https://doi.org/10.1016/j.cscm.2021.e00642

Pressure Exerted on Formwork by Self-Compacting Concrete at Early Ages: A Review

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Highlights

- The exerted lateral pressure of self-compacting concrete on formwork was reviewed.
- Theoretical models of exerted lateral pressure by self-compacting concrete were discussed.
- The main factors contributing to the lateral pressure of self-compacting concrete on the formwork panel were explained.
- Major issues and unpublished studies on lateral pressure of self-compacting concrete were discussed in detail.

Abstract

Self-Compacting Concrete (SCC) is a flowable concrete that exerts high pressure on formwork. SCC is the most commonly used concrete worldwide for construction applications due to its cost-effectiveness. The high flow of SCC reduces both the number of workers and the casting time required. It also eliminates vibration and removes noise pollution. This study is a review of previous investigations into the pressure exerted by fresh-state SCC on formwork. The paper discussed various factors that affect lateral pressure on formwork. These factors are included theoretical predictions, the effect of temperature, casting rate, rheology, types of pressure sensors, geometry and workability. Considering these various factors, the paper discussed major factors related to lateral pressure of SCC at early ages. However, internal temperature measurement of concrete effects at fresh state appears to be an important factor.

Keywords

Self-Compacting Concrete; Lateral pressure; Early age concrete properties; Casting rate; Rheology

1. Introduction to Self-Compacting Concrete (SCC)

Self-compacting concrete (SCC), also known as self-consolidating concrete, is recognised as flowing concrete. It is a new type of concrete developed in the construction field with several advantages over conventional concrete. The development of SCC began in 1988 and was introduced in Japan to produce durable concrete with less labour [1].

Other studies have described SCC as a new type of concrete, with advanced mix design concepts, which is capable of flowing and compacting itself under its own weight [2]. They also list the main advantages of SCC, the most important being decreased labour cost, reduced construction time and the elimination of vibration and noise. SCC also has the advantages of better flowability around congested reinforcement, the use of lower pump pressures and an excellent smooth surface finish. It also avoids honeycombing around congested reinforcement in the concrete and, as a result, demand for this flowable concrete has increased worldwide [3]. Another significant benefit of SCC is its increased casting rate (placing rate) which assists in reducing concrete delivery time and construction duration [4].

However, given recent rapid developments, further investigation is required, particularly with respect to Australian temperature and dry climatic conditions. In order to formulate a detailed investigation, an extensive review has been carried out on the SCC mix design methods [5] and early age properties. The review clearly indicates that further comprehensive laboratory testing is required, particularly the exerted lateral pressures when constructing tall columns and walls such as 10m high structures. The major cost of construction components is the formwork, which comprises approximately 40%~60% of the cost [6, 7]. Therefore, further studies on lateral pressure of SCC could contribute to reduce formwork cost.

To assess the use of SCC worldwide, it is essential to investigate the previously well-documented research such as the information on Scopus. For that purpose, VOSviewer software was used to collect the previous research available on SCC. Mymoon, Mahendran, Poorna, Hariharan, Suryakala and Sudhagar [8] used the same software to map SCC research worldwide. In the current study, the paper used VOSviewer to discover how many studies on SCC have been presented globally. **Fig.1** shows a remarkable density of countries that have been investigating SCC from 1988 to 2019. The scientometric statistics are vital for construction industries to identify the increasing application of SCC recently. **Fig. 1** shows countries that have mentioned SCC (self-compacting concrete) in their research. This set of the database was collected from the engine search of Scopus which is the most trustable recorded data for the scientific community. Scopus has a rich source of data and is easy to use when searching for resources [9]. It can be used to extract data and analyse it in VOSviewer.

