Report on Form Pressure Exerted by Self-Consolidating Concrete: Primary Factors and Prediction Models

Report by ACI Committee 237

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Given the high flowability and relatively fast casting rate of self-consolidating concrete (SCC), such concrete can exert high form pressure. Accurate assessment of form pressure is necessary from safety and economic points of view. The maximum form pressure and pressure decay are dependent on the structural build-up of the concrete at rest following placement, as well as placement parameters. The structural build-up at rest is affected by the thixotropy of the mixture. This report presents information on key parameters, including constituent materials; mixture proportioning; and casting parameters, such as the casting rate, concrete temperature, and reinforcement density, affecting thixotropy and SCC form pressure. Prediction models available for estimating SCC form pressure are presented. Findings from two round-robin field studies conducted to validate these models are also discussed. This report should be of interest to concrete professionals, including concrete suppliers and formwork builders, because it covers: 1) the influence of SCC proportions and casting parameters on form pressure; 2) means to estimate the formwork pressure with examples; and 3) techniques to measure formwork pressure in field applications.

Keywords: form pressure; lateral pressure; self-consolidating concrete; structural build-up at rest; thixotropy.

CONTENTS
CHAPTER 1—INTRODUCTION

1.1—Introduction

Self-consolidating concrete (SCC) is highly flowable nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation. SCC is designed to have very low yield stress (minimum yield stress to initiate flow), that is, high fluidity. Due to the high fluidity of SCC, formwork systems are often designed to sustain full-hydrostatic pressure. Accurate estimation of form pressure for field application of SCC is necessary for the economical design of formwork and to ensure safety during and after casting. Field and laboratory investigations involving the measurement of lateral pressure exerted by SCC on formwork systems indicate that form pressure can be considerably lower than hydrostatic pressure (Assaad and Khayat 2005c; Assaad et al. 2003b; Billberg et al. 2014; Gardner et al. 2016). Form pressure is affected by the structural build-up at rest (Assaad et al. 2003b), which enables the material to regain its shear strength when left at rest without any shearing action (Assaad and Khayat 2005c). The rate of structural buildup is dependent on the concrete mixture characteristics including:

a) Binder constituent (Assaad et al. 2003b)

b) Type and content of chemical admixtures (Assaad et al. 2003b; Khayat and Assaad 2006)
c) Water-cementitious materials ratio ($w/cm$) (Khayat and Assaad 2006)

d) Maximum aggregate size and the total aggregate content (Assaad and Khayat 2005a)

For a given casting rate ($R$), lower form pressure can be observed for concrete with a higher rate of structural build-up at rest (Assaad and Khayat 2006a). The structural build-up of the concrete is due to thixotropy, a physical effect that is reversible, as well as chemical hydration of the cement-based materials, which is irreversible. At very early age, the thixotropy component is dominant, and the structural build-up is reversible and can be broken down if the mixture is agitated. However, as hydration progresses with time, the structural build-up gradually become less reversible (Roussel et al. 2012). The placement of SCC mixtures with high rate of structural build-up, at relatively low to moderate casting rates, for example, 6.5 to 16.4 ft/hour (2 to 5 m/hour), can result in lateral pressures on the order of 50 to 60 percent of hydrostatic pressure (Khayat and Omran 2010b; Omran et al. 2014).

In addition to SCC mixture characteristics, form pressure is affected by the casting parameters including:

a) Casting rate (Assaad and Khayat 2006a)

b) Concrete temperature (Omran et al. 2014)

c) Waiting period between successive lifts (Omran et al. 2014)

d) Formwork material (Arslan et al. 2005; Omran and Khayat 2016)

e) Minimum formwork dimension (Omran and Khayat 2017a)

f) Reinforcement density (Perrot et al. 2009).

The value of casting rate for SCC can vary by construction type (new construction or repair) and size of the element. Concrete temperature, casting rate, and waiting period between the successive lifts influence the structural build-up of SCC, thereby affecting the form pressure (Omran et al. 2014). Formwork materials and its dimensions (Omran and Khayat 2017a) and the reinforcement density (Omran and Khayat 2017b; Perrot et al. 2009) affect the amount SCC weight transferred onto the formwork, and thus the form pressure.

Additionally, the form pressure is also affected by various other factors, such as placement method used (pumping or chute) (Assaad and Khayat 2006a), formwork leaks, tie placement, and nearby vibration (heavy traffic). As a result, job-site controls or form-monitoring strategies (ACI SP-4 2014 [Chapters 11 and 12], ACI 347R- [Chapter 5]) should be employed by the contractor before, during, and after casting. Various theoretical and empirical models are developed by the researchers for the assessment of the form pressure exerted by SCC, and some of these will be covered in this report.

The objective of this report is to provide detailed information to concrete professionals, including concrete suppliers and formwork builders, regarding SCC mixture characteristics and casting parameters that influence form pressure. This report also presents models available to assess the form pressure exerted by SCC and the accuracy of these models are evaluated based on measurements collected from two round-robin field studies.
1.2—Scope
This report summarizes the main parameters affecting the form pressure exerted by SCC and presents most prevalent models to estimate form pressure. Additionally, test procedures for measuring thixotropy and other parameters needed for determining form pressure using these models are discussed. Details regarding the instrumentation needed for field measurement of form pressure and major round-robin field studies conducted to validate these models are presented.

Chapter 2 presents notations and definitions specific to this document. Chapter 3 describes the thixotropy of cement-based materials, test methods, and the effect of thixotropy on SCC form pressure. Chapters 4 and 5 identify the main material and casting parameters that influence form pressure characteristics, respectively. Chapter 6 presents the primary models available to estimate SCC form pressure. Chapter 7 discusses the results of two major round-robin field validation studies conducted in 2012 and 2014 to evaluate the suitability of various models to estimate SCC form pressure. Chapter 8 summarizes the key findings from this report.

CHAPTER 2—NOTATIONS AND DEFINITIONS

2.1—Notations

1. $IP_{\tau_{\text{rest}}}$ = yield stress at rest measured using inclined plane test setup, psi (Pa)
2. $IP_{\tau_{\text{rest}}}(t)$ = rate of gain in yield stress with time of rest measured using inclined plane test setup, psi/minute (Pa/minute)
3. $P_{\text{hydrostatic}}$ = equivalent hydrostatic pressure, psi (Pa)
4. $P_{\text{max}}$ = maximum lateral pressure exerted by concrete on formwork, psi (Pa)
5. $PV_{\tau_{\text{rest}}}$ = yield stress at rest measured using portable vane test setup, psi (Pa)
6. $PV_{\tau_{\text{rest}}}(t)$ = rate of gain in yield stress with time of rest measured using portable vane test setup, psi/minute (Pa/minute)
7. $R$ = casting rate, ft/hour (m/hour)
8. $\tau_{\text{rest}}$ = yield stress at rest, psi (Pa)
9. $\tau_{\text{rest}}(t)$ = rate of gain in yield stress with time of rest; also referred to as $A_{\text{thix}}$, psi/minute (Pa/minute)
10. $w$ = unit weight of concrete, lbf/ft$^3$ (kN/m$^3$)
11. $w/c$ = water-to-cement ratio, by mass
12. $w/cm$ = water-to-cementitious materials ratio, by mass
13. $w/p$ = water-to-powder ratio, by mass; $w/p$ is only used in mixtures containing a filler as a partial replacement of portland cement, such as limestone filler

2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

- casting rate – the vertical rate of concrete deposition into the formwork.
- cohesion – the ability of concrete to hold together due to the flocculation and hydration of the particles.
- filling ability (unconfined flowability) – the ability of SCC to flow into and fill completely all spaces within the formwork, under its own weight.
flocculation – aggregation of the fine particles present in concrete due to inter-particle forces such as van der Waals attraction and Brownian motion. Aggregated particles due to flocculation are referred to as flocs and they can be broken down with the application of shear. This process of breakdown of the flocs is referred to as deflocculation.

nonnewtonian fluid – the fluid that does not follow Newtonian law for viscosity, which states that viscosity is constant and is independent of the shear stress applied. The nonnewtonian fluid could follow the Bingham model, that is a two-parameter model used for describing the flow behavior of viscoplastic fluids exhibiting a yield stress.

\[ \tau = \tau_B + \eta_p \dot{\gamma} = 0 \text{ for } \tau < \tau_B \]

where \( \tau = \) shear stress; \( \tau_B = \) yield stress measured using Bingham model (also denoted as \( \tau_0 \)); \( \eta_p = \) plastic viscosity; and \( \dot{\gamma} = \) shear rate.

passing ability (confined flowability) – the ease with which concrete can pass among various obstacles and narrow spacing in the formworks without blockage. Blockage refers to the condition that can arise from local aggregate segregation in the vicinity of the obstacles that give rise to interlocking and blockage of the flow in the absence of any mechanical vibration.

pressure decay – the decrease in the lateral pressure exerted by the concrete on the formwork with an increase in resting time.

rheology – the science of deformation and flow of matter; evaluated using rheometers that enable one to relate variations in shear stress to shear rate.

shear thinning – the decrease in viscosity with increasing shear rate during steady shear flow.

slump flow – a measure of unconfined flow potential of a freshly mixed self-consolidating concrete; value is equal to the average of two perpendicular diameters of the material measured to the nearest 1/2 in. (10 mm) after it is released from the slump cone and stops flowing.

stability – the ability of a material to maintain the homogeneous distribution of its various constituents during its flow and setting.

structural breakdown – the decrease in the viscosity when a constant shear rate is applied to the material at rest; decrease is due to the breakage of the flocculated particles and hydration products.

structural build-up – increase in shear stress when the material is left at rest due to flocculation and hydration.

yield stress – a critical shear stress value below which an ideal plastic or viscoplastic material behaves like a solid (that is, will not flow); once the yield stress is exceeded, a plastic material yields (deforms plastically), while a viscoplastic material flows like a liquid.
yield stress at rest—represents the static yield stress of the material, that is, minimum shear stress needed to initiate flow measured after a given time of rest.

CHAPTER 3—THIXOTROPY AND FORM PRESSURE

Understanding thixotropy is critical to the understanding of self-consolidating concrete (SCC) form pressure, and subsequent chapters of this report cite the effects of concrete materials and mixture proportioning as well as placement conditions (for example, temperature) on SCC thixotropy and form pressure. This chapter is meant to provide discussion on the principles of thixotropy, methods available to measure it, and the relationship between thixotropy and form pressure. The reader can refer to ACI 238.2T for further information on thixotropy.

3.1—Thixotropy

According to ACI 238.2T, thixotropy is a reversible, isothermal, time-dependent decrease in viscosity when the fluid is subjected to increase in shear stress or shear rate; therefore, when the fluid is at rest, viscosity increases back to its original value. Thus, thixotropy can be considered as the continuous decrease of viscosity with time when there is an increase in shear stress or shear rate causing flow to occur, and the subsequent recovery of viscosity in time when the shearing is discontinued (Mewis 1979; Mewis and Wagner 2009). Thixotropy should be distinguished from irreversible changes in viscosity. Such changes may be caused by hydration of the cementitious materials. On the other hand, form pressure developed by SCC is a function of both the reversible structural changes due to thixotropy and the irreversible structural changes due to hydration (Assaad and Khayat 2005c; Assaad et al. 2003b).

Thixotropy of cement-based materials is strongly dependent on the mixture characteristics, mixing, and casting parameters such as casting rate. Tattersall and Banfill (1983) reported that cement characteristics, such as packing density, fineness, and chemical composition can significantly affect thixotropy. When a cement-based suspension is sheared, its network structure is broken and, with continued shearing, there is eventually an equilibrium state at which no additional deflocculation happens in the paste. When the shearing is stopped, that is, the suspension is at rest, the particles undergo reflocculation to form a network structure.

