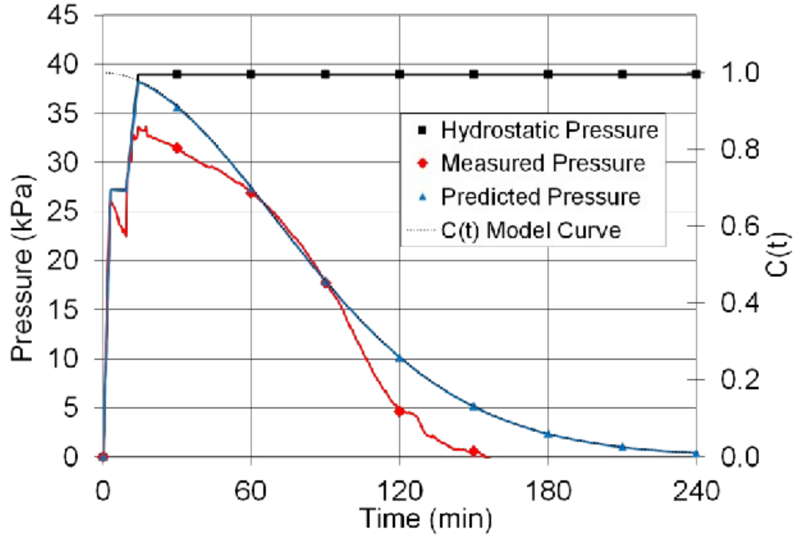
Wall 8511 Panel 9-10

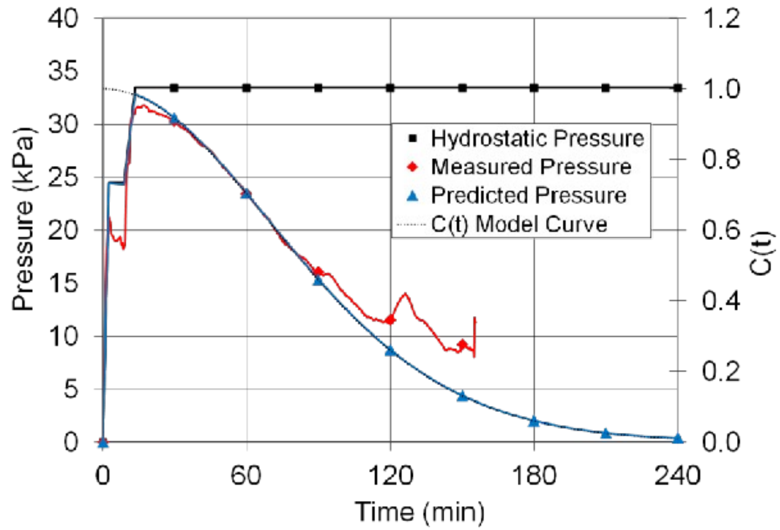




- Height 6.0 m
- 2 sensors at 5.6 m from top
  - 1 at bulkhead
  - 2 under drop chute