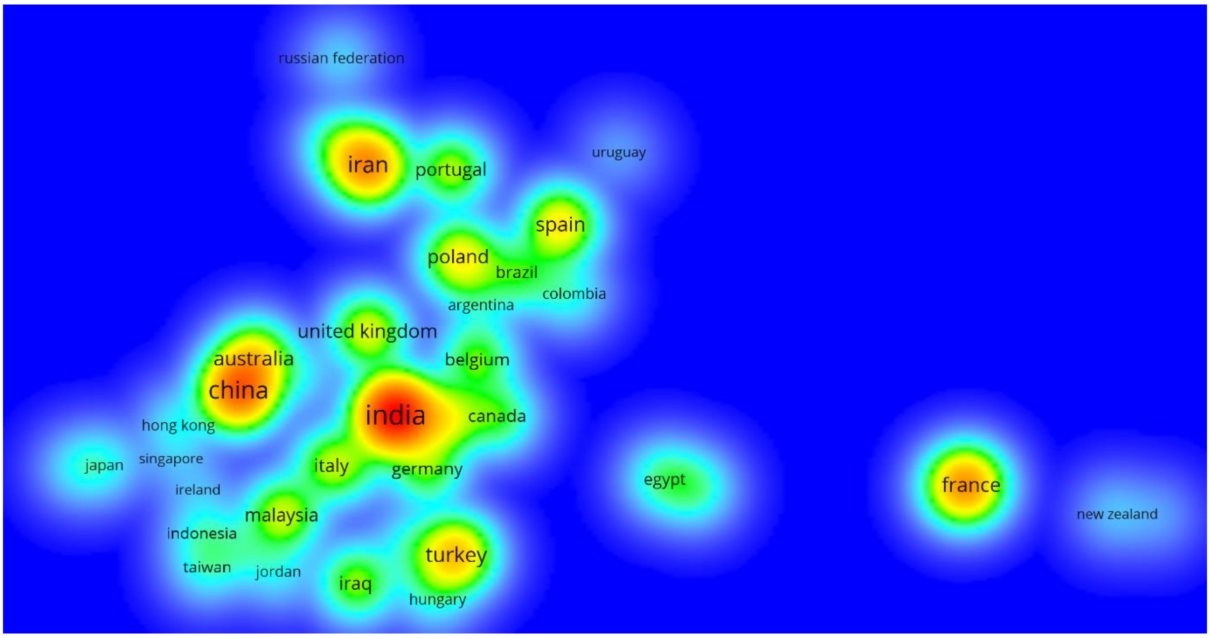

Fig. 1 The density of SCC studies in various countries from 1988-2019

The scientometric analysis of most research studies of SCC is shown in **Fig.2**. The link strength in network visualization among authors was observed in a wide range of regions, with the major authors in that field being investigated (De Shutter G.) (Aslani F.) (Xie Y.) (Barros J.A.O) (Nunes S.) (Roussel N.) (Zhang X.) (Liu X) [10-17]. That figure shows 19 clusters, 596 links and a total link strength of 1680. For example, the term "self-compacting concrete", was used in the Scopus search engine, using a hyphen between the words "self" and "compacting", and is compatible with the term used by most authors. **Fig. 2** might not identify all authors if the research is not registered in Scopus or if they have used the term "self consolidating" instead of "self compacting" thereby limiting the outcomes of the study.