The influence of rest time on the thixotropy is shown in terms of the structural breakdown in Fig. 3.1(a) (Assaad et al. 2003a) and structural build-up in Fig. 3.1(b) (Omran et al. 2011). In Fig. 3.1(a), the concrete is subjected to a constant rotational velocity of 0.9 revolutions per second (rps) after leaving it to rest for 2 minutes. The application of the rotational velocity resulted in breakdown of the flocculated structure. Such breakdown with time indicates that the concrete is thixotropic. An equilibrium structure is achieved after approximately 10 seconds in Fig. 3.1(a), where a balance between flocculation and deflocculation is reached. When shearing is stopped, and the material is allowed to rest for 4 minutes, the material is then
resheared at the same rotational velocity of 0.9 rps. The results in Fig. 3.1(a) show that the measured viscosity is initially higher, indicating reflocculation during the rest time, and eventually a decrease in the viscosity to the same equilibrium value indicating the reversible behavior of thixotropy. During the rest time, the reflocculation of individual particles happens. In addition to the flocculation, hydration products can also form between particles, leading to a further increase in structural build-up (Khayat et al. 2002; Roussel et al. 2012). The longer the material is at rest, the more the structural build-up becomes significant, thus requiring higher stress to breakdown the structure. This increase in the structural build-up is measured in terms of the change in static yield stress with rest time in Fig. 3.1(b). The three mixtures shown in Fig. 3.1(b) exhibit different levels of thixotropic behavior in that all show an increase in static yield stress with time. SCC Mixture A has a higher thixotropy than Mixtures B and C as it exhibits greater static yield stress values after rest periods of 15 to 60 minutes. The rheology test protocol for the determination of the static yield stress is presented in 3.2.

![Fig. 3.1 – Thixotropy in terms of: (a) structural breakdown measured as variation of viscosity with time for concrete after 2 and 4 minutes of rest (Assaad et al. 2003a); and (b) structural build-up for concretes with different degrees of thixotropy measured as variation of static yield stress with rest time (Omran et al. 2011). (Note: 1 psi = 6894.76 Pa.)](image)

### 3.2—Thixotropy test methods

There are a number of test methods that can be used to quantify the thixotropy and structural build-up of concrete. These experiments often consist of either conducting rheological tests at a constant shear rate, such as steady-state flow curves (Ghezal et al. 2002; Tattersall and Banfill 1983) and stress-growth tests (Assaad et al. 2003a), or using varied sheared rates, such as hysteresis curves (Ish-Shalom and Greenberg 1960; Wallevik 2003) and break down area curves (Khayat et al. 2002). Steady-state flow, hysteresis, and breakdown area curves measure thixotropy in terms of the breakdown of the structure whereas stress growth tests measure the structural build-up. The breakdown of the structure quantifies the reversible structural changes due to thixotropy whereas the structural build-up measurements include both reversible structural changes due to thixotropy and the irreversible structural changes due to hydration. In this report, emphasis
is placed on the structural build-up measurements as the form pressure estimation models (Khayat and Omran’s (2010b) and Ovarlez and Roussel’s [2006] models) described in Chapter 6 include the structural build-up as a parameter.

3.2.1 Structural build-up measurement—One of the ways of quantifying the structural build-up is to measure the yield stress of the material at rest \( \tau_{0,\text{rest}} \). \( \tau_{0,\text{rest}} \) indicates the strength and number of inter-particle bonds that are ruptured due to the applied shear or stress (Tattersall and Banfill 1983). The rheology test protocol for the determination of \( \tau_{0,\text{rest}} \) (also referred to as static yield stress and shear-growth yield stress) consists of applying a small rotational velocity (that is, 0.03 rps) to a vane immersed into fresh concrete (or mortar) and recording the variations of torque as a function of time, as shown in Fig. 3.2.1a. The shear-growth profile in Fig. 3.2.1a shows a linear-elastic region followed by a yielding moment where the torque exerted on the vane shaft reaches a maximum value corresponding to the beginning of flow. The maximum value during this profile corresponds to \( \tau_{0,\text{rest}} \). The presence of such maximum torque response can be explained by the concept of structural deformation and breakdown of the bond in the flocculated system (Barnes 1997; Dzuy and Boger 1985). The calculation of \( \tau_{0,\text{rest}} \) from the measured maximum torque \( (T_{\text{max}}) \) requires knowledge of the geometry of the yield surface and shear stress distribution on the surface. Dzuy and Boger (1985) assumed that the material is sheared along a localized cylindrical surface circumscribed by the vane, and this shear stress is uniformly distributed over this surface. Based on this assumption, a good approximation of \( \tau_{0,\text{rest}} \) can be calculated as per Eq. (3.2.1a). The details regarding the derivation and assumptions used for estimation can be found in Koehler and Fowler (2004).

\[
\tau_{0,\text{rest}} = \frac{T_{\text{max}}}{K} \quad (3.2.1a)
\]

\[
K = 2\pi R^2 H + \frac{4}{3}\pi R^3
\]

where \( K \) is a constant and \( H \) and \( R \) are the height and radius of the vane.
Fig. 3.2.1a – Typical torque-time profile for SCC with 26 in. (650 mm) slump flow at a constant rotational velocity of 0.03 rps (Assaad et al. 2003a). (Note: 1 lbf.ft = 1.36 N.m.)

The change in concrete yield stress with resting time can also be used to determine the degree of structural build-up and is expressed as the rate of gain in yield stress with the time of rest ($\tau_{0\text{rest}}(t)$). The portable vane test is a simplified and manual version of the aforementioned test. The test setup consists of square containers to prevent plug flow of the material, and a vane that is attached to a torque meter to measure the torque needed to breakdown the structural build-up following a certain period of rest. The portable vane shown in Fig. 3.2.1b has four vanes of different sizes to determine yield stress at different times of rest. A single size of vane can be also used with a sample of different heights. The variations of yield stress at rest measured using the portable vane ($P\tau_{0\text{rest}}$) for SCC mixtures with slump flow values between 24 and 28 in. (600 and 720 mm) were determined using four vanes of different sizes (Fig. 3.2.1b). The results show that the $P\tau_{0\text{rest}}$ increased in a linear fashion over 60 minutes of rest. Thixotropy can be quantified as the slope of each line ($\tau_{0\text{rest}}(t)$), as well as the product of $\tau_{0\text{rest}}$ and $\tau_{0\text{rest}}(t)$.

For the purpose of form pressure prediction, it is recommended that the measurement of thixotropy is done as soon as practical after the completion of mixing and agitation. It is recommended to perform at least three static yield tests to determine thixotropy by using 30 to 60 minute rest times to ensure that the rate of increase in static yield stress is linear, as indicated in Fig. 3.2.1c.
Fig. 3.2.1b – Portable vane test setup: (a) square containers; (b) torque meter; and (c) vanes of different sizes (Omran et al. 2011). (Note: 1 in. = 25.4 mm.)

Fig. 3.2.1c – Typical variations of yield stress as a function of rest time for SCC mixtures determined using portable vane test (Omran et al. 2011). (Note: 1 psi = 6894.76 Pa.)

As an alternative to a rheometer, Khayat et al. (2010) developed an inclined plane test setup for measuring $\tau_{0\text{rest}}$ and $\tau_{0\text{rest}(t)}$. The inclined plane test setup consists of a movable plate whose inclination ($\theta$) can be adjusted as shown in Fig. 3.2.1d. To measure $\tau_{0\text{rest}}$ for mortar or SCC, the sample is placed on the movable plate and is slowly lifted. Details regarding the volume and placement of the sample can be found in (Khayat et al. 2010).
Depending on the value of $\theta$, the gravitational ($F_g$) and frictional ($F_k$) forces acting on the sample along the inclined plane vary as shown in Fig. 3.2.1e(a). In the case of a solid sample, at a critical value of $\theta$, the sample would begin to slide downward and this sliding initiates when $F_g$ is equal to $F_k$. However, for fresh mortar or SCC sample, if the $F_k$ is high enough to prevent sliding of the entire sample (achieved by increasing the roughness of the surface by covering it with sandpaper), shearing of the top layer happens resulting in the flow of the material, as shown in Fig. 3.2.1e(b). The critical angle ($\alpha$) at which the shearing happens and the vertical height to which the plate is lifted is used for estimation of $\tau_{\text{yield}}$ as shown in Eq. (3.2.1b). The test is conducted on samples subjected to different rest times to measure $\tau_{\text{y}}(t)$ and results of yield stress at rest obtained using inclined plane test for the SCC mixtures with slump flow between 22 and 28 in. (560 and 720 mm) are shown in Fig. 3.2.1f.

Fig. 3.2.1d—Schematic of the inclined plane test (Khayat et al. 2010).
\[ IP_{\text{test}} = gh \sin (3.2.1b) \]

where \( h \) is the thickness of the spread of SCC at the horizontal position; \( \rho \) is SCC density, \( \alpha \) is the critical angle at which shearing of the sample occurs, and \( g \) is the acceleration due to gravity.

Fig. 3.2.1e – (a) SCC sample at zero inclination; (b) forces acting along the inclined plane on mass \( m \) at inclination angle \( \theta \); and (c) shearing of the sample indicating flow initiation at critical angle \( \alpha \) (Khayat et al. 2010).
Amziane et al. (2008) developed an alternative approach known as the plate test for measuring $\tau_{0_{\text{rest}}}$ and $\tau_{0_{\text{rest}}}(t)$ for thixotropic materials. The schematic of the plate test setup is shown in Fig. 3.2.1g. The test setup consists of a plate attached below a balance and is partly immersed in SCC. The plate is covered with sandpaper with an average roughness of 0.008 in. (200 µm) to prevent slippage between the plate and the SCC; this roughness corresponds to a grit size of 70 or a U.S. mesh of 60. The apparent mass of the plate is monitored over time. The plate remains static during the test, and the change in apparent mass is attributed to mobilization of shear stress on the plate due to the slight deformation in the test material (mortar or concrete) under its own weight, which includes deformation due to settlement, segregation, bleeding, and evaporation of the test material. This deformation is limited at early age but sufficient to reach a critical value inducing material yielding. As a result, the mobilized shear stress can be considered as $\tau_{0_{\text{rest}}}$. The dimensions of the plate are 0.1 in. (3 mm) thick, 3 in. (75 mm) wide and 4 in. (100 mm) long and the concrete is placed to a height of 8 in. (200 mm) in a vessel made of smooth PVC and has dimensions of 8 in. (200 mm) diameter and 8 in. (200 mm) in height. These dimensions are chosen such that the vessel is large enough compared to the size of the plate so that material can be assumed to be homogenous. To avoid losses due to evaporation and its influence on the apparent mass measured, an oil film is added on the top of the material. $\tau_{0_{\text{rest}}}(t)$ is calculated from apparent mass evolution ($\Delta M(t)$) using Eq. (3.2.1c).

$$\tau_{0_{\text{rest}}}(t) = \frac{gM(t)}{2S} \quad (3.2.1c)$$

where $S$ is the area of the immersed surface, that is, plate width ($L$) times the immersed height ($H$).
The comparison between the calculated yield stress values using the plate test and measured yield stress values using a vane rheometer for SCC with the water-cement ratio (w/c) of 0.47 is shown in Fig. 3.2.1h.

![Plate test setup](image)

Fig. 3.2.1g – Schematic of plate test setup (Perrot et al. 2009).

![Static yield stress comparison](image)

Fig. 3.2.1h – Comparison between calculated static yield stress values of SCC using the plate test and measured static yield stress values using a vane rheometer (Perrot et al. 2009). (Note: 1 psi = 6894.76 Pa.)