Wall 81 Panel R

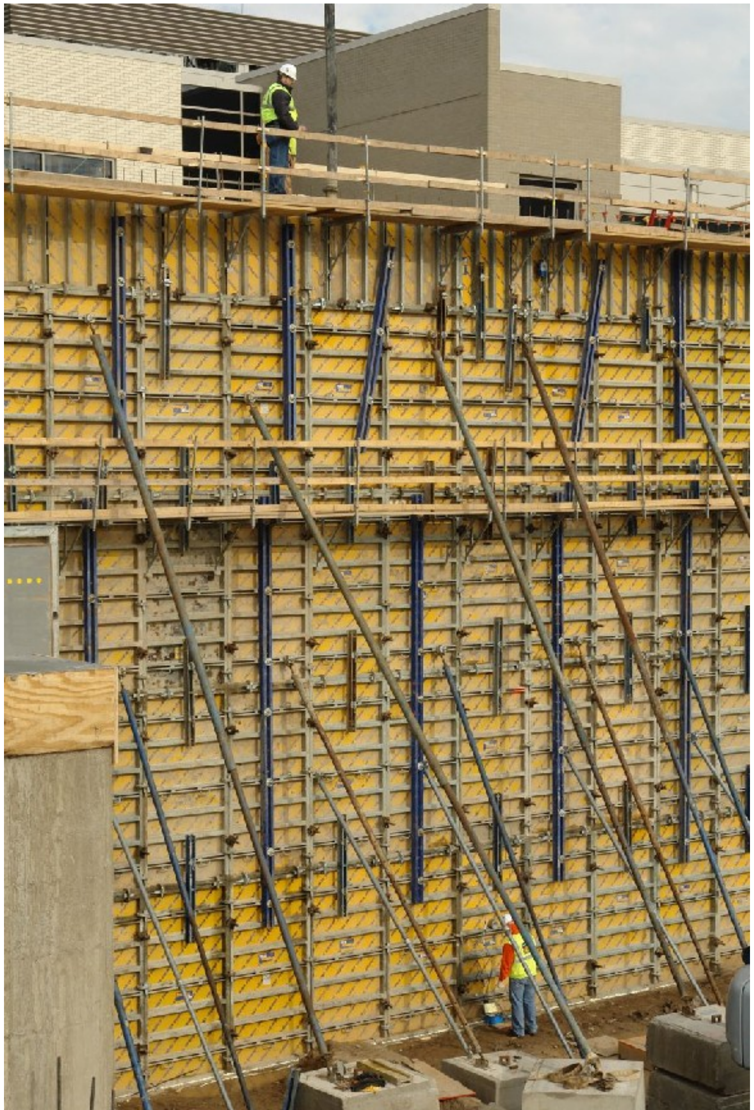




- Height: 2 m
- 2 sensors at 1.7 m
  - 1 under drop chute
  - 2 at bulkhead

Field Validation #2
OSF Hospital Milestone Project

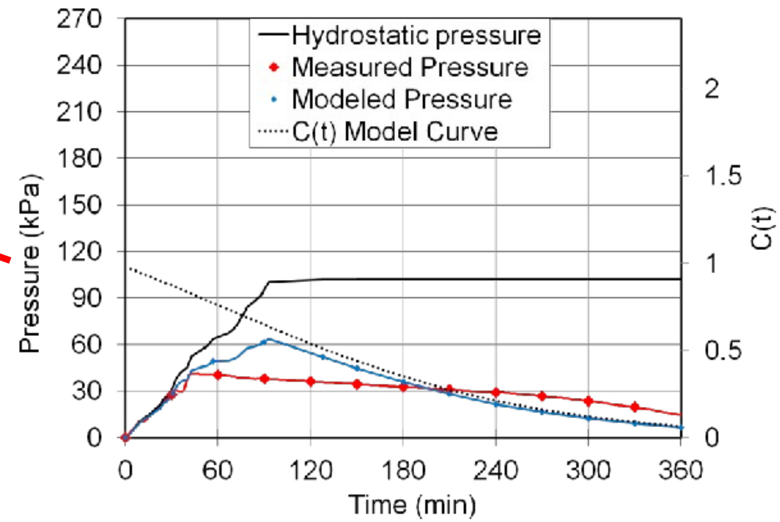
OSF Hospital Milestone Project



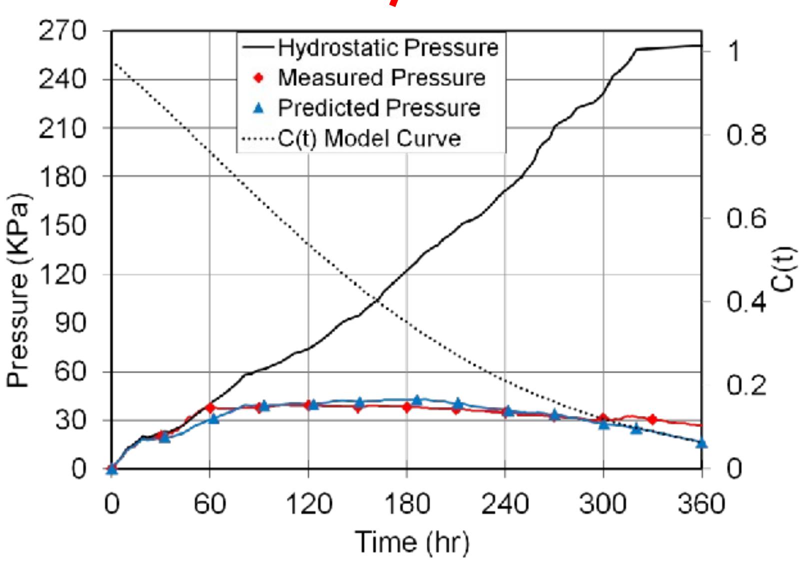
- Foundation wall construction
- Continuous placement
- Slump flow: 60-70 cm
- Height: 12-15 m

Wall #1

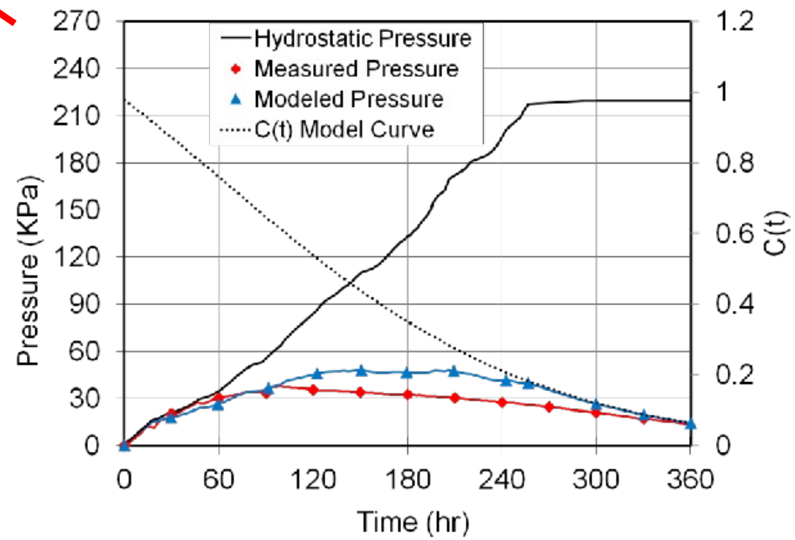
Genie S-65



Hydrostatic pressure
Measured Pressure
Modeled Pressure
C(t) Model Curve
Pressure (kPa)
C(t)
Time (min)
0 60 120 180 240 300 360
0 30 60 90 120 150 180 210 240 270
0 0.5 1 1.5 2

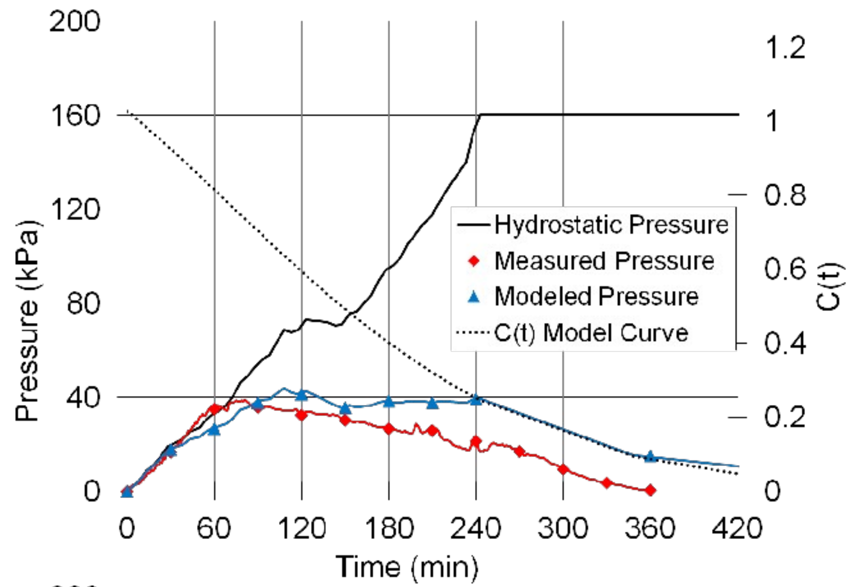


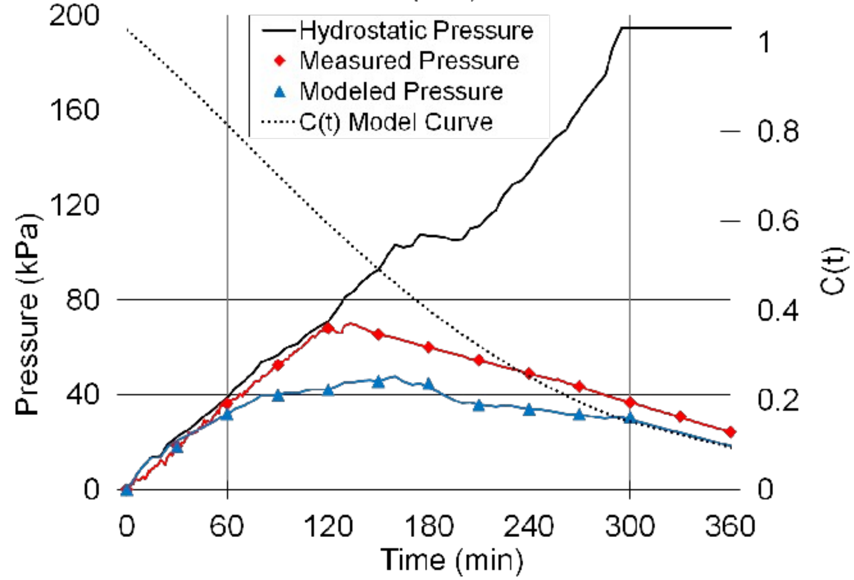
Hydrostatic Pressure
Measured Pressure
Predicted Pressure
C(t) Model Curve
Pressure (KPa)
C(t)
Time (hr)
0 60 120 180 240 300 360
0 30 60 90 120 150 180 210 240 270
0 0.2 0.4 0.6 0.8 1