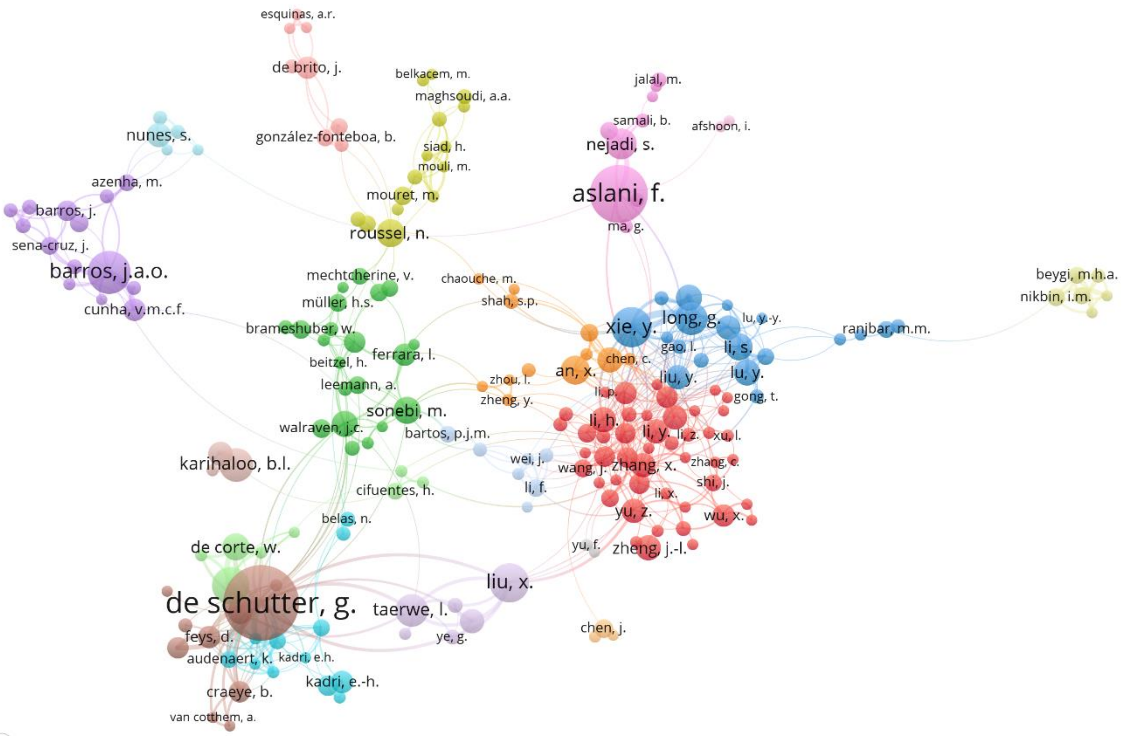

Fig. 2 Link between authors in the research of Self Compacting Concrete

However, most of the studies mentioned in **Fig.2** do not focus on lateral pressure exertion of SCC on the formwork. Therefore, this paper is attempted to identify the effect of the lateral pressure of SCC at various heights on the formwork, the casting rate, the ambient temperature, the concrete internal temperature and the geometry of the formwork. Because the type of pressure sensors and calibration methods are additional factors that influence pressure readings, it is also essential to consider them. However, the link between authors would be reasonably different if searches focussed on "self", "consolidating", "concrete" which is the term most used in North America. **Fig.3** shows the link between authors in research related to SCC in Northern America. The engine search shows that in Northern America, many prefer to use the term "self consolidating" compared with the rest of the world, making it difficult to obtain both groups of studies in one dataset. It would be preferable for authors to use both terms of SCC in their research until engine research identify it under the same field category.