### 3.3—Influence of thixotropy on form pressure
Concrete that can exhibit a higher degree of thixotropy (that is, higher rate of structural build-up) can develop greater cohesiveness soon after casting, thus acting as a cohesive body exerting less pressure than the full-hydrostatic pressure state. Assaad and Khayat (2004, 2005) evaluated the relationship between the form pressure characteristics and the structural build-up of SCC mixtures. The lateral pressure values were measured at different depths in the formwork, that is, 3.3, 13.1, 26.2, and 39.4 ft (1, 4, 8, and 12 m) and the structural build-up of the mixtures were assessed by measuring $\tau_{0\text{rest}}$ after 15 minutes of rest ($\tau_{0\text{rest}@15\text{min}}$) and $\tau_{0\text{rest}}(t)$ using the portable vane test setup. Based on the results, a linear relationship ($R^2$ ranging from 0.82 to 0.92) was observed between the lateral pressure and structural build-up measured using different indexes, that is, $\tau_{0\text{rest}@15\text{min}}$, $\tau_{0\text{rest}}(t)$, $\tau_{0\text{rest}@15\text{min}} \times \tau_{0\text{rest}}(t)$ as shown in Fig. 3.3a through 3.3c, respectively. Additionally, the lateral pressure decay during the first 60 minutes after casting and the pressure decay until reaching the pressure cancellation time ($t_c$), were correlated to the structural build-up as shown in Fig. 3.3d through 3.3f.

**Fig. 3.3a** – Variations of relative lateral pressure with $PV\tau_{0\text{rest}@15\text{min}}$ at different heights of placement (adapted from Khayat and Assaad [2005]). (Note: 1 ft = 0.3 m; 1 in. = 25.4 mm; 1 psi = 6894.76 Pa.)

**Fig. 3.3b** – Variations of relative lateral pressure with $PV\tau_{0\text{rest}}(t)$ at different heights of placement (adapted from Khayat and Assaad [2005]). (Note: 1 ft = 0.3 m; 1 in. = 25.4 mm; 1 psi = 6894.76 Pa.)
Fig. 3.3c – Variations of relative lateral pressure with $P V_{\tau_0 \text{rest} @ 15 \text{min}} \times \tau_{\text{rest}}(t)$ at different heights of placement (adapted from Khayat and Assaad [2005]). (Note: 1 ft = 0.3 m; 1 in. = 25.4 mm; 1 psi = 6894.76 Pa.)

Fig. 3.3d – Variations of relative pressure decay with $P V_{\tau_0 \text{rest} @ 15 \text{min}}$ (Khayat and Assaad 2005). (Note: 1 psi = 6894.76 Pa.)

Fig. 3.2e – Variations of relative pressure decay with $P V_{\tau_0 \text{rest}(t)}$ (Khayat and Assaad 2005). (Note: 1 psi = 6894.76 Pa.)
Fig. 3.3f – Relative pressure decay versus $PV_{\tau_0 \text{rest} @ 15\text{min}} \times \tau_0 \text{rest}(t)$ (Khayat and Assaad 2005). (Note: 1 psi = 6894.76 Pa.)

**CHAPTER 4—EFFECT OF MIXTURE CHARACTERISTICS ON FORM PRESSURE**

**4.1—Introduction**

The functional requirements in proportioning SCC include filling ability, passing ability, and stability. SCC proportioning is discussed extensively in ACI 237R. This section is meant to provide discussion on how mixture proportioning for SCC has been found to affect form pressure characteristics. Studies have shown that altering any of the following parameters that have significant effect on thixotropy can affect lateral form pressure: cement type and content; supplementary cementitious materials types and contents; w/cm; high-range water-reducing admixture (HRWRA) types and content; viscosity-modifying admixture (VMA) types and content; and aggregate size, gradation, and content. Table 4.1 summarizes the effect of increasing any of these parameters on form pressure and pressure decay.

**Table 4.1 - Overall effect of increasing mixture proportioning parameters on form pressure**

<table>
<thead>
<tr>
<th>Increase of</th>
<th>Initial lateral pressure</th>
<th>Pressure decay</th>
<th>Main reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder content (lowering w/cm; fixed HRWRA)</td>
<td>Decrease</td>
<td>Faster</td>
<td>Increase in thixotropy (Billberg 2006)</td>
</tr>
<tr>
<td>Aggregate content</td>
<td>Decrease</td>
<td>Faster</td>
<td>Increase in internal friction amplified by increased aggregate content decreases the mobility of concrete (Assaad and Khayat 2005a; Omran et al. 2012)</td>
</tr>
<tr>
<td>Maximum size of aggregate (MSA)</td>
<td>Decrease or limited effect</td>
<td>Faster or limited effect</td>
<td>Depends on variation in the packing density with changes in MSA (Assaad and Khayat 2005a)</td>
</tr>
<tr>
<td>Paste content (fixed w/cm)</td>
<td>Increase (1)</td>
<td>Faster (2)</td>
<td>1) Decrease in internal friction due to lower coarse aggregate volume</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2) Increase in cohesion due to higher paste content (Alexandridis and Gardner 1981; Assaad and Kamal 2004; Omran et al. 2012)</td>
</tr>
<tr>
<td>Water content (reduced HRWRA to maintain fixed slump flow)</td>
<td>Increase (1)</td>
<td>Faster, slower, or no change (2)</td>
<td>1) Low shear strength properties due to high water content</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2) Depends on the workability retention characteristics of the HRWRA and the initial starting dosage being used. Some HRWRA’s lose workability relatively quickly (less than 1 hour), while others are developed to maintain workability for longer times (greater than 2 hours). (Khayat and Assaad 2006)^\dagger</td>
</tr>
<tr>
<td>HRWRA content (fixed w/cm)</td>
<td>Increase</td>
<td>Faster, slower, or no change</td>
<td>Depends on the workability retention characteristics of the HRWRA and the initial starting dosage being used. Some HRWRAs lose workability relatively quickly, while others are developed to maintain workability for longer times. (Khayat and Assaad 2006)^\dagger</td>
</tr>
</tbody>
</table>
VMA†
(fixed initial slump flow and increased HRWRA dosage)

No change or increase (1)
Slower (2)

1) Depending on VMA type and dosage, HRWRA demand can vary, leading to either no significant change in initial pressure or a slight increase in pressure at high VMA dosage
2) Higher HRWRA demand, especially if HRWRA improves slump retention (Assaad and Khayat 2006c; Khayat 1998)

VMA†
(with fixed HRWRA, that is, reduced slump flow)

Decrease
Faster

Addition of VMA typically increases the degree of thixotropy (Prakash and Santhanam 2006) (Ghio et al. 1994)

Set retarding admixtures†

Increase/limited effect
Slower
Retards rate of cohesion development (Assaad et al. 2003b).

Set accelerating admixtures†

Decrease/limited effect
Faster
Accelerates the rate of hydration (Assaad et al. 2003b)

*Observed behavior is based on studies listed in the references. General observations are valid for materials in use at specific ranges considered in these studies. Changing mixture proportioning parameters may affect other factors (for example, increasing VMA content normally increases HRWRA demand), which can affect form pressure characteristics.

†The reader should consult admixture manufacturers on the effect of chemical admixtures on form pressure characteristics as the effect varies based on the chemical composition of the admixture and its interaction with other constituents including binders.

4.2—Binder constituents and content

Assaad and Khayat (2005b) investigated the effects of binder content and composition on form pressure using SCC. As illustrated in Fig. 4.2a, this study examined five different binder compositions, including mixtures made with Type I/II cement; Type III cement; binary binder (BIN) with silica fume (SF); a ternary binder (TER) with SF and Class F fly ash (FA); and a quaternary binder (QUA) with SF, FA, and slag (SL). The amounts of HRWRA and air-entraining admixture were adjusted to maintain constant initial slump flow of 26 in. (650 mm). The VMA content was constant (4 oz. per 100 lb of cement [260 ml per 100 kg of cement]) in all mixtures.

![Initial slump flow = 650 mm](image)
Fig. 4.2a – Variations in lateral pressure characteristics of SCC made with 450 kg/m³ (760 lb/yd³) of various binder types; slump values are those determined at the end of pressure monitoring. Slump values at end of pressure monitoring are noted (Assaad and Khayat 2005b). (Note: 1 in. = 25.4 mm.)

For a given binder content, the binder composition significantly affected the initial lateral pressure and the pressure decay due to their varying degrees of thixotropy. The Type III cement had the lowest initial lateral pressure and the fastest pressure decay due to its high thixotropy. By comparing the ternary binder (6 percent SF, 22 percent FA, and 72 percent cement) content at values of 675 lb/yd³ (400 kg/m³), 760 lb/yd³ (450 kg/m³), 840 lb/yd³ (500 kg/m³), and 927 lb/yd³ (550 kg/m³), Assaad and Khayat (2005b) found increasing the binder content resulted in a higher initial lateral pressure, as shown in Fig. 4.2b. Pressure decay depends significantly on the rate of structural-buildup, thus the increase in binder content leads to sharper pressure decay. Similar results were observed by Omran et al. (2012) with increasing the binder content. The effect of supplementary cementitious materials (SCMs) and fillers depends on their physical and chemical properties (Andreas and Frank 2005; Assaad and Khayat 2005b).

Fig. 4.2b – Variations in lateral pressure characteristics of SCC made with various contents of the ternary binder. Slump values at end of pressure monitoring are noted (Assaad and Khayat 2005b). (Note: 1 in. = 25.4 mm.)

4.3—Water content

Khayat and Assaad (2006) reported significant differences in lateral pressure and pressure decay with changes in w/cm. Keeping the slump flow consistent at 26 in. (650 mm), SCC with 760 lb/yd³ (450 kg/m³) binder (6 percent SF, 22 percent FA, and 72 percent cement) at w/cm 0.36, 0.40, and 0.46 were analyzed. Figure 4.3a (mixtures with carboxylate [PC] based HRWRA) and Fig. 4.3b (mixtures with naphthalene [PNS] based HRWRA) show that the mixtures with 0.46 w/cm exhibit greater initial pressure, as well as faster pressure decay compared to the other two mixtures. The high initial pressure at 0.46 w/cm was
attributed to the increased water and paste contents as well as the reduction in coarse aggregate volume, leading to lower shear strength properties of the plastic concrete. The faster pressure decay was due to the reduction in HRWRA demand of the SCC made with 0.46 w/cm, which reduces the interference of the HRWRA on cement hydration.

![Graph](image1)

Fig. 4.3a – Effect of w/cm on lateral pressure characteristics of SCC made with PC-based HRWRA. Slump values at end of pressure monitoring are noted (Khayat and Assaad 2006). (Note: 1 in. = 25.4 mm.)

![Graph](image2)

Fig. 4.3b – Effect of w/cm on lateral pressure characteristics of SCC made with PNS-based HRWRA. Slump values at end of pressure monitoring are noted (Khayat and Assaad 2006). (Note: 1 in. = 25.4 mm.)

### 4.4—Aggregate characteristics

Aggregate properties, such as coarse aggregate content, gradation, the maximum size of aggregate (MSA), and packing density influence form pressure. Amziane and Baudeau (2000), using conventional concrete mixtures, showed that the maximum lateral pressure decreased as the volume of coarse aggregate increased. They suggested that the degree of internal friction is limited while the volume of mortar is dominant. Assaad and Khayat (2005a) found similar results for SCC mixtures with slump flow consistent at 26 in. (650 mm), ternary binder (6 percent SF, 22 percent FA, and 72 percent cement) at w/cm 0.40. As illustrated in Fig. 4.4a, the decrease in the sand-to-total aggregate volume ratio from 1, 0.75, 0.50, 0.46,
0.40, 0.36, to 0.30, corresponding to coarse aggregate volumes of 0, 14.8, 29.9, 32.1, 35.8, 38, to 41.7 percent, respectively, resulted in reduction of lateral pressure and increase in pressure decay.

Fig. 4.4a – Variations of lateral pressure with time for mixtures made with different sand-to-total aggregate ratio of 0.30 to 1.0, which correspond to coarse aggregate contents of 0 to 41.7 percent, respectively. Slump values at end of testing are noted. (Assaad and Khayat 2005a). (Note: 1 in. = 25.4 mm.)