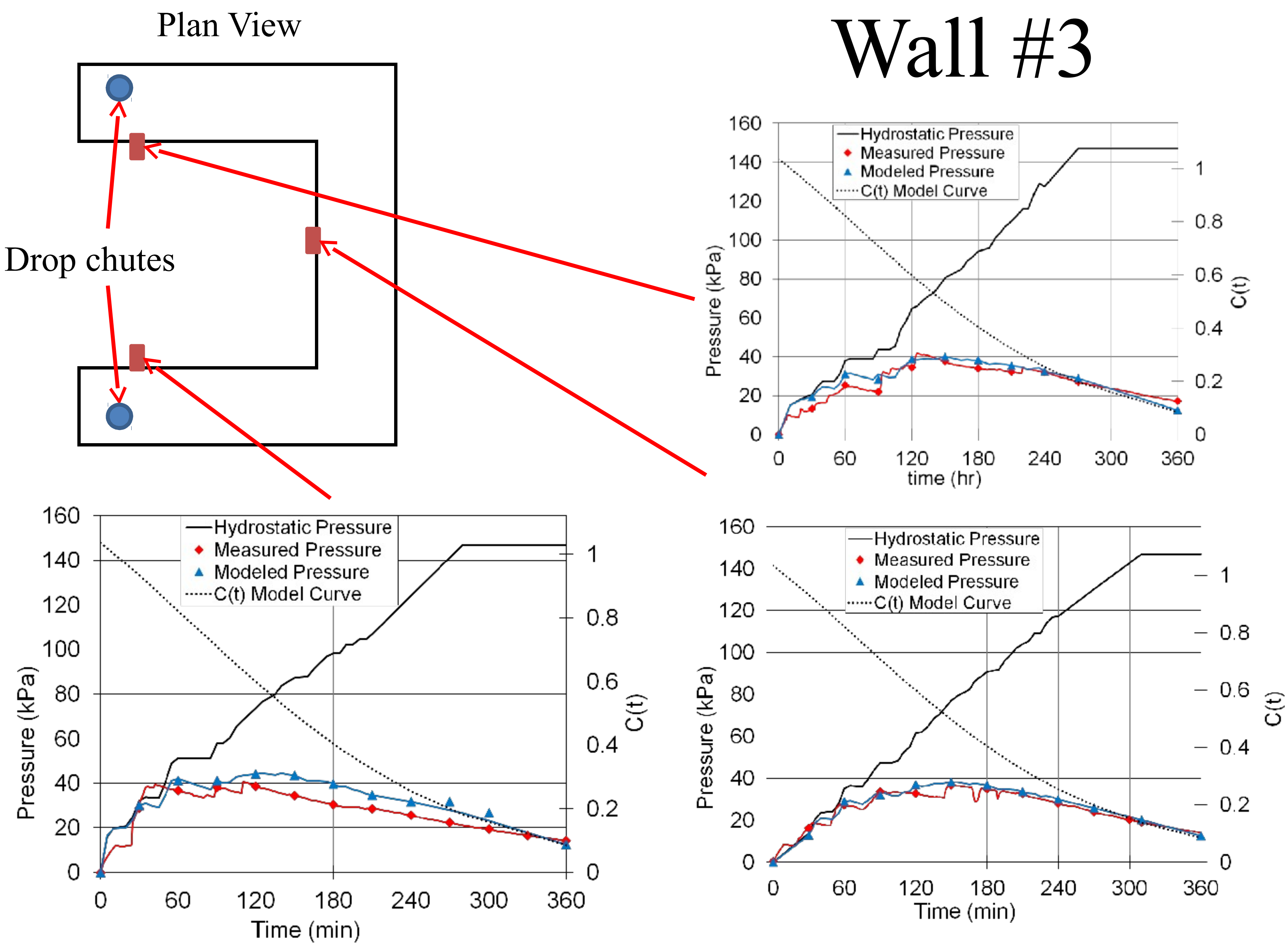
Hydrostatic Pressure
Measured Pressure
Modeled Pressure
C(t) Model Curve
Pressure (KPa)
C(t)
Time (hr)
0 60 120 180 240 300 360
0 30 60 90 120 150 180 210 240 270
0 0.2 0.4 0.6 0.8 1 1.2

Wall #2


Pressure (kPa)
C(t)
Time (min)
Hydrostatic Pressure
Measured Pressure
Modeled Pressure
C(t) Model Curve
0
60
120
180
240
300
360
420
40
80
160
200
0.2
0.4
0.6
0.8
1
1.2