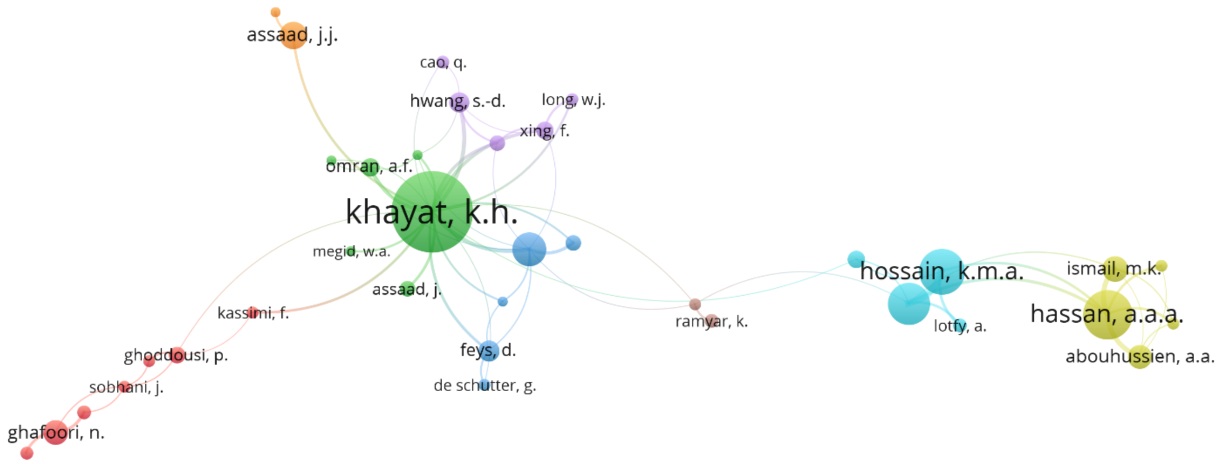

Fig. 3 Link between authors in the research of Self Consolidating Concrete

Fig.3 shows that most of the work on SCC has been conducted by Khayat and Feys [18], with their interaction and linking occurring with only a few other researchers such as Feys [19], Hossain [20] and Omran [21]. All researchers are from North America and they use a similar term for their research, however, these studies are not all on the lateral pressure of SCC on the formwork. Most of them focus on the materials characterization and mixed design of materials. Furthermore, in many studies on SCC, changing the mix of materials changes the entire mechanical and physical characterisation of materials including the lateral pressure. Therefore, this review paper attempts to highlight the most vital points that are counted as major causes of the lateral pressure exertion from SCC.

Table 1 shows the researchers who have published papers on lateral pressure exerted by SCC on the formwork panel. Those studies have focussed particularly on lateral pressure which most of them shows high pressure positioned at the bottom of the formwork. **Table 1** shows an investigation of the lateral pressure on conventional concrete which began in 1963 [22].

Table 1. Published papers on exerted lateral pressure of SCC

Studies	Country	Year
[23, 24]	France	2006, 2009
[25]	United Kingdom	1991
[26]	Korea	2012
[27, 28]	USA	2010, 2011
[29-33]	Canada	2003, 2005, 2006, 2008
[2, 34]	Canada	2009, 2010

[35]	Italy	2008
[36, 37]	Sweden	2002, 2014
[38]	Germany	2014
[7, 39]	USA	2005, 2008
[40]	Saudi Arabia	2017
[41]	Canada	2013
[24, 42]	France	2009, 2015
[43, 44]	France	2002, 2004
[45, 46]	Switzerland	2003, 2006
[47]	United Kingdom	2012
[48]	Uruguay	2013
[49, 50]	China	2014, 2013
[51]	India	2015
[52]	Spain	2016
[53, 54]	Lebanon	2018, 2017
[55]	Iran	2019
[56]	Australia	2019
[57]	Poland	2021

To clearly identify researchers who worked specifically on the lateral pressure of self-compacting concrete, the term “lateral pressure self compacting concrete” was searched on the Scopus research engine. **Fig. 4** shows the clear links between those who cited each other and worked on a similar topic. The graph in **Fig.4** assigned the minimum number of documents of an author to number 1 until all authors could be included in the graph.