Amziane and Baudeau (2000) examined the effects of aggregate gradation and found higher lateral pressure when using discontinuously graded aggregate having a higher MSA compared to a continuously graded aggregate with a lower MSA. Assaad and Khayat (2005a) evaluated the effect of MSA, that is, 0.40, 0.55, and 0.80 in. (10, 14, and 20 mm) on lateral pressure characteristics of SCC mixtures with slump flow consistent at 26 in. (650 mm), ternary binder (6 percent SF, 22 percent FA, and 72 percent cement) at w/cm 0.40. As illustrated in Fig. 4.4b, the increase in the MSA from 0.40 to 0.55 in. (10 to 14 mm) resulted in the reduction of lateral pressure and increase in pressure decay. However, no significant change in the initial lateral pressure and slightly slower pressure decay was observed with the increase in the MSA from 0.55 to 0.80 in. (14 to 20 mm). This was attributed to the increase in the packing density from 56 to 62 percent with the increase in the MSA from 0.40 to 0.55 in. (10 to 14 mm) and slight drop in the packing density from 62 to 60 percent with increase MSA from 0.55 to 0.80 in. (14 to 20 mm).
Fig. 4.4b – Variations of lateral pressure characteristics with time for mixtures made with different MSA. Slump values at end of testing are noted (Assaad and Khayat 2005a). (Note: 1 in. = 25.4 mm.)

4.5—Chemical admixtures

4.5.1 High-range water-reducing admixtures—Khayat and Assaad (2006b) performed a study using three types of HRWRA (polycarboxylate, polynaphthalene sulphonate, and polymelamine sulphonate) while keeping the slump constant at 26 in. (650 mm). For any given w/cm, the type of HRWRA appears to have limited effect on the initial lateral pressure. However, depending on the synergistic characteristics of the constituent materials of the HRWRAs, the pressure decay varied. Mainly, polycarboxylate-based HRWRA that had a greater fluidity retention resulted in slower pressure decay. Additionally, some HRWRAs designed to retain workability for extended periods of time can slow down the rate of structural build-up and the rate of decrease in lateral pressure without affecting the setting time (Yamada et al. 2000).

4.5.2 Viscosity/thixotropy-modifying admixtures—VMAs have an effect on increasing the yield stress and viscosity of cement-based materials and are widely available in the market. On the other hand, thixotropy-modifying admixtures (TMAs) are less widely available materials that can mainly increase yield stress at rest with limited change in viscosity (Khayat et al. 2002). VMAs can necessitate an increase in HRWRA demand. VMAs can reduce the risk of bleeding, segregation, and surface settlement through various mechanisms, including association of water with the VMA and entanglement of polymer chains of the VMA (Khayat 1998; Palacios and Flatt 2016). Alternatively, TMAs function by inducing a network structure in the liquid phase through increased interactions of the solid particles (Khayat et al. 2002), leading to an increase in stability. Assaad and Khayat (2006c) conducted an experimental program to determine the influence of the type and concentration of VMA on form pressure exerted by SCC. Various VMA types (liquid polysaccharide-based, powder polysaccharide-based, cellulose-based) were tested along with varying dosages of HRWR. Irrespective of the combinations tested, the results indicated that the incorporation of the VMA at low concentrations resulted in lower initial form pressure and a faster pressure decay when compared to mixtures with medium or high concentrations of VMA. This effect was attributed to the increased demand of HRWRA. This study also found that the initial pressure and the pressure decay correlate to the thixotropy of the SCC mixture. Khayat and Assaad (2008) conducted a research study that evaluated the impact of TMAs on the variation in thixotropy and their effect on lateral form pressure for mixtures with a slump flow of 25.5 ± 0.5 in. (650 ± 15 mm). The study compared the effect of using VMAs and TMAs. The results showed that mixtures containing TMA have a lower form pressure compared to similar mixtures containing VMAs. This was attributed to the higher degree of thixotropy that the mixtures with TMAs experienced. Combining a conventional VMA with TMA at low concentrations, was found to
be beneficial in reducing the lateral pressure and also increasing the pressure decay compared with mixtures containing only VMA at similar concentrations.

4.5.3 Set-modifying admixtures—Various studies have been done that directly relate the form pressure exerted by SCC to the thixotropy of the mixture. Assaad et al. (2003b) investigated the relationship between pressure decay and the addition of either set-retarding admixture (RET) or set-accelerating admixture (ACC). With the addition of a RET in an SCC mixture, it was found that there was a delay in cement hydration, thus leading to a slower pressure decay in lateral pressures. This was compared to an SCC mixture proportioned with ACC, leading to accelerated rate of hydration and faster pressure decay. In the study, both mixtures exhibited similar lateral pressures immediately after casting, but experienced significantly different pressure decay.

CHAPTER 5—EFFECT OF CASTING PARAMETERS ON FORM PRESSURE

5.1—Introduction

In addition to the SCC mixture characteristics, the casting parameters such as concrete temperature, casting rate, formwork dimensions, and reinforcement density also affect the initial lateral pressure and pressure decay. The effect of these parameters on form pressure and pressure decay are discussed in detail in the following subsections and are summarized in Table 5.1.

<table>
<thead>
<tr>
<th>Increase of</th>
<th>Initial lateral pressure</th>
<th>Pressure decay</th>
<th>Main reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete temperature</td>
<td>Limited change or decrease</td>
<td>Faster</td>
<td>Accelerated rate of hydration leading to faster development of cohesion (Assaad and Khayat 2006a; Omran et al. 2014)</td>
</tr>
<tr>
<td>Rate of casting</td>
<td>Increase</td>
<td>No effect observed</td>
<td>No stiffening allowed to reduce lateral pressure (Assaad and Khayat 2006a; Omran et al. 2014)</td>
</tr>
<tr>
<td>Formwork width (thickness of concrete element)</td>
<td>Increase</td>
<td>Slower</td>
<td>Reduction in arching action with increasing width (Omran and Khayat 2017a)</td>
</tr>
<tr>
<td>Formwork roughness</td>
<td>Decrease</td>
<td>Information not available</td>
<td>Increase of friction between formwork and concrete (Djelal et al. 2002; Tchamba et al. 2008)</td>
</tr>
<tr>
<td>Reinforcement density</td>
<td>Decrease</td>
<td>No effect observed</td>
<td>Partial support from reinforcement reduces load transferred to formwork (Matar and Assaad 2017; Omran and Khayat 2017b; Perrot et al. 2009)</td>
</tr>
</tbody>
</table>

5.2—SCC mixture temperature

The effect of temperature on form pressure for conventional concrete was studied by Roby (1935), The Portland Cement Association (Rodin 1952), and Gardner (1984). Assaad and Khayat (2006a) investigated the effect of concrete temperature (50°F [10°C], 68°F [20°C], and 86°F [30°C]) on form pressure.
characteristics of SCC mixtures made with ternary binder (6 percent SF, 22 percent FA, and 72 percent cement) and have w/cm of 0.4 and slump flow of 25.5 ± 0.5 in. (650 ± 15 mm). The results shown in Fig. 5.2a indicate that for lower temperatures, the rate of cement hydration is decreased, resulting in reduced rate of pressure decay. Additionally, a higher initial concrete temperature results in lower lateral pressure. This behavior is more evident in the work of Omran et al. (2014) for an SCC mixture with water-to-powder (w/p) of 0.37 and slump flow of 27.5 ± 1 in. (700 ± 20 mm) shown in Fig. 5.2b. The set time of concrete has similar effects in that after placement, mixtures with longer setting times display longer lateral pressure cancellation time (Omran and Khayat 2017b). The lateral pressure cancellation time corresponds to the time elapsed when the measured lateral pressure is zero.

Khayat and Omran (2010b) considered the effect of temperature on lateral pressure and proposed two different prediction models. The first model involves the measurement of thixotropy at room temperature (72 ± 4°F [22 ± 2°C]) and includes the concrete temperature as a variable in the model, as shown in Eq. (5.2a). The second model includes the thixotropy of the concrete at the target temperature, as indicated in Eq. (5.2b). Equation (5.2b) is valid in the range 53 to 86 ± 4°F (12 to 30 ± 2°C).

\[
P_{\text{max}} = \frac{wH}{100} \left[ 109.5 - 3.9H + 0.7R - 0.6T + 0.003D_{\text{min}} - 0.29PV_{\tau_{\text{rest}}(T=22\pm2\,\text{C})}(t) \right] \quad (5.2a)
\]

\[
P_{\text{max}} = \frac{wH}{100} \left[ 95.9 - 3.84H + 0.71R + 0.0041D_{\text{min}} - 0.29PV_{\tau_{\text{rest}}(T=22\pm2\,\text{C})}(t) \right] \quad (5.2b)
\]

where \(w\) is the concrete unit weight (kip/ft\(^3\) [kN/m\(^3\)]); \(T\) is the average concrete temperature (°F [°C]); \(H\) is element height (ft [m]); \(R\) is the casting rate (ft/hour [m/hour]); \(D_{\text{min}}\) is the minimum lateral dimension of the formwork (ft [m]); \(PV_{\tau_{\text{rest}}(T=22\pm2\,\text{C})}(t)\) is the rate of gain in yield stress with time of rest (psi/minute [Pa/minute]) measured at 72 ± 4°F (22 ± 2°C) using portable vane; and \(PV_{\tau_{\text{rest}}(T)}(t)\) rate of gain in yield stress with time of rest (psi/minute [Pa/minute]) measured at a given concrete temperature.
Fig. 5.2a - Effect of temperature (50, 68, and 86°F [10, 20, and 30°C]) on lateral pressure characteristics. Slump at end of pressure monitoring is noted (Assaad and Khayat 2006a). (Note: 1 ft = 0.3 m; 1 in. = 25.4 mm; 1°F = °C.)

Fig. 5.2b – Effect of SCC temperature on relative lateral pressure (Omran et al. 2014). (Note: 1 ft = 0.3 m; 1 in. = 25.4 mm; 1°F = °C.)

5.3—Casting rate
The casting rate is another critical parameter that influences the form pressure of SCC. Several investigations have been carried out to determine the influence of casting rate on the development of lateral pressure (Assaad and Khayat 2006a; Beitzel and Muller 2004; Fedroff and Frosch 2004; Leemann and Hoffmann 2003; Omran et al. 2014; Tejeda-Dominguez et al. 2005; Vanhove et al. 2001). Ritchie (1962) conducted experiments on conventional concrete with varying cement-to-total-coarse-aggregate ratios with varying casting rates and found that irrespective of the composition and workability of the mixture, lateral
pressure was found to increase with the casting rate. Similar results have been observed by Omran et al. (2014) shown in Fig. 5.3a for SCC mixtures with varying degrees of thixotropy and slump flow of 27.5 ± 1.0 in. (700 ± 20 mm) and by Assaad and Khayat (2006a) (Fig. 5.3b) for SCC made with ternary binder (6 percent SF, 22 percent FA, and 72 percent cement) and have w/cm of 0.4 and slump flow of 25.5 ± 0.5 in. (650 ± 15 mm). At faster casting rates, no structural build-up of the material occurs and the SCC form pressure could reach hydrostatic pressure. This condition typically occurs in small volume pours that can be completed in one single lift; examples includes casting SCC for repair/strengthening applications. However, from form pressure measurements performed in larger placements where the casting rates are slower, the maximum pressure is considerably smaller than the hydrostatic pressure due to structural build-up (Assaad and Khayat 2005c; Assaad et al. 2003b; Billberg et al. 2014; Gardner et al. 2016).

The method of casting also has a significant effect on form pressure. When comparing between the concrete cast from the top of the formwork and pumped from the bottom of the formwork, higher lateral pressure is exerted in the latter case. This is because the concrete is in constant motion (or shear) during pumping from the bottom; As a result, no structural build-up is allow to happen until after placement is completed. This lack of structural build-up results in high lateral pressure that is close to the full-hydrostatic pressure (Leemann and Hoffmann 2003).

Fig. 5.3b – Effect of casting rate on relative lateral pressure (Omran et al. 2014). (Note: 1 in. = 25.4 mm; 1 ft = 0.3 m.)
Fig. 5.3b – Effect of casting rate on lateral pressure characteristics (Assaad and Khayat 2006a). (Note: 1 in. = 25.4 mm; 1 ft = 0.3 m.)