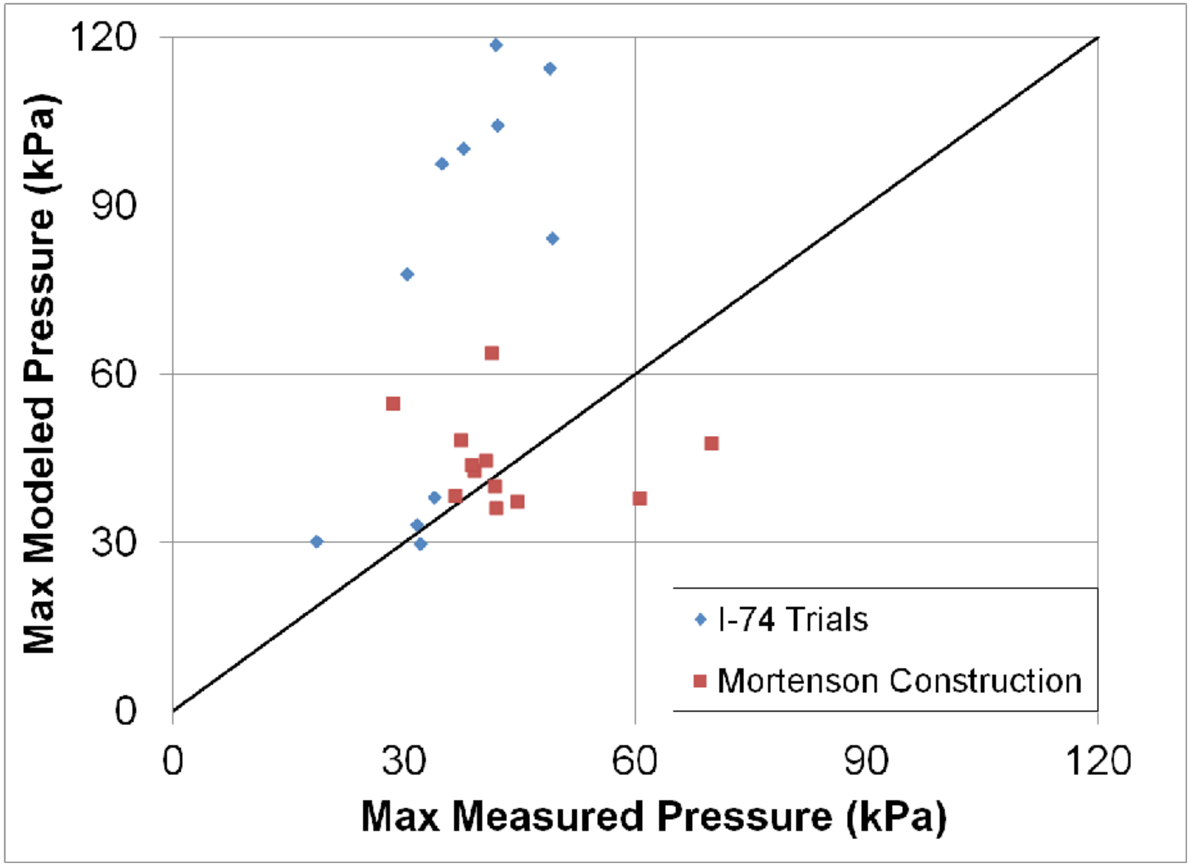

Pressure (kPa)
C(t)
Time (min)
Hydrostatic Pressure
Measured Pressure
Modeled Pressure
C(t) Model Curve
0
60
120
180
240
300
360
40
80
120
160
200
0.2
0.4
0.6
0.8
1

Wall #3



Plan View
Drop chutes
Hydrostatic Pressure
Measured Pressure
Modeled Pressure
C(t) Model Curve
Pressure (kPa)
C(t)
time (hr)
Time (min)
0
20
40
60
80
100
120
140
160
0.2
0.4
0.6
0.8
1
60
120
180
240
300
360

Field Trial Summary



IlliForm: Model implemented in Excel

IlliFormV0.92.xls

IlliForm 0.92

Prof. David A. Lange, University of Illinois at Urbana-Champaign

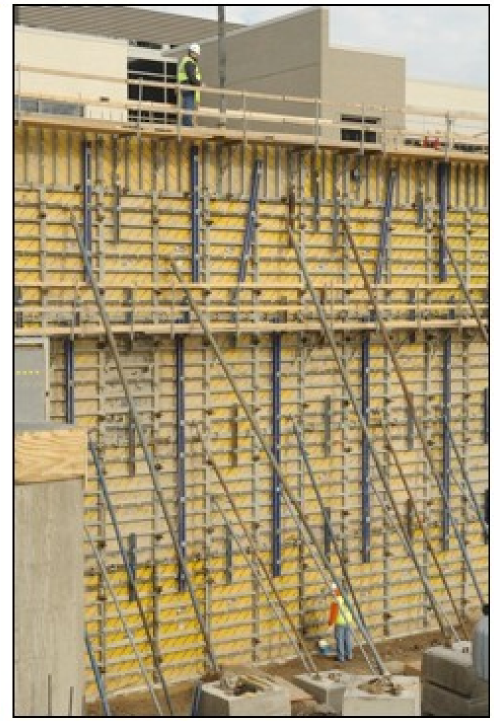
IlliForm is a model for predicting formwork pressure for projects that use self consolidating concrete (SCC). The model is useful for selecting required formwork strength or determining maximum safe filling rate. The model provides guidance that can help decision-making, optimize economy, and improve safety of construction with SCC.

This excel file contains worksheets to use the model. The user provides several input parameters, including the SCC characteristic decay signature, formwork geometry, formwork strength, and form-filling rate. Before using the worksheets, the test column data from a representative sample of the SCC should be acquired.

Worksheet procedure are shown in **YELLOW boxes**, and user entered variables are in **YELLOW cells**. Alisting of worksheets and user interaction is as follows:

A. Introduction (this worksheet; no user input)
B. Data Entry. User enters column test data and concrete densityparameters.
C. Decay curve. User adjusts curve fit parameters.
D. Prediction. User changes parameters to plan project with SCC.
E. Acknowledgements

ILLINOIS
University of Illinois at Urbana-Champaign

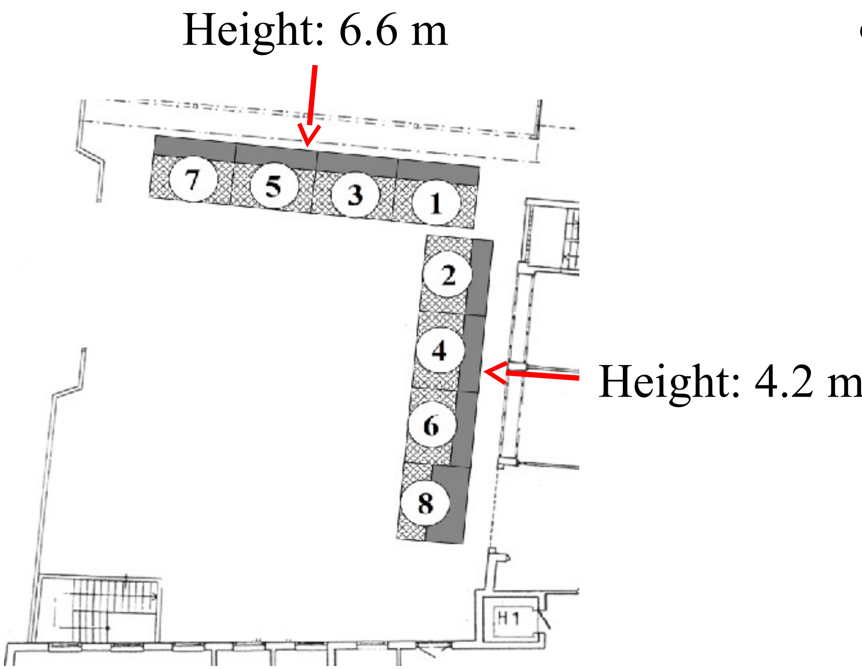


Introduction | Data Entry | Decay Curve | Prediction | Acknowledgements

Ready

Field Validation #3
Stockholm Round Robin Tests

Round robin tests in Stockholm for 10 different form pressure models



- RILEM TC 233-FPC
  - Stockholm, June 2012
  - Comparison of 10 models
  - Theoretical
  - Lab tests
  - Field tests
  - 8 wall sections tested over 4 days

Reference: Billberg, P et. al, "Field validation of models for predicting lateral form pressure exerted by SCC," Cement and Concrete Composites, accepted 2014.