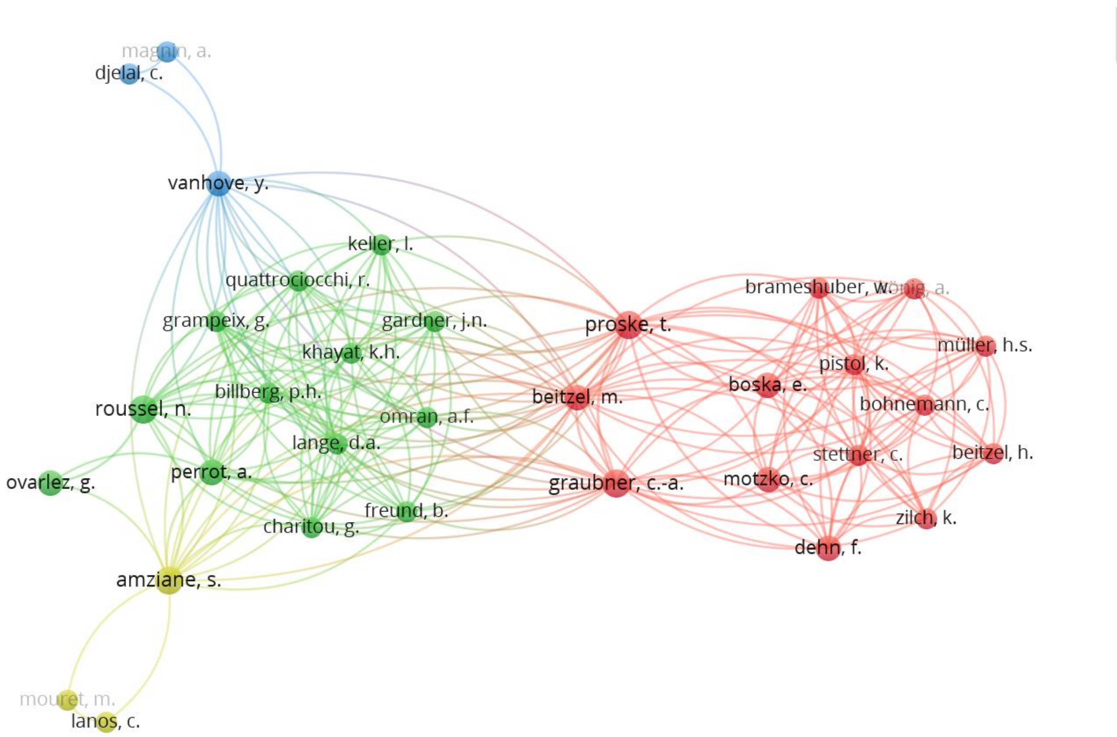

Fig. 4 Links between authors in the research of lateral pressure of SCC

In the present paper, results of the pressure of the SCC at different heights, casting rates and an overview of the theoretical model for prediction of pressure and rheology of the materials were correlated with pressure exertion on the formwork. Limitations in the previous research are also identified and addressed.

2. Effect of temperature on the pressure distribution in formwork

Ambient temperature is a major contributor to the SCC product during and after casting the concrete. Schmidt, Brouwers, Kühne and Meng [58] found that SCC with a high cement content mix, at low temperature, achieved excellent performance (such as better flowability and compressive strength). However, at high temperatures, this concrete showed a reduction in flow properties. If the flow or slump of materials reduced at a high temperature, then certainly lateral pressure would reduce. Slump flow of materials directly related to the amount of pressure exerted on confined specimens. Further studies on the internal temperature profiles of concrete are necessary. In particular, if the concrete remains for a long period in the mixer or in the formwork, then this would produce an enormous amount of heat among their particles due to the high cement content in the SCC mix [59].

The mix design of SCC varies globally due to differences in the chemical properties of materials in different locations. Therefore, it will be variations in density, temperature, rate of casting, humidity in the air, and casting procedure. For example, the temperature is one of the challenges which differ around the globe and even in seasons has enormous differences in one location. This seasonal variation in temperature, in some countries reaches 60°C. For example, Australia has a varied temperature range among the states. To understand the effect of ambient temperature on the concrete while casting, temperature values were obtained from the Australian Bureau of Meteorology. **Table 2** shows the mean temperature values for Australian capital cities [60].

Table 2. Mean temperatures for capital cities at 9 AM, reproduced after [60] in degrees Celsius

City	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Sydney	23	23	22	18	14	12	11	12	15	18	20	22
Melbourne	19	19	18	15	11	9	8	10	12	15	16	18
Brisbane	26	25	24	22	18	15	14	16	19	22	24	25
Adelaide	22	22	20	17	14	11	10	11	14	17	19	20
Perth	24	24	22	18	15	13	12	12	14	17	20	23
Hobart	17	16	15	13	10	7	7	8	10	12	14	15
Darwin	28	28	27	27	25	23	22	24	27	29	29	29
Canberra	19	19	16	12	8	5	4	6	9	13	16	18