5.4—Formwork characteristics

Research over the years has evaluated the effects of formwork geometry and surface roughness to determine their contribution to the overall form pressure. Rodin (1952) reported that the general trends indicate that the maximum pressure appears to be lower in form systems of smaller cross sections. This can be attributed to the increased degree of the arching effect, which reduces lateral pressure. The arching effect herein refers to the interaction between coarse aggregate particles and the formwork, reinforcement, or both. Omran and Khayat (2017a) evaluated the effect of formwork width on form pressure for SCC mixtures (SCC 1 and SCC 2) and the results are shown in Fig. 5.4. SCC 1 mixture is made of 5 percent SF, 25 percent SL, and 70 percent cement and has a slump flow of 28 in. (705 mm) and static yield stress at 15 minutes rest is 0.11 psi (755 Pa); SCC 2 is made of 5 percent SF, 23 percent FA, and 72 percent cement and has slump flow of 26 in. (660 mm) and static yield stress at 15 minute rest is 0.05 psi (320 Pa). Omran and Khayat (2017a) observed an increase in the lateral pressure and a slower pressure decay with an increase in formwork width. With an increase in formwork width, the increase in the lateral pressure was due to the reduction in the arching effect and the slower pressure decay was due to an increase in pressure cancellation time.
Fig. 5.4 – Effect of formwork width on relative lateral pressure (left) and pressure decay (right) (Omran and Khayat 2017a). (Note: 1 in. = 25.4 mm; 1 ft = 0.3 m.)

Rigid and smooth formwork materials result in higher lateral pressure (Khayat and Omran 2010b). The roughness of the forms plays a role due to the dynamic friction that develops upon concrete placement. The application of demolding agents, such as form release oil can decrease friction and lead to an increase in lateral pressure (Djelal et al. 2002; Khayat and Omran 2010b). Tchamba et al. (2008) observed a decrease in the form pressure with an increase in the surface roughness of the formwork. This was attributed to the increase in the shear stress supported by the formwork wall. Khayat et al. (2005) also found that the surface roughness, formwork geometry, and the structural build-up of the concrete mixture all played important roles in the accuracy of predicted values of the form pressure.

5.5—Reinforcement density

The presence of reinforcement can decrease form pressure because the reinforcement can support part of the concrete weight. Perrot et al. (2009) introduced the lateral pressure prediction model shown in Eq. (5.5a) that accounts for the effect of the reinforcement.

\[
\frac{P_{\text{max}}}{P_{\text{hydrostatic}}} = 1 - \left( \frac{\varphi_b + 2S_b}{(e - S_b)\varphi_b} \right) \tau_{\text{rest}}(t) \frac{H}{gR} \quad (5.5a)
\]

where \(P_{\text{max}}/P_{\text{hydrostatic}}\) is the relative lateral pressure, \(\varphi_b\) is the average diameter of the vertical reinforcing bars (ft [m]); \(S_b\) is the horizontal steel section per linear foot (meter) of width (ft [m]) that corresponds to the ratio of the total cross-sectional area of the vertical reinforcing bars (ft² [m²]) to the formwork width (ft [m]); \(e\) is the formwork thickness (ft [m]), that is, shortest dimension in case of a rectangular formwork; \(\tau_{\text{rest}}(t)\) is the structural build-up measured as rate of increase in yield stress with rest time (kip/minute...
[Pa/minute]); $H$ is the height of concrete in formwork (ft [m]); $\rho$ is the density of concrete (lb/ft$^3$ [kg/m$^3$]);
g is the acceleration due to gravity (ft/second$^2$ [m/second$^2$]); and $R$ is the casting rate (ft/minute [m/minute]).

Omran and Khayat (2017b) introduced a coefficient ($f_{pov}$) to account for reinforcement density ($\rho_{sv}$ is measured as a percentage of total cross section area of vertical bars to gross column area) and concrete cover (in. [mm]) on form pressure, shown in Eq. (5.5b) and Fig. 5.5.

$$f_{pov} = 1 - \rho_{sv} \left( 4.63 + \frac{106.3}{\text{concrete cover}} \right)$$ (5.5b)

Fig. 5.5 - Effect of reinforcing bar density on lateral pressure reduction (Omran and Khayat 2017b). (Note: 1 in. = 25.4 mm; 1 ft = 0.3 m.)

CHAPTER 6—PREDICTION MODELS FOR SCC FORM PRESSURE

6.1—Introduction
A number of models have been developed based on theoretical principles, laboratory studies, and field studies to predict the lateral pressure exerted by SCC. Four of these models are covered in this chapter. These models mentioned herein do not take into account the reduction in form pressure due to the presence of reinforcement, which can have a substantial effect on lateral pressure depending on the concrete cover depth and reinforcement density, as shown in 5.5. More details on such considerations can be found in Perrot et al. (2009) and Omran and Khayat (2017b).

6.2—Model by Gardner et al. (2012)
This model is based on field observations by Gardner et al. (2012) and includes the following parameters:
- concrete unit weight, $w$ (lb/ft$^3$ [kN/m$^3$])
- casting rate ($R$ (ft/hour [m/hour]), time to fill the formwork to height $H$ (tH [hour]), and time for the slump flow of concrete to theoretically reach zero ($t_0$ [hour]); $t_0$ is considered to correspond to the time when the concrete could support its own weight. The $t_0$ parameter is obtained by linearly extrapolating the rate of slump flow loss, which is measured using an inverted slump cone (ASTM C1611/C1611M, Procedure B), with time to decrease to 15.75 in. (400 mm) ($t_{400}$ hour), as indicated in Eq.
The lateral pressure \( P_{\text{max}} \) exerted by SCC can be calculated using Eq. (6.2b) and (6.2c). Mixtures of initial slump flow of 600 to 700 mm (24 to 28 in.) were used to develop the model.

\[
t_0 = t_{15.75\text{ in.}} \left( \frac{\text{Initial slump flow (in.)}}{(\text{Initial slump flow (in.)} - 15.75)} \right) \text{ (in.-lb units) } \quad (6.2a)
\]

\[
t_0 = t_{400\text{ mm}} \left( \frac{\text{Initial slump flow (mm)}}{(\text{Initial slump flow (mm)} - 400)} \right) \text{ (6.2a) (SI units)}
\]

\[
P_{\text{max}} = wR \left( t_H - \frac{t_H^2}{2t_0} \right) \text{ for } t_H < t_0 \text{ (in.-lb units) } \quad (6.2b)
\]

\[
P_{\text{max}} = \frac{wRt_0}{2} \text{ for } t_H \geq t_0 \text{ (in.-lb units) } \quad (6.2c)
\]

\[
P_{\text{max}} = \frac{wRt_0}{2} \text{ for } t_H \geq t_0 \text{ (SI units)}
\]

### 6.3—Model by Khayat and Omran (2010b)

A number of models are established based on laboratory tests conducted using a pressure column that is 2.3 ft (0.7 m) tall and with an internal diameter of 0.7 ft (0.2 m) as shown in Fig. 6.3a. The column is designed to simulate a concrete placement height of up to 43 ft (13 m) by applying overhead pressure. The models to predict the lateral pressure are developed using linear regression analysis by fitting approximately 780 data points while taking into account the following parameters: concrete unit weight \( w \) [lb/ft\(^3\) (kN/m\(^3\))]; element height \( H \) [ft (m)]; and casting rate \( R \) [ft/hour (m/hour)]; equivalent minimum lateral dimension of the formwork \( D_{\text{min}} \) [ft (m)] with its value changed depending on the actual minimum dimension of the formwork \( d \) [ft (m)] as shown in Table 6.3a, maximum size of the aggregate (MSA) \( f_{\text{MSA}} \), waiting period (WP) between successive lifts \( f_{\text{WP}} \), and SCC thixotropy. The \( f_{\text{MSA}} \) and \( f_{\text{WP}} \) values can be obtained using Table 6.3b and Fig. 6.3b, respectively. Thixotropy is measured using a portable vane and different models are proposed based on various thixotropic indexes; that is, rate of change in the yield stress with rest time.
(PVτ_{0\text{rest}}(t) (lb/ft^2/minute [Pa/minute]) and yield stress after 15 minutes of rest (PVτ_{0\text{rest}@15\text{min}} (lb/ft^2 [Pa])) (Khayat and Omran 2010b). The models that consider the variation in structural build-up at rest (PVτ_{0\text{rest}}(t)) are presented in Eq. (6.3a) and (6.3b) and the models that consider PVτ_{0\text{rest}@15\text{min}}, and the coupled effect of PVτ_{0\text{rest}}(t) and PVτ_{0\text{rest}@15\text{min}} can be found in (Omran et al. 2011). The thixotropic indexes in these equations are determined at a given concrete temperature. Equation (5.2a) offers an alternative approach where the concrete temperature is a variable, and the thixotropic index is determined at 72 ± 4°F (22 ± 2°C). Further discussion on the effect of temperature on the thixotropy and form pressure is discussed by Khayat and Omran (2010b). These models are shown in Table 6.3c. A numerical example for the prediction of the lateral pressure using these models is presented in A2.

\[
P_{\text{max}} = \frac{wH}{100}[93.61 - 1.166H + 0.222R + 4.222D_{\text{min}} - 13.76 PV\tau_{0\text{rest}}(t)]x_{\text{f MS}}, x_{\text{f WP}} \text{ (in.-lb units)} \quad (6.3a)
\]

\[
P_{\text{max}} = \frac{wH}{100}[95.9 - 3.844H + 0.711R + 4.1D_{\text{min}} - 0.29 PV\tau_{0\text{rest}}(t)]x_{\text{f MS}}, x_{\text{f WP}} \text{ (SI units)}
\]

\[Fig. 6.3a – Portable pressure column setup (Khayat and Omran 2010b).\]
Fig. 6.3b – Correction factor of WP (Khayat and Omran 2010b).

Table 6.3a – Equivalent minimum dimension of the formwork

<table>
<thead>
<tr>
<th>d</th>
<th>D_{min}</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.2 m  (7.9 in.)</td>
<td>0.2 m (7.9 in.)</td>
</tr>
<tr>
<td>0.2 m (7.9 in.) &lt; d &lt; 0.5 m (19.7 in.)</td>
<td>D</td>
</tr>
<tr>
<td>&gt; 0.5 m (19.7 in.)</td>
<td>0.5 m (19.7 in.)</td>
</tr>
</tbody>
</table>

Table 6.3b – Correction factors for MSA

<table>
<thead>
<tr>
<th>PV_{T0rest@15min}, Pa</th>
<th>H, m</th>
<th>MSA, mm</th>
<th>f_{MSA}</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 700</td>
<td>&lt; 4</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>4 to 12</td>
<td>10</td>
<td>1 + \frac{1.26H - 5.04}{100}</td>
</tr>
<tr>
<td>&gt; 700</td>
<td>1 to 12</td>
<td>10 and 20</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: 1 m = 3.25 ft; 1 mm = 0.039 in.; 1 psi = 6894.76 Pa.