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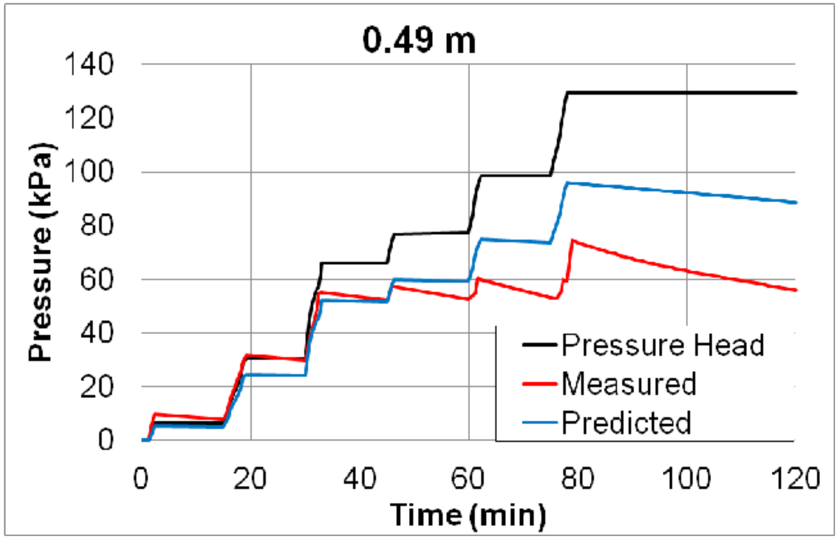
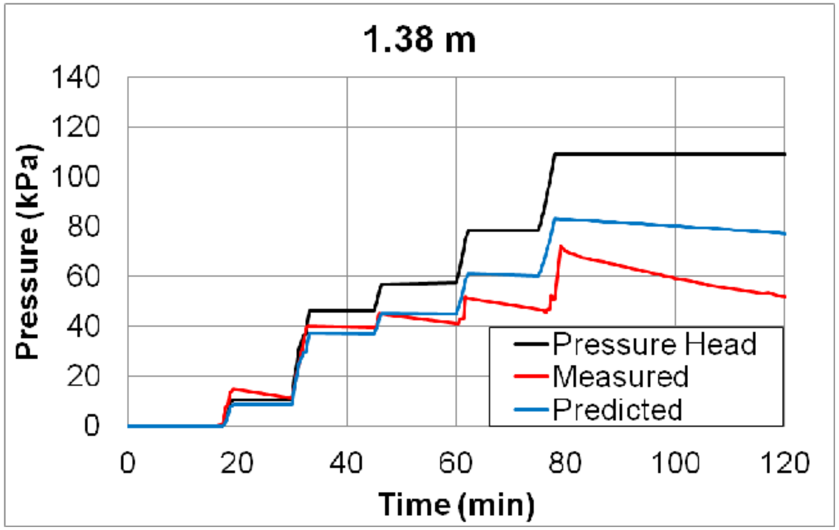
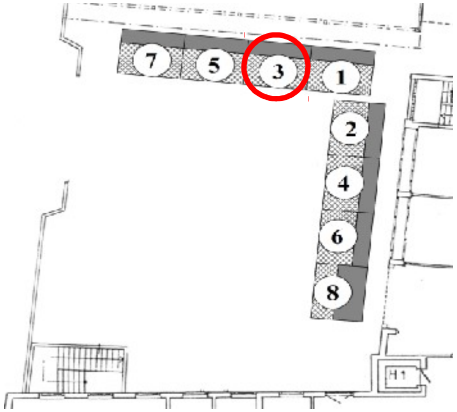
Corresponding author: Peter H. Billberga

Nicolas Rousselb, Sofiane Amzianec, Marc Beitzeld, George Charitoue,Björn Freundf, John N. Gardnerg, Guillaume Grampeixh, Carl-Alexander Graubneri, Lloyd Kellerj, Kamal H. Khayatk, David A. Langel, Ahmed F. Omranm, Arnaud Perrotn, Tilo Proskeo, Robert Quattrociocchip, Yannic Vanhoveq

Round Robin Results



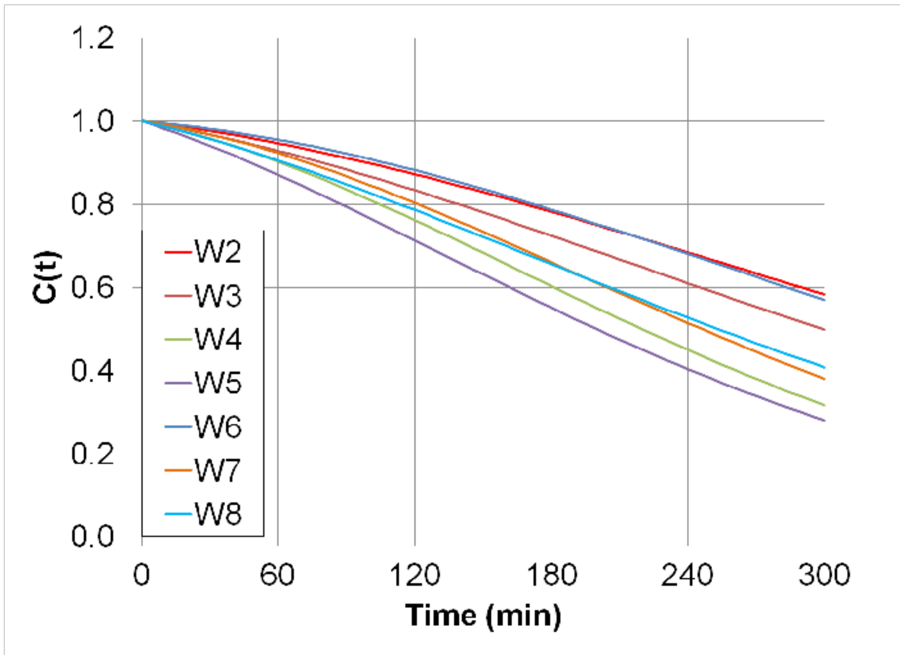




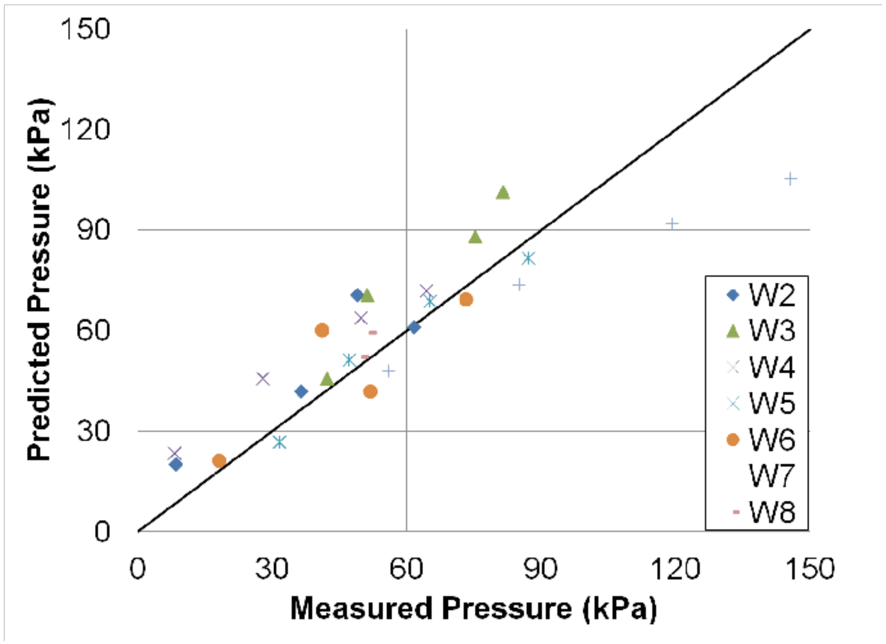
- Walls filled step-wise
- Pauses can cause deviation