The major temperature differences are seen in **Table 2**. Temperature varies in cities according to their location and seasonal temperature changes. The ambient temperature may be a major influence that should be considered while using SCC in different areas and during different seasons. For example, Canberra city has a seasonal variation of 15˚C, therefore, it is necessary to have a remarkable change in the mix design of concrete in different seasons. In addition to the ambient temperature while casting concrete, the internal temperature of the concrete should be considered as a factor that might cause an increase in lateral pressure. However, those places have low temperatures which expected to maintain lateral pressure for a longer period on the formwork. This has been confirmed by an earlier study, SCC at high temperature could achieve a high compressive strength at an early age which is due to faster flocculation occurred between particles than SCC in normal or cooler temperature [61]. They also found that compressive strength magnitude may reach as high as 300% compared to normal temperature. Having high strength at an early age would assist in reducing the duration of lateral pressure on formwork. Therefore, the mixed design of materials should be used accelerator and air-entraining admixture at low-temperature to increase the durability of concrete at the hardened stage. However, these admixtures rarely contribute to the lateral pressure at early ages, it is reducing the dormant period of pressure but it is not causing a reduction in maximum pressure value.

Fig.5 presents the results of pressure and temperature in relation to the time when the SCC is highly fluid with an enormous quantity of admixtures and cement. **Fig.5** shows that the maximum pressure on the formwork was reached at 1-2 hours after casting. The concrete may be at its initial set after 1-2 hours and the pressure then increased due to rapid internal hydration after approximately 15 hours. This was a preliminary investigation and further study is currently underway to gain an understanding of the effect of the heat of hydration within the period of 12 hours after casting of the concrete.

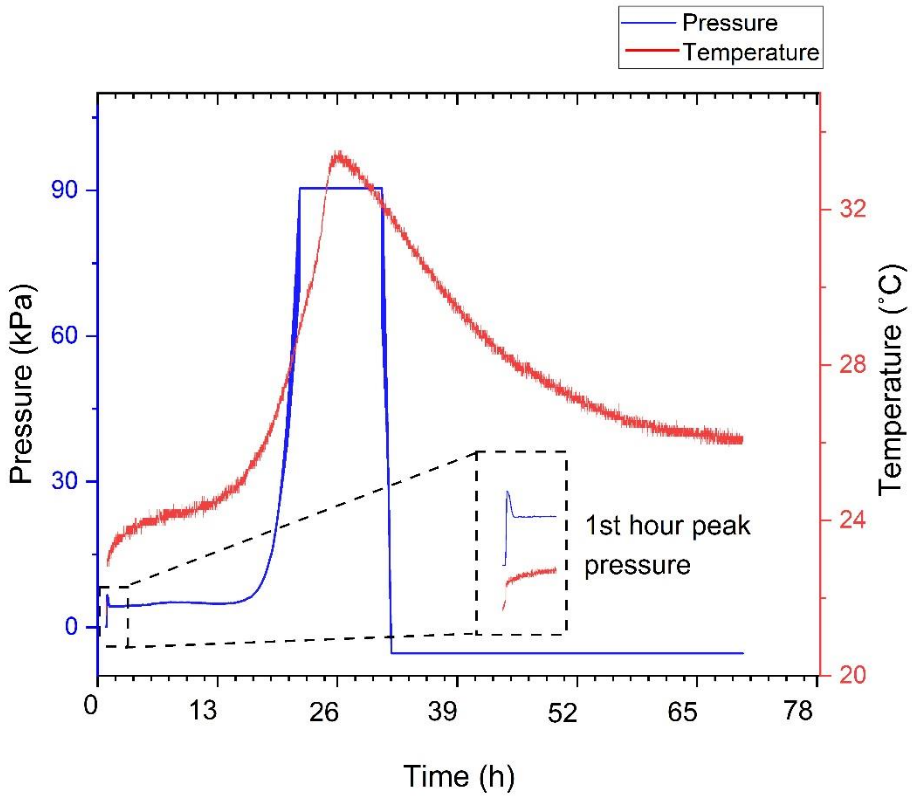

Fig. 5 Prediction of exerted pressure, the internal temperature of fluid concrete and casting time [62]

As shown in **Fig.5**, the early age of SCC pressure increased due to the rate of casting. In the early stage, the heat of materials would not be evolved rapidly. The heat evolution displayed increased after the first hour of casting. However, in **Fig. 5** the increasing rate of pressure after 15 hours of casting might be attributable to a gadget reading fault or having a large particle in front of the diaphragm of the sensor which caused a false reading. In addition, Omran, Elaguab and Khayat [63] stated that increasing concrete temperature resulted in less lateral pressure which is contrary to current findings as shown in **Fig. 5**.