Table 6.3c – Parameter ranges for Khayat and Omran’s model (2010b)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Investigated ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump flow</td>
<td>24 to 28 in. (600 to 720 mm)</td>
</tr>
<tr>
<td>Element height (H)</td>
<td>3.3 to 42.6 ft (1 m to 13 m)</td>
</tr>
<tr>
<td>Concrete temperature</td>
<td>53 to 86 ± 4°F (12 to 30 ± 2°C)</td>
</tr>
<tr>
<td>Maximum size of the aggregate (MSA)</td>
<td>0.4 in (10 mm); 0.6 in. (14 mm); 0.8 in. (20 mm)</td>
</tr>
<tr>
<td>Minimum lateral dimension of the formwork (D_{min})</td>
<td>8 to 14 in. (200 to 350 mm)</td>
</tr>
<tr>
<td>Waiting period between successive lifts (WP)</td>
<td>Continuous; 30 min WP at the middle of casting; two WPs of 30 min each at middle of casting</td>
</tr>
</tbody>
</table>
### 6.4—Model by Tejeda-Dominguez et al. (2005)

Tejeda-Dominguez et al. (2005) developed a mathematical model for the prediction of lateral pressure exerted by SCC. The model was developed assuming that the lateral pressure is a function of the vertical pressure and shear strength of SCC. Tejeda-Dominguez et al. (2005) defined the characteristic function \( C(t) \) as the ratio of lateral (\( P_{\text{max}} \)) and hydrostatic (\( P_{\text{hydrostatic}} \)) concrete pressures. The lateral pressure exerted during the casting of SCC is predicted by estimating the \( C(t) \) using a small-scale instrumented PVC column that is 3 ft (920 mm) in length and 0.82 ft (250 mm) in diameter shown in Fig. 6.4. The test column is instrumented with flush-mounted pressure sensors installed at 0.5 ft (152 mm) from the base shown in Fig. 6.4. The sensor measures the lateral pressure exerted by concrete on the PVC column and \( C(t) \) is computed as normalized value, that is, the ratio of the lateral pressure measured and hydrostatic pressure. The computed \( C(t) \) is fit with a hyperbolic function shown in Eq. (6.4a) and the variables \( C_0, a, \) and \( \alpha \) are determined for the best-fit obtained. The values of the variables obtained from the test column are used for predicting the on-site lateral pressure using Eq. (6.4b). Based on lab testing, a \( C_0 \) value of 0.95 was selected. A numerical example both in inch-pound and in SI units for the prediction of the lateral pressure using this model is presented in A3.

\[
C(t) = \frac{C_0}{(at^2 + 1)^\alpha} \tag{6.4a}
\]

\[
P_{\text{max}} = wRt C(t) \tag{6.4b}
\]

The maximum lateral pressure (\( P_{\text{max}} \)) occurs when time from the start of casting (\( t \)) is

\[
\sqrt{\frac{1}{2a(\alpha - 1)}}
\]
Fig. 6.4 – (a) Instrumented PVC column; and (b) placement of pressure sensor in the formwork (Tejeda-Dominguez et al. 2005).

6.5—Model by Ovarlez and Roussel (2006)

Ovarlez and Roussel’s (2006) model follows a theoretical approach, and it considers SCC as an elastic material confined in the formwork and follows Tresca plasticity criterion (that is, the maximum stress sustainable by an internal plane is the yield stress of the concrete). This model uses the Janssen model (Sperl 2006) to predict the relation between the lateral ($P_{\text{max}}$) and hydrostatic ($P_{\text{hydrostatic}}$) concrete pressures. Ovarlez and Roussel (2006) state that the pressure exerted by concrete at a certain depth ($H$) is equal to a hydrostatic pressure reduced by the vertical stress at the walls, which is between 0 and the concrete yield stress at rest. It is also assumed that the weight of the concrete could cause SCC to deform vertically and this deformation is sufficient to increase the shear stress to the yield stress of concrete. The yield stress of concrete is considered to increase linearly with time $\bar{\tau}_{0\text{rest}}(t)$ (psi/hour [Pa/hour]), which is the case for a relatively short duration. Equations (6.5) is based on the aforementioned assumptions and considering the Janssen parameter ($K$) is 1. The model uses the following parameters: unit weight $w$ (psi/ft [kN/m$^3$]), height $H$ (ft [m]), width or diameter of cross section $e$ (ft [m]), and casting rate $R$ (ft/hour [m/hour]). Other details about the derivation of the equation and assumptions made can be found in Ovarlez and Roussel (2006). A numerical example n for the prediction of the lateral pressure using this model is presented in A4.

\[
P_{\text{max}} = wH \left(1 - \frac{H\bar{\tau}_{0\text{rest}}(t)}{weR}\right) \text{ (in.-lb units)} \tag{6.5}
\]
\[ P_{\text{max}} = wH \left( 1 - \frac{H \tau_{0\text{rel}}(t)}{1000wER} \right) \text{ (SI units)} \]

CHAPTER 7—MEASUREMENT TECHNIQUES

There have been a number of methods developed and implemented to measure the lateral pressure exerted by plastic concrete on formwork. Brameshuber and Uebachs (2003) used a series of measuring anchors and strain measuring devices to determine the form pressure using SCC. Strain gauges were also used in Cambridge-type load cells that were employed by Gardner (1985) to determine lateral pressure developed by fresh concrete. In field studies described in Chapter 8, the strain-gauge-based pressure sensors were used to monitor the form pressure. These pressure sensors are commercially known as flush diaphragm, millivolt output pressure transducers, and examples of these sensors are shown in Fig. 7a. The diameter of the sensor depends on the MSA of the mixture being monitored; the larger the aggregate, the greater the diameter, though typically for an SCC mixture the diameters range from 0.6 to 1 in. (15 to 25 mm).

Fig. 7a – Examples of flush diaphragm and millivolt output pressure transducers (image courtesy of Honeywell).
Fig. 7b – Calibrating pressure sensors and data acquisition system.

Fig. 7c – Pressure sensor adaptors.

The measured values of the sensors were calibrated against an analog pressure gauge using either an oil pump or air compressor, as seen in Fig. 7b. The process of calibrating the sensors commences with zeroing the sensor with no applied pressure then incrementally increasing the pressure to a value of slightly less than the capacity of the sensor.

The installation of these pressure sensors requires setting them through a drilled hole flush with the inner face of the form by means of a secured adaptor. These adaptors are not commercially available and were designed and fabricated based on each specific sensor, as they come in varying geometries based on supplier and product generation. Adaptors can be machined or 3D printed, as seen in Fig. 7c, for their intended use with these considerations in mind: sacrificial or reusable, fixed or adjustable, form thickness, method of securing the adaptor to the form, and if spacers will be used or not.

In field studies described in Chapter 8, the first sensors were located at a distance of $H/2$ from the bottom of the formwork ($H$ being the total height of the formwork) to avoid the shear restraint imposed on the concrete by the foundation. Further sensors were installed at set intervals, approximately 3.3 ft (1 m), above
the initial location to collect pressure data throughout the element. A thin film of form release agent or
grease was also applied to the sensors to protect them from the concrete.

There are different methods, systems, and programs for reading the information relayed by the sensors,
but each requires the sensors to be connected to a data acquisition system. For these studies, the system
involved a data-logger with a scanning voltage of 5 mV, an adaptor to record the data, and a program to
translate the information into pressure, as shown in Fig. 7b. More advanced systems wirelessly translate the
information in real time and store it online without the need of an adaptor or personally running the data
through a program.

CHAPTER 8—FIELD VALIDATION OF PREDICTION MODELS

Two full-scale field studies were conducted to validate the prediction models discussed in Chapter 6
(Billberg et al. 2014; Gardner et al. 2016). The details regarding the mixture designs, field tests conducted,
and the measured and predicted pressure data are presented in the following.

8.1—Stockholm, Sweden, 2012

Full-scale testing was conducted in Stockholm, Sweden, to evaluate various existing form pressure
models (Billberg et al. 2014). A total of eight walls were cast using two SCC mixtures with different levels
of structural build-up at rest. The dimensions of the eight walls are as follows: four walls (Walls 1, 3, 5,
and 7) were 21.7 ft (6.6 m) in height, 7.9 ft (2.4 m) in length, and 7.9 in. (0.2 m) in thickness. Three other
walls (Wall 2, 4, and 6) were 13.8 ft (4.2 m) in height, 7.9 ft (2.4 m) in length, and 7.9 in. (0.2 m) in
thickness. One wall (Wall 8) was 13.8 ft (4.2 m) in height, 7.9 ft (2.4 m) in length, and 15.7 in. (0.4 m) in
thickness. A more thixotropic mixture was used for casting Walls 1, 2, 5, 6, 7, and 8, while a low thixotropic
mixture was used for casting Walls 3 and 4. The casting was done stepwise in relatively small but frequent
steps to enable a continuous placement of concrete in the form. A laser meter was used to measure the rising
of the concrete level with time and the casting rate was measured to be between 8.8 and 21 ft/hour (2.7 and
6.4 m/hour). The lateral pressure was measured for each wall at different elevations using pressure sensors
flush mounted to vertical formwork surfaces. The maximum relative pressure and the casting rates
measured for each wall are shown in Fig. 8.1a.

The key parameters needed for prediction of the maximum lateral pressure are measured using the
portable vane shown in Fig. 3.1, Lange’s static column (Fig. 6.4(a)), and the slump flow loss test (Fig. 8.1b)
and the results are shown in Table 8.1. Using these parameters, the maximum lateral pressure for each wall
was estimated and these values were compared to the measured lateral pressures as shown in Fig. 8.1c. The
slope of the trend lines vary between 1.09 and 1.30 and regression coefficients ($R^2$) are between 0.77 and
0.86. The slope values greater than 1 indicate that the estimated pressure is greater than the measured ones,
and high $R^2$ values for all four models mean that they can accurately predict the measured lateral pressure.
Fig. 8.1a - Casting rate and maximum relative form pressure ($P_u/P_{hyd}$) for all eight walls (Billberg et al. 2014). (Note: 1 ft = 0.3 m.)

Fig. 8.1b – Concrete characterization using slump flow loss test.
Fig. 8.1c – Predicted vs. measured pressures for: (a) Gardner et al. (2012); (b) Khayat and Omran (2009); (c) Tejeda-Dominguez et al. (2005); and (d) Ovarlez and Roussel (2006) (Billberg et al. 2014). (Note: 1 psi = 6894.76 Pa.)

Table 8.1 – Key parameters related to models in Chapter 6 (Billberg et al. 2014).

<table>
<thead>
<tr>
<th>Model/parameter</th>
<th>Wall No.</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1*</td>
<td>2*</td>
<td>3*</td>
<td>4†</td>
<td>5*</td>
<td>6†</td>
<td>7*</td>
</tr>
<tr>
<td>Gardner et al. (2012)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_0$ (hr)</td>
<td>4.0</td>
<td>9.7</td>
<td>4.2</td>
<td>11.3</td>
<td>6.6</td>
<td>8.3</td>
<td>9.3</td>
</tr>
<tr>
<td>Khayat and Omran (2010)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV$\tau_{\text{rest}}$ (t) (Pa)</td>
<td>410</td>
<td>176</td>
<td>261</td>
<td>215</td>
<td>307</td>
<td>254</td>
<td>319</td>
</tr>
<tr>
<td>PV$\tau_{\text{rest}}$ (Pa/minute)</td>
<td>16.0</td>
<td>5.8</td>
<td>9.9</td>
<td>2.3</td>
<td>11.2</td>
<td>9.6</td>
<td>18.5</td>
</tr>
<tr>
<td>Tejeda-Dominguez et al. (2005)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C$_0$</td>
<td>-</td>
<td>0.94</td>
<td>0.86</td>
<td>1.04</td>
<td>0.90</td>
<td>0.90</td>
<td>0.84</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>-</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>a</td>
<td>-</td>
<td>0.32</td>
<td>0.40</td>
<td>0.80</td>
<td>0.75</td>
<td>0.40</td>
<td>0.70</td>
</tr>
<tr>
<td>Ovarlez and Roussel (2006)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV$\tau_{\text{rest}}$ (Pa/minute)</td>
<td>16.0</td>
<td>5.8</td>
<td>9.9</td>
<td>2.3</td>
<td>11.2</td>
<td>9.6</td>
<td>18.5</td>
</tr>
</tbody>
</table>

Note: 1 Pa = 0.000145 psi; 1 Pa/minute = 0.000145 psi/minute.