Round Robin Results

Decay curves



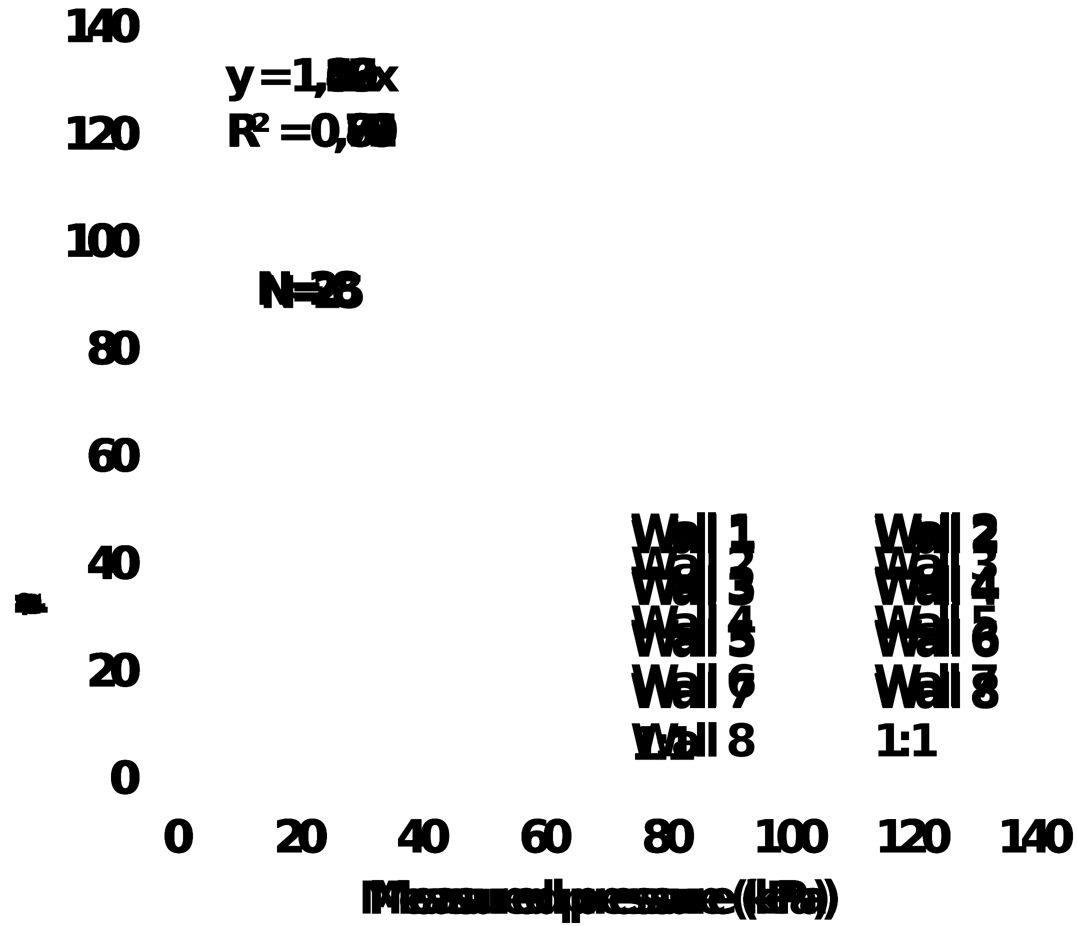
Maximum pressure



What parameters do other models use to characterize change in SCC with time?

- **pressure decay** by column test
- **structural buildup** by concrete rheometer
- **slump-loss** by slump tests
- **setting time** by vicat test
- **pore pressure** by pressure sensor on form

Do these 10 models work?



Comparison of Models

Model	Slope	R^2
Khayat/Omran	1.16	0.78
Ovarlez/Roussel	1.22	0.77
Lange/Tejeda-Dominguez	1.09	0.80
Perrot et al	1.20	0.71
Gardner et al	1.30	0.86
Beitzel	1.23	0.82
Proske mean	1.23	0.69
Proske design	1.40	0.85
DIN 18218 mean	1.37	0.85
DIN 18218 design	1.42	0.85
Average	1.26	

Summary

- Formwork pressure of SCC is difficult to characterize with a single parameter i.e. filling rate or slump flow
- Pressure decay signature approach provides reasonable prediction of formwork pressure
- Several modeling approaches have been developed based, giving industry a choice of tools to use for pressure prediction

Acknowledgements

Our projects:

Illinois Department of Transportation

Mortenson construction

LAFARGE

Stockholm Round Robin:

Swedish Cement and Concrete Research Institute (CBI)

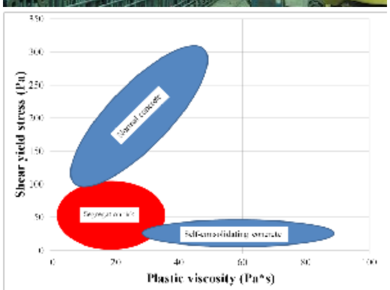
Development Fund of the Swedish Construction Industry (SBUF)

rilem

aci
American Concrete Institute
Always advancing

SDC
The Concrete Industry's
Strategic Development Council

Self-consolidating concrete (SCC)



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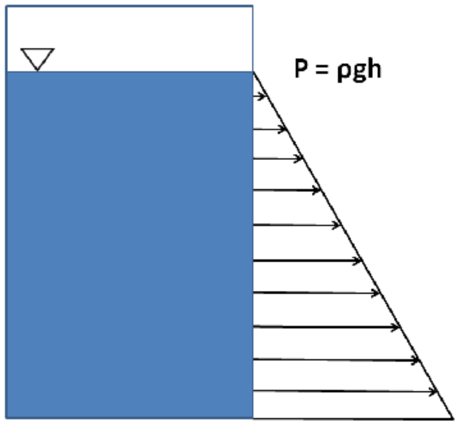
- No vibration necessary
- Casting in dense reinforcement

www.selfconsolidatingconcrete.org

Formwork Pressure



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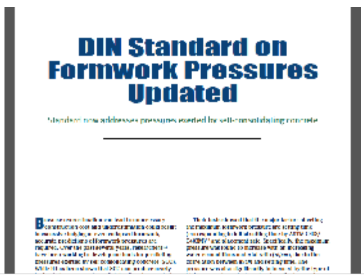