Another investigation by Assaad and Khayat [64] stated that temperature has a limited effect on the maximum lateral pressure while casting, however, in the later age of cohesion development temperature does not have a significant effect. There is not a piece of solid evidence to show that temperature directly affects lateral pressure, on the other hand, a study by Wang, Ge, Grove, Ruiz, Rasmussen and Ferragut [65] showed that higher heat generation resulted in higher compressive strength which is related to developing flocculation in the concrete matrix, this is causing by early relaxation of materials from the formwork panel.

3. Effect of casting rate (placing rate) on the formwork

Casting rate is considered one of the most significant factors directly related to exerting lateral pressure on formwork. Graubner & Proske (2005) found that the time-dependent behaviour of the concrete was consistent with silo theory behaviour in a real stress state. Overall, the assumption of hydrostatic pressure could not be considered for concrete. The lateral pressure of concrete was highly dependent on casting rate, setting time of the mix and formwork width. In their study, they used different rates of casting such as 2m/h and 10 m/h and discovered that the lower rate of casting exerted lower lateral pressure when compared with higher rates. They also discovered that casting concrete manually at 25m/h exerted similar pressure to the rate of casting at 19 m/h when using the pumping process.

The study of Perrot, Amziane, Ovarlez and Roussel [24] used a constant rate of casting with the height of the formwork being proportional to the time of casting (*H=Rt).* They found that exerted pressure by SCC mainly relies on thixotropic properties, casting rate and shape of formwork. They also validated the theoretical models with experimental programs.

According to Kwon, Kim and Shah [26] maximum lateral pressure is highly dependent on the rate of casting (placement rate) and properties of used materials, as shown in equation (1):

$$\sigma_{max} = wR.f(a,b) \qquad (1)$$

where *w* is a unit weight (kN/m^3), *R* is a rate of casting(m/h), and *f(a,b)* is an arbitrary function. Both coefficients of *a* and *b* were found using exerted lateral pressure on formwork with the assist of small equipment, this research was conducted by Perrot, Amziane, Ovarlez and Roussel [26].

Kwon, Kim and Shah [26] found that when the casting time was more than 7 h, the peak pressure was always less than 3.6 *wR*. However, if the casting time was less, the peak pressure could be further decreased.

Jae Hong Kim, Beacraft, Kwon and Surendra [28] stated that the maximum pressure of σ_{max} always occurred at the maximum time t_{max}, irrespective of *R*, σ_L represented as a lateral pressure, as shown in equation (2):

$$\sigma_{max} = \sigma_L(t_{max}) \qquad (2)$$

The proposed model in the study of [28] is useful in determining the reduced lateral pressure of SCC with slowing down of casting rate. They also stated that changing in mix compositions could change pressure response.

Andreas Leemann and Frank [66] investigated whether the results of filling self-compacting concrete to the top of the formwork would depend on the rate of continuous pressure of casting the SCC and the speed of casting.

Fig.6 shows the results of the effect of casting rate on measured pressure, expressed as a percentage of hydrostatic pressure. The results show that the measured pressure/hydrostatic pressure varied between 20% and 85%. The higher values were achieved with a casting rate greater than 3 m/h and most of the values were around 60%. The lower values of measured pressure/hydrostatic pressure were obtained with a casting rate lesser than 3 m/h and most of the values were between 18 and 23%.