*Wall dimensions (L x B x H) = 7.9 ft x 7.9 in. x 21.7 ft (2.4 x 0.2 x 6.6 m)
†Wall dimensions (L x B x H) = 7.9 ft x 7.9 in. x 13.8 ft (2.4 x 0.2 x 4.2 m)
‡Wall dimensions (L x B x H) = 7.9 ft x 15.7 in. x 13.8 ft (2.4 x 0.4 x 4.2 m)
8.2—Toronto, Canada, 2014

Full-scale testing was conducted at a concrete production plant in Toronto, Canada (Gardner et al. 2016). Eight columns with dimensions of 20 ft (6.1 m) in height and a cross section of 2 x 2 ft (0.61 x 0.61 m) were cast. The casting rate, reinforcement density (note that the reinforcement density for the Toronto trials was significantly less (1/10) of what would be considered typical in production elements), and SCC thixotropy were varied. The lateral pressure was measured at different elevations using pressure sensors similar to those employed for the Stockholm project.

To minimize lateral pressure effects due to the impact of falling concrete, seven of the eight columns were placed using a modified tremie. The system comprised of an 8 in. (200 mm) diameter flexible PVC tube fastened to a hopper extending to approximately 15.75 (400 mm) from the bottom of the column. Ports measuring 6 x 4 in. (150 x 100 mm) were cut into alternating sides of the tube along its length, as shown in Fig. 8.2a. A crane and bucket were used to fill the hopper at specified intervals to match the appropriate casting rate with the exception of Column 7 that was pumped from the base at 167 ft/hour (51 m/hour). Pressure sensors were mounted with the sensor face flush to the surface of the formwork at varying elevations. The maximum pressure values measured at each elevation with the sensors mounted at the sparse and dense reinforcement are reported in Table 8.2a.

![Fig. 8.2a – Modified tremie.](image)

<p>| Table 8.2a – Summary of maximum pressure values measured at each elevation, in kPa (Gardner et al. 2016) |</p>
<table>
<thead>
<tr>
<th>Gauge elevation, mm</th>
<th>200</th>
<th>450</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>3800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete head, m</td>
<td>5.8</td>
<td>5.5</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column 1</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>116.6</td>
<td>116.6</td>
<td>107.3</td>
<td>88.7</td>
<td>—</td>
<td>56</td>
</tr>
<tr>
<td>Sparse</td>
<td>121.3</td>
<td>—</td>
<td>112</td>
<td>84</td>
<td>65.3</td>
<td>56</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column 2</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>102.2</td>
<td>105.4</td>
<td>97.9</td>
<td>93.1</td>
<td>72.8</td>
<td>54.2</td>
</tr>
<tr>
<td>Sparse</td>
<td>98</td>
<td>98</td>
<td>93.3</td>
<td>70</td>
<td>65.5</td>
<td>53.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column 3</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>80.9</td>
<td>—</td>
<td>84.7</td>
<td>—</td>
<td>75.1</td>
<td>—</td>
</tr>
<tr>
<td>Sparse</td>
<td>80.9</td>
<td>—</td>
<td>86.2</td>
<td>—</td>
<td>81.8</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column 4</th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>93.3</td>
<td>98</td>
<td>84</td>
<td>65.3</td>
<td>56</td>
<td>46.6</td>
</tr>
<tr>
<td>Sparse</td>
<td>98</td>
<td>114.3</td>
<td>86.3</td>
<td>70</td>
<td>65.3</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column 5</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>93.3</td>
<td>107.5</td>
<td>88.6</td>
<td>79.3</td>
<td>56</td>
<td>46.7</td>
</tr>
<tr>
<td>Sparse</td>
<td>101.1</td>
<td>99.1</td>
<td>101.5</td>
<td>74.7</td>
<td>70</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column 6</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>106.5</td>
<td>—</td>
<td>100.8</td>
<td>87.2</td>
<td>78.1</td>
<td>—</td>
</tr>
<tr>
<td>Sparse</td>
<td>118</td>
<td>—</td>
<td>100.2</td>
<td>90.2</td>
<td>72</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column 7</th>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>144.7</td>
<td>135.4</td>
<td>116.7</td>
<td>93.4</td>
<td>79.4</td>
<td>51.3</td>
</tr>
<tr>
<td>Sparse</td>
<td>—</td>
<td>135.4</td>
<td>123.7</td>
<td>98</td>
<td>70</td>
<td>42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column 8</th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>31.6</td>
<td>—</td>
<td>82.6</td>
<td>76.7</td>
<td>60.4</td>
<td>—</td>
</tr>
<tr>
<td>Sparse</td>
<td>83.6</td>
<td>—</td>
<td>—</td>
<td>92.3</td>
<td>60.8</td>
<td>—</td>
</tr>
</tbody>
</table>

Note: 1 kPa = 0.145 psi; 1 m = 3.25 ft; 1 m/hour = 3.25 ft/hour.
Fig. 8.2b – Concrete characterization results using portable vane (top) and ICAR (bottom) (Gardner et al. 2016). (Note: 1 psi = 6894.76 Pa.)
Concrete characterization results using Lange’s static column (top) and slump cone (bottom) (Gardner et al. 2016). (Note: 1 psi = 6894.76 Pa.)

Concrete mixtures with varying thixotropy levels were developed in laboratory tests. During the program, concrete acceptance was based on slump flow and time required for SCC to spread to a diameter of 19.7 in. (500 mm) (ASTM C1611/C1611M) target ranges. Thixotropy was determined using the portable vane method at 15 minutes. Low thixotropy mixtures were defined as having shear strength below 0.102 psi (700 Pa) and high thixotropy mixtures were defined as having shear strength greater than 0.181 psi (1250 Pa). Concrete characterization to evaluate the structural build-up at rest was performed using the portable vane (Fig. 3.1) and the inclined plane method (Fig. 3.2.1d), Lange’s static column (Fig. 6.4(a)), and the slump flow loss test (Fig. 8.1b), and the results are shown in Table 8.2b, Fig. 8.2b, and Fig. 8.2c. Each of the
prediction models used one or more of the concrete characterization test results. These characterization test results are independent of the prediction models, but the prediction models are not independent of the characterization test results. The predicted pressure versus the measured pressure results are shown in Fig. 8.2d.

Table 8.2b – Concrete characterization results (Gardner et al. 2016)

<table>
<thead>
<tr>
<th>Column</th>
<th>Thixotropy</th>
<th>Portable vane Slope, Pa/minute</th>
<th>Inclined plane 15 minutes, Pa</th>
<th>Vane rheometer (ICAR) Slope, Pa/minute</th>
<th>Tejeda-Dominguez et al. (2005) static column Coefficients</th>
<th>Time at zero slump flow hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Medium</td>
<td>815</td>
<td>41.4</td>
<td>390</td>
<td>0.30 0.12</td>
<td>3.17</td>
</tr>
<tr>
<td>2</td>
<td>High</td>
<td>1032</td>
<td>40.1</td>
<td>586</td>
<td>0.17 0.26</td>
<td>2.95</td>
</tr>
<tr>
<td>3</td>
<td>High</td>
<td>1627</td>
<td>24.3</td>
<td>74</td>
<td>0.92 0.08</td>
<td>2.62</td>
</tr>
<tr>
<td>4</td>
<td>Low</td>
<td>541</td>
<td>6.7</td>
<td>274</td>
<td>0.30 0.65</td>
<td>4.15</td>
</tr>
<tr>
<td>5</td>
<td>High</td>
<td>2053</td>
<td>50.9</td>
<td>519</td>
<td>0.75 0.13</td>
<td>1.37</td>
</tr>
<tr>
<td>6</td>
<td>High</td>
<td>2191</td>
<td>34.6</td>
<td>592</td>
<td>0.82 0.17</td>
<td>3.53</td>
</tr>
<tr>
<td>7</td>
<td>High</td>
<td>1465</td>
<td>36.4</td>
<td>229</td>
<td>0.53 0.15</td>
<td>2.68</td>
</tr>
<tr>
<td>8</td>
<td>High</td>
<td>1459</td>
<td>17.3</td>
<td>314</td>
<td>0.47 0.15</td>
<td>2.68</td>
</tr>
</tbody>
</table>

Note: 1 Pa = 0.000145 psi; 1 Pa/minute = 0.000145 psi/minute.

The measured lateral pressures were predicted with acceptable accuracy using each of the methods described. It is important to note that the column sections were relatively small (2.9 yd³ [2.25 m³] concrete per column) so that even though the level of thixotropy has an effect on the lateral pressures, the heights of the columns (20 ft [6 m]), and relatively high rates of concrete placement prevented it from being pronounced in these results.

**8.3—Validation of the models**

The results using the Gardner et al. (2012), Khayat and Omran (2009), Tejeda-Dominguez et al. (2005), and Ovarlez and Roussel (2006) models from the Stockholm 2012 and Toronto 2014 field studies are shown in Fig. 8.3(a), (b), (c), and (d), respectively. The plots are derived from 78 to 103 data points (N) and the standard error of the estimates are also noted in Fig. 8.3.
The trend-line equations and standard error of the estimates are shown in Fig. 8.3, and indicate that these models can be used to predict the mean measured lateral pressure with accuracy ranging from -2 percent to +12 percent, and standard error of the estimates ranging approximately between 1.7 to 2 psi (12 to 14 kPa). The -2 percent and +12 percent error correspond to underestimation and overestimation of measured pressures, respectively. The standard error of the estimate ($S$), as defined in Eq. (8.3), represents the average distance that the predicted pressure values ($Y$) fall from the best-fit line, shown in red. A smaller value of $S$ indicates that predicted values are closer to the best-fit line.

$$\textit{Standard error of the estimate} (S) = \sqrt{\frac{\sum (Y - Y')^2}{N - 2}} \quad (8.3)$$

$Y'$ indicates predicted pressure from best-fit line for a given value of measured pressure ($X$).

Fig. 8.3 – Measured versus predicted lateral pressure from Stockholm and Toronto studies: (a) Gardner et al. model (2012); (b) Khayat and Omran’s (2009) model; (c) Tejeda-Dominguez et al. (2005) model; and (d) Ovarlez and Roussel (2006) model. (Note: 1 psi = 6894.76 Pa.)
The four experimentally based models can predict lateral pressure with reasonable accuracy. However, the models do not include any correction factor and safety factor. Such factors should be applied to mean predicted pressures to obtain design values that provide conservative estimates of form pressure.

**8.4—Considerations for Formwork Design**

The development of factors of safety for use in formwork design, including those used for the allowable stress design (ASD) and load and resistance factor design (LRFD) methodologies, is outside of the scope of this report. The correction factors or safety factors will be dependent upon the capability of the ready-mixed concrete producer to control the rheological parameters (and workability tolerances, such as those based on ASTM C1611/C1611M: slump flow, T50, and visual stability index (VSI)) of the SCC mixture. Site personnel should also understand the variations in these parameters so that a decision for acceptance or rejection of a batch of concrete can be assessed prior to casting into forms that are designed for pressures less than hydrostatic pressure. When approaching critical pressure, the placing rate should be reduced until the pressure decay rate is such that the lateral pressure does not jeopardize formwork capacity.

It is important to note that the models and the field validations that are presented herein are suitable for applications involving open forms. However, these models may not be suitable for formed applications in highly confined areas, such as in the case of concrete enlargement applications, where lateral pressure can be higher. In the case of concrete pumped from the bottom of the formwork, ACI 347R recommends designing formwork for the full concrete hydrostatic head plus a minimum allowance of 25 percent for pump surge pressure.

**CHAPTER 8—SUMMARY**

Thixotropy (structural build-up at rest) can significantly affect the maximum lateral pressure exerted by SCC and the pressure decay. As discussed in this report, the form pressure characteristics are highly influenced by constituent materials, including binder composition and chemical admixture types and combinations, and mixture proportioning. The concrete temperature, casting rate, reinforcement density, and formwork material and dimensions also have a significant effect on form pressure characteristics. The four experimental models presented to predict lateral pressure are based on the measured thixotropic characteristics. It is important to note that these models require testing, both during mixture development and at the point of placement to ensure that the predicted pressures are not exceeded during actual concrete placement.
It is also important to keep in mind that the experimental models are not design models. It is outside of the scope of this document to make design recommendations for formwork placed with SCC. It is recommended that the reader consult the latest design recommendations published by ACI Committee 347.