DIN Standard on Formwork Pressures Updated

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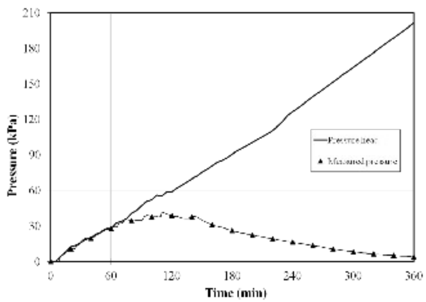
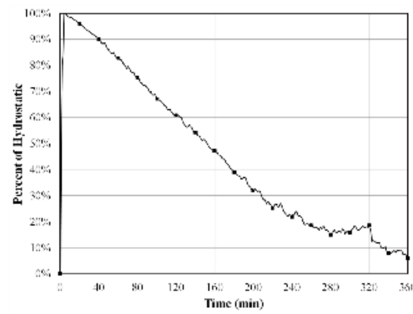
where $\sigma_{hk,max}$ represents the 95th percentile value of the maximum pressure exerted by the fresh concrete, γ_c is the unit weight of fresh concrete = 25 kN/m³ (159 lb/ft³), t_E is the setting time of the concrete (using the Vicat needle test per Reference 9), and v is the mean rate of concrete placement. Equation (1) is valid for t_E from 5 to

Measured pressures



- Maximum pressures typically lower than hydrostatic



Can we accurately model formwork pressure?

- Minimize testing
- Accurate and robust
- Field deployment

First step, measuring formwork pressure

- Honeywell full bridge pressure transducer
- Sensor brackets hold sensor face flush to formwork surface

Field Validations

- Illinois DOT I-74 retaining walls
- OSF Hospital Milestone Project
- Stockholm Round Robin Tests

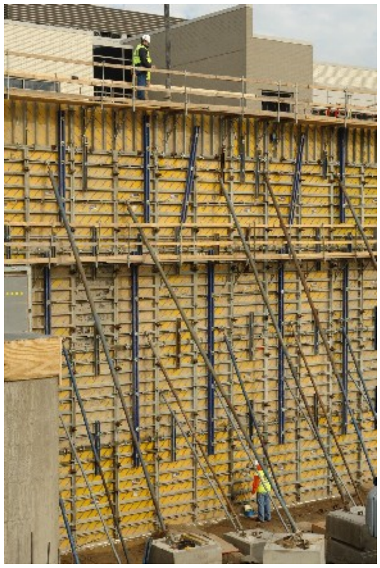
Field Validation #1
Illinois DOT I-74 retaining walls

I-74 Retaining wall

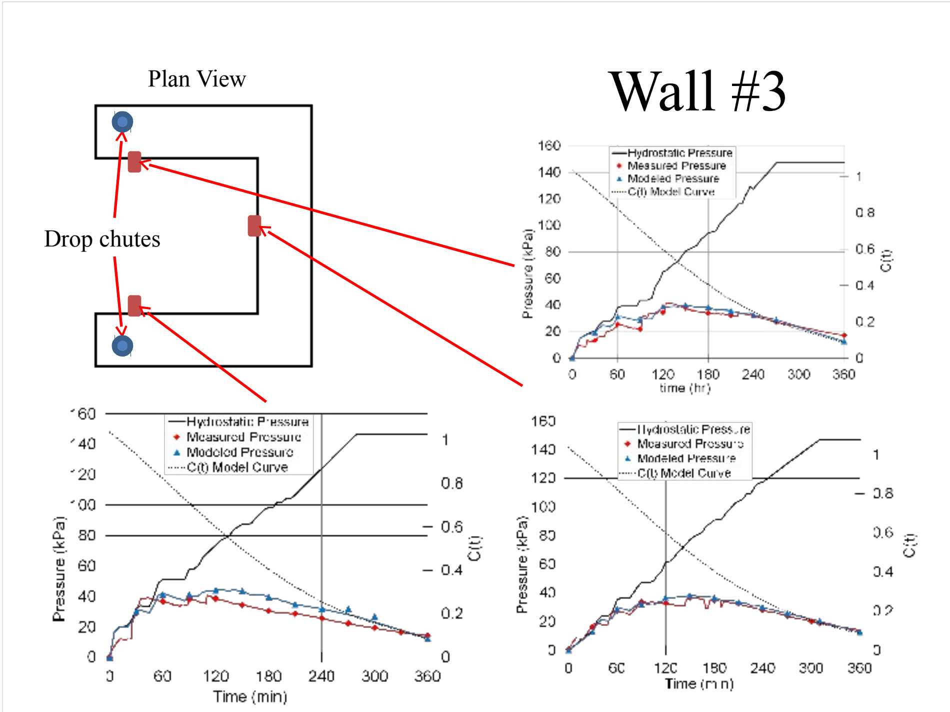
- SCC used for aesthetics
- Slump flow: 71 cm
- Wall height: ~7 m
- Placed with tremie or pump

Field Validation #2
OSF Hospital Milestone Project

OSF Hospital Milestone Project

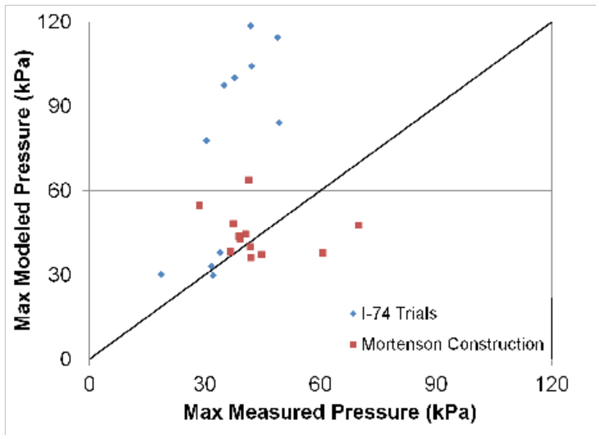


- Foundation wall construction
- Continuous placement
- Slump flow: 60-70 cm
- Height: 12-15 m

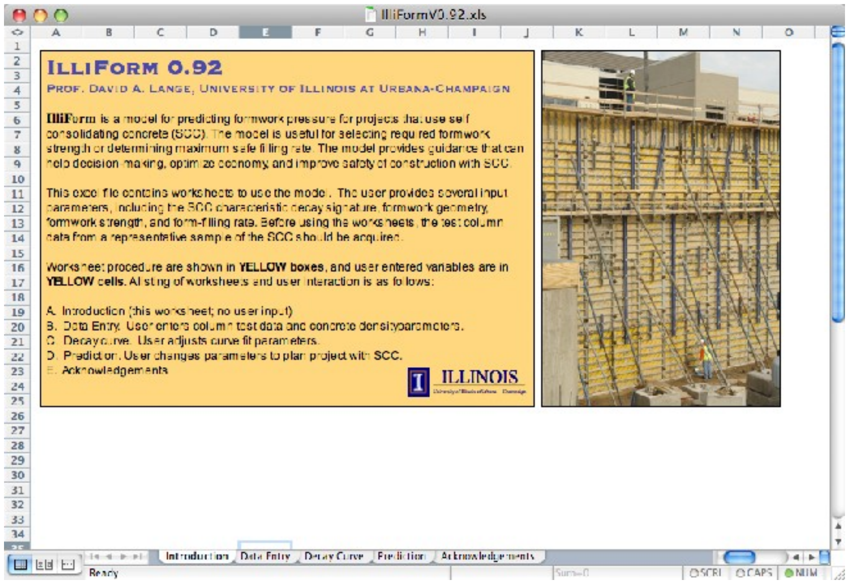


Wall #3
Plan View
Drop chutes
Hydrostatic Pressure
Measured Pressure
Modeled Pressure
C(t) Model Curve
Pressure (kPa)
C(t)
time (hr)
Time (min)

Field Trial Summary

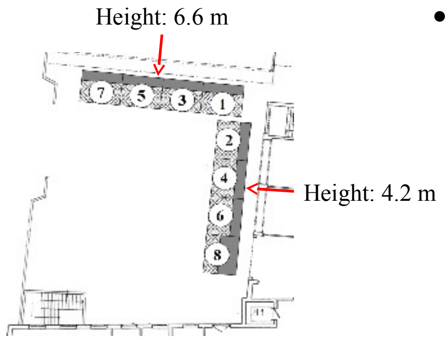


IlliForm: Model implemented in Excel



Field Validation #3
Stockholm Round Robin Tests

Round robin tests in Stockholm for 10 different form pressure models



- RILEM TC 233-FPC
  - Stockholm, June 2012
  - Comparison of 10 models
  - Theoretical
  - Lab tests
  - Field tests
  - 8 wall sections tested over 4 days

Reference: Billberg, P et. al, "Field validation of models for predicting lateral form pressure exerted by SCC," Cement and Concrete Composites, accepted 2014.

Reference: Billberg, P et. al, “Field validation of models for predicting lateral form pressure exerted by SCC,” Cement and Concrete Composites, accepted 2014.

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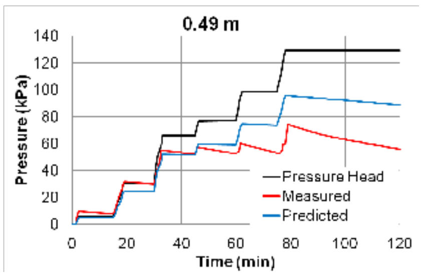
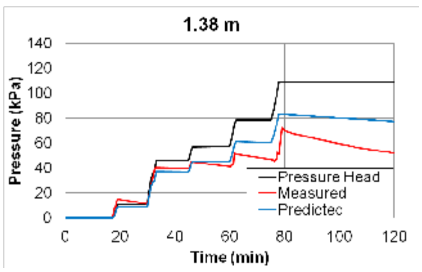
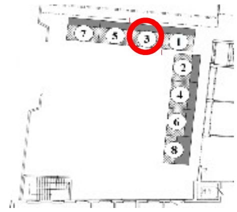
Nicolas Rousselb, Sofiane Amzianec, Marc Beitzeld, George Charitoue,Björn Freundf, John N. Gardnerg, Guillaume Grampeixh, Carl-Alexander Graubneri, Lloyd Kellerj, Kamal H. Khayatk, David A. Langel, Ahmed F. Omranm, Arnaud Perrotn, Tilo Proskeo, Robert Quattrociocchip, Yannic Vanhoveq

Round Robin Results



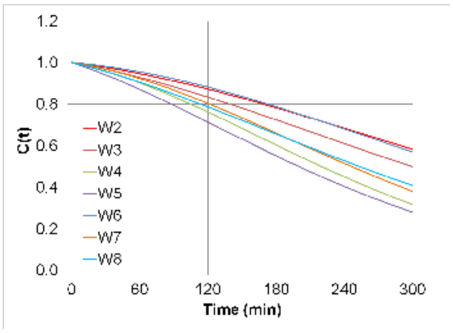




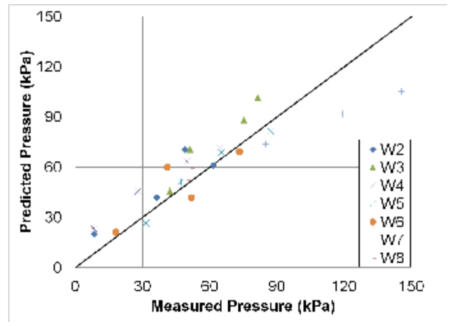
- Walls filled step-wise
- Pauses can cause deviation

Round Robin Results

Decay curves



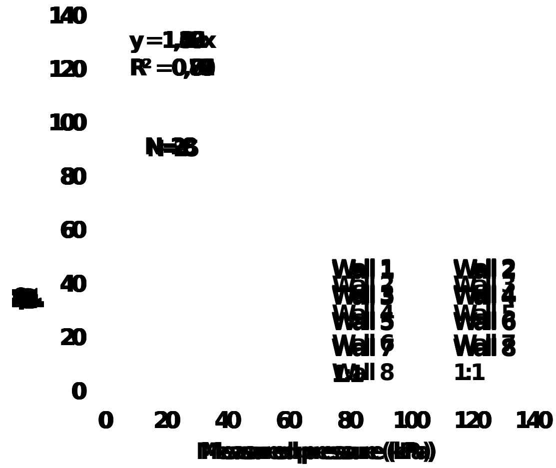
Maximum pressure



What parameters do other models use to characterize change in SCC with time?

- **pressure decay** by column test
- **structural buildup** by concrete rheometer
- **slump-loss** by slump tests
- **setting time** by vicat test
- **pore pressure** by pressure sensor on form

Do these 10 models work?



Comparison of Models

Model	Slope	R^2
Khayat/Omran	1.16	0.78
Ovarlez/Roussel	1.22	0.77
Lange/Tejeda-Dominguez	1.09	0.80
Perrot et al	1.20	0.71
Gardner et al	1.30	0.86
Beitzel	1.23	0.82
Proske mean	1.23	0.69
Proske design	1.40	0.85
DIN 18218 mean	1.37	0.85
DIN 18218 design	1.42	0.85
Average	1.26	

Summary

- Formwork pressure of SCC is difficult to characterize with a single parameter i.e. filling rate or slump flow
- Pressure decay signature approach provides reasonable prediction of formwork pressure
- Several modeling approaches have been developed based, giving industry a choice of tools to use for pressure prediction

Acknowledgements

Our projects:

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Mortenson construction

LAFARGE

Stockholm Round Robin:

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Development Fund of the Swedish Construction Industry (SBUF)

rilem

aci American Concrete Institute *Always advancing*

SDC The Concrete Industry's Strategic Development Council