CHAPTER 9—REFERENCES

American Concrete Institute
ACI 237R-07(19)—Self-Consolidating Concrete
ACI 238.2T-14—Concrete Thixotropy
ACI 347R-14—Guide to Formwork for Concrete
ACI SP-4(14)—Formwork for Concrete

ASTM International

Authored references


Fedroff, D., and Frosch, R., 2004, “Formwork for Self-Consolidating Concrete,” *Concrete International*, V. 26, No. 10, pp. 32-37.


Khayat, K.; Assaad, J.; Mesbah, H.; and Lessard, M., 2005, “Effect of Section Width and Casting Rate on Variations of Formwork Pressure of Self-Consolidating Concrete,” Materials and Structures, V. 38, No. 1, pp. 73-78. doi: 10.1007/BF02480577


Robby, H., 1935, “Pressure of Concrete on Forms,” Civil Engineering, V. 5, No. 3.

Rodin, S., 1952, “Pressure of Concrete on Formwork,” Proceedings - Institution of Civil Engineers, V. 1, No. 6, pp. 709-746. doi: 10.1680/iicep.1952.10980


APPENDIX—EXAMPLE CALCULATIONS

A1—Calculation of form pressure using model by Gardner et al. (2012)

Inch-pound units

Height of Column = 20 ft
Casting Rate = 8 ft/hour
Total casting time \( (t_H) = 20/8 = 2.5 \) hour
Concrete unit weight \( (w) = 144 \text{lbf/ft}^3 \)
Initial slump flow = 27 in.
Time to decrease the slump flow to 15.75 in. = 1.5 hour
Using Eq. (6.2a), time for the concrete slump to theoretically reach zero, \( t_0 \) can be computed as

\[
t_0 = t_{15.75} \left[ \frac{\text{Initial slump flow (in)}}{\text{Initial slump flow (in)} - 15.75} \right] = 1.5 \left[ \frac{27}{27 - 15.75} \right] = 3.6 \text{ hr}
\]

Because \( t_H = 2.5 \) hours is less than \( t_0 = 3.6 \) hours, \( P_{\text{max}} \) is computed using Eq. (6.2b).

\[
P_{\text{max}} = wR \left( t_H - \frac{t_H^2}{2t_0} \right) = 144 \times 8 \left( 2.5 - \frac{2.5^2}{2 \times 3.6} \right) = 1880 \text{ psf} = 13 \text{ psi}
\]

SI units

Height of column = 6.0 m
Casting Rate = 2.4 m/hour
Total casting time = 2.5 hour
Concrete Unit Weight = 22.6 kN/m$^3$
Initial slump flow = 700 mm
Time to decrease the slump flow to 400 mm = 1.5 hour
Using Eq. (6.2a), time for the concrete slump to theoretically reach zero, $t_0$ can be computed as

$$t_0 = t_{400 \text{ mm}} \left[ \frac{\text{Initial slump flow (mm)}}{(\text{Initial slump flow (mm)} - 400)} \right] = 1.5 \left[ \frac{700}{700 - 400} \right] = 3.5 \text{ hr}$$

Because $t_H = 2.5$ hours is less than $t_0 = 3.5$ hours, $P_{\text{max}}$ is computed using Eq. (6.2b).

$$P_{\text{max}} = \omega R \left( t_H - \frac{t_H^2}{2t_0} \right) = 22.6 \times 2.4 \left( 2.5 - \frac{2.5^2}{2 \times 3.5} \right) = 87.17 \text{ kPa}$$

A2—Calculation of form pressure using model by Khayat and Omran (2010b)

**Inch-pound units**

- Height of the column = 20 ft
- Casting rate ($R$) = 8 ft/hour with no waiting period, that is, continuous casting
- Concrete unit weight ($\omega$) = 144 lbf/ft$^3$
- Change in yield stress with rest time ($\tau_{\text{rest}}(t)$) = 0.37 psi/hour = 0.888 psf/minute;
- Yield stress measured after 15 minutes of rest ($\tau_{\text{rest@15min}}(t)$) = 0.11 psi
- Maximum size of the aggregate (MSA) = 0.8 in.
- Diameter of the cross section ($d$) = 2 ft
- $D_{\text{min}}$ = equivalent minimum form dimension. Based on Table 6.3a, for $d > 1.64$ ft, $D_{\text{min}} = 1.64$ ft
- Based on Table 6.3b, for MSA 0.8 in. and $\tau_{\text{rest@15min}}(t)$ of 0.11 psi, $f_{\text{MSA}} = 1.0$
- Based on Fig. 6.3b, for continuous casting, $f_{\text{WP}} = 1$.
- Maximum lateral pressure exerted by SCC on the formwork ($P_{\text{max}}$) can be computed using Eq. (6.3a).

$$P_{\text{max}} = \frac{\omega H}{100} \left[ 93.61 - 1.166H + 0.222R + 4.22D_{\text{min}} - 13.76 PV \tau_{\text{rest}}(t) \right] x_f \frac{\text{MSA}}{x_f_{\text{WP}}}$$

$$P_{\text{max}} = \frac{144 \times 20}{100} \left[ 93.61 - 1.166(20) + 0.222(8) + 4.22(1.64) - 13.76(0.888) \right] x_1x_1 = 1922.92 \text{ psf} = 13.35 \text{ psi}$$

**SI units**

- Height of the column = 6.1 m
- Casting rate ($R$) = 2.44 m/hour with no waiting period, that is, continuous casting
- Concrete unit weight ($\omega$) = 22.6 kN/m$^3$
Change in yield stress with rest time ($\tau_{\text{rest}}(t)$) = 42.5 Pa/minute

Yield stress measured after 15 minutes of rest ($\tau_{\text{rest@15min}}$) = 758 Pa

Maximum size of the aggregate (MSA) = 20 mm

Diameter of the cross section ($d$) = 0.61 m

$D_{\text{min}}$ = equivalent minimum form dimension. Based on Table 6.3a, for $d > 0.5$ m, $D_{\text{min}} = 0.5$ m

Based on Table 6.3b, for MSA 20 mm and $\tau_{\text{rest@15min}}$ of 758 Pa, $f_{\text{MSA}} = 1$

Based on Fig. 6.3b, for continuous casting, $f_{WP} = 1$

Maximum lateral pressure exerted by SCC on the formwork ($P_{\text{max}}$) can be computed using Eq. (6.3a).

$$P_{\text{max}} = \frac{wH}{100} \left[ 95.9 - 3.84H + 0.71R + 4.1D_{\text{min}} - 0.29PV\tau_{\text{rest}}(t) \right]x_{\text{fMSA}}x_{\text{WP}}$$

$$P_{\text{max}} = \frac{22.6 \times 6.1}{100} \left[ 95.9 - 3.84(6.1) + 0.71(2.44) + 4.1(0.5) - 0.29(42.5) \right] \times 1 \times 1 = 88.34 \text{kPa}$$

A3—Calculation of form pressure using model by Tejeda-Dominguez et al. (2005)

Inch-pound units

Height of the column = 20 ft

Casting rate ($R$) = 8 ft/hour = 0.133 ft/minute

Total casting time = 20/8 = 2.5 hour = 150 minute

Temperature = 68°F

Concrete unit weight ($w$) = 144 lbf/ft$^3$

The values of $a$, $\alpha$, and $C_0$ are taken as $10^{-5.5}$, $\alpha = 12$, and 0.95, respectively. These values were taken from (Tejeda-Dominguez et al. 2005).

Using Eq. (6.4a), the decay function $C(t)$ can be computed as

$$C(t) = \frac{C_0}{(at^2 + 1)^\alpha} = \frac{0.95}{(10^{-5.5}t^2 + 1)^{12}}$$

The decay function $C(t)$ is shown in Fig. A1.
Fig. A1 – Variations in \( C(t) \) with time.

\[
\text{Lateral pressure exerted by SCC} = \left( wRt \right) \times C(t) = \left( 144 \times 0.133 \times t \right) \times C(t) \frac{\text{lbf}}{\text{ft}^2} = 19.2t \times C(t) \frac{\text{lbf}}{\text{ft}^2} = 0.133t \times C(t) \text{ psi}
\]

The variation in the lateral pressure with time is shown in Fig. A2. The maximum pressure \( (P_{\text{max}}) \) is identified as 8.9 psi. This function is maximized when:

\[
t = \sqrt{\frac{1}{2a\alpha - a}} = \sqrt{\frac{1}{2 \times 10^{-5.5} \times 12 \times 10^{-5.5}}} = 117.3 \text{ min}
\]

Fig. A2 – Prediction of lateral pressure using the model by Tejeda-Dominguez et al. (2005).

**SI units**

Height of the column = 6 m

Casting rate \((R) = 2.4 \text{ m/hour} = 0.04 \text{ m/minute}\)

Total casting time = \(6/2.4 = 2.5 \text{ hour} = 150 \text{ minute}\)
Temperature = 20°C
Concrete unit weight \( (w) \) = 22.6 kN/m³
The values of \( a \), \( \alpha \), and \( C_0 \) are taken as \( 10^{-5.5} \), \( \alpha = 12 \), and 0.95, respectively. These values were taken from (Tejeda-Dominguez et al. 2005).

\( C_0 = 0.95 \) (typical value for the tests run in the lab)

Using Eq. (6.4a), the decay function \( C(t) \) can be computed as

\[
C(t) = \frac{C_0}{(ar^2 + 1)^\alpha} = \frac{0.95}{(10^{-5.5}r^2 + 1)^{12}}
\]

The decay function \( C(t) \) is shown in Fig. 44.

\[ \text{Lateral pressure exerted by SCC} = (wRt)xC(t) = (22.6 \times 0.04 \times t)xC(t) \text{kPa} = 0.9t \times C(t) \text{kPa} \]

The variation in the lateral pressure with time is shown in Fig. A4. The maximum pressure \( (P_{\text{max}}) \) is identified as 60 kPa. This function is maximized when:

\[
t = \sqrt{\frac{1}{2a\alpha - a}} = \sqrt{\frac{1}{(2 \times 10^{-5.5} \times 12) - 10^{-5.5}}} = 117.3 \text{min}
\]
**Fig. A4 – Prediction of lateral pressure using the model by Tejeda-Dominguez et al. (2005).**

**A4—Calculation of form pressure using model by Ovarlez and Roussel (2006)**

*Inch-pound units*

Height of the column = 20 ft  
Casting rate (R) = 8 ft/hr  
Concrete unit weight (w) = 144 lbf/ft^3 = 1 psi/ft  
Change in yield stress with rest time (τ_{0rest}(t)) = 0.37 psi/hour  
Diameter of the cross section (e) = 2 ft  
Horizontal or lateral pressure exerted by SCC on the formwork (P_H) can be computed using Eq. (6.5).

\[ P_H = P_{max} = wH \left( 1 - \frac{H \tau_{0rest}(t)}{weR} \right) \times 20 \left( 1 - \frac{20 \times 0.37}{1 \times 2 \times 8} \right) = 10.75 \text{ psi} \]

*SI units*

Height of the column = 6 m  
Casting rate (R) = 2.4 m/hour  
Concrete unit weight (w) = 22.6 kN/m^3  
Change in yield stress with rest time (τ_{0rest}(t)) = 42 Pa/minute = 2520 Pa/hour  
Diameter of the cross section (e) = 0.61 m  
Horizontal or lateral pressure exerted by SCC on the formwork (P_H) can be computed using Eq. (6.5).

\[ P_H = P_{max} = wH \left( 1 - \frac{H \tau_{0rest}(t)}{1000weR} \right) = 22.6 \times 6 \left( 1 - \frac{6 \times 2520}{1000 \times 22.6 \times 0.61 \times 2.4} \right) = 73.63 \text{ kPa} \]