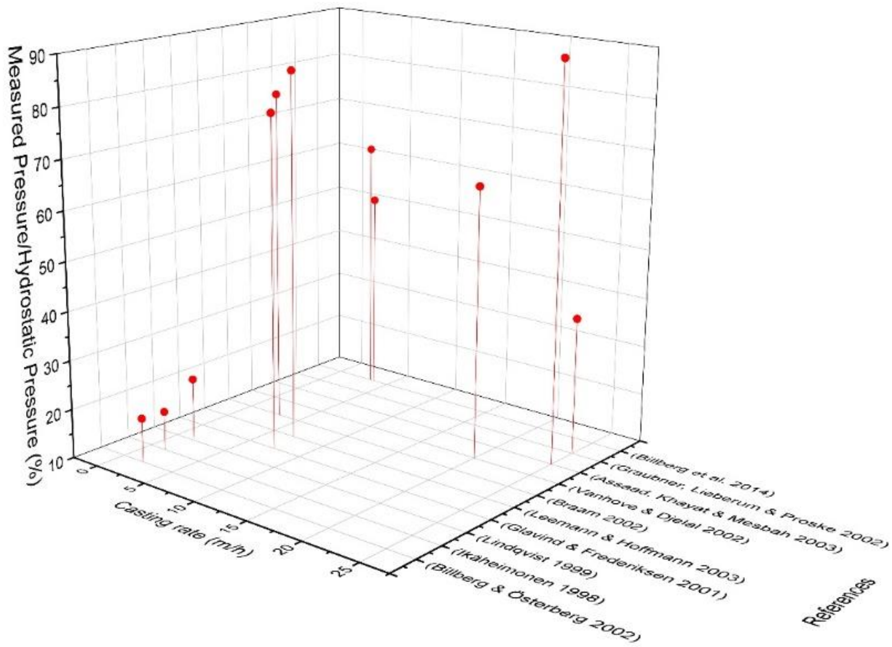

Fig. 6 Casting rate compared with measured pressure/hydrostatic pressure in the literature of the earlier studies [33, 36, 37, 43, 45, 67-71]

The casting rate of concrete is to some extent influenced by pressure exertion on formwork, however, there are many other factors that could be more potent than the casting rate [36]. Nevertheless, their study found that the casting rate would be in the range of 50% and 90% of hydrostatic pressure when the placement rate was increased from 2.7 to 6.4 m/h, respectively. This is evidence that the casting rate is the major factor exerting pressure on the formwork panel, despite still not reaching hydrostatic pressure.

However, some studies expected that the casting rate of the SCC could be a replacement for the vibration of conventional concrete [24]. It is obvious that SCC depends on its weight to spread and flow in the entire cross-section of the formwork. Therefore, in their study they proposed replacing the dynamic yield stress with the static yield stress equation and presented the lateral stress on the cylindrical form as shown in equation (3):

$$\sigma H(z,t) = (\rho g - \frac{2(\tau_{00} - A_{thix} t)}{R - r_b}) z \qquad (3)$$

Where τ_{00} is dynamic yield stress after strong shearing, A_{thix} is a structural rate, and *t* is resting time, *R* is the radius of the formwork, r_b is the radius of the steel rebar, *z* represents the vertical direction which is oriented downwards in the section.

Omran, Elaguab and Khayat [63] claimed that the casting rate could be varied according to the size and casting method. They also claimed that lateral pressure of casting SCC is close to hydrostatic pressure at shallow depth, however, when the depth was greater than 3m, the pressure started to envelop. However, this is unlikely because even at a height of 3m, the enveloped lateral pressure on the formwork can be observed.

In another study on the casting rate of SCC, Assaad and Khayat [64] confirmed that a casting rate in the range of 25 to 5 m/h could reduce the maximum initial pressure by 15% without having any further effect on the pressure with time.

Overall, casting rate has a major impact on the formwork in terms of lateral pressure. The high casting rate results in high lateral pressure on the formwork. However, this is not only the case, the materials flow will role a major influence on the pressure exertion on the formwork. This have been discussed in next section about rheology of SCC.

4. <u>Rheology of SCC and pressure exerted on the formwork</u>

Rheology and materials properties are considered the major factors that exert enormous pressure on the panel of the formwork. Concrete at the fresh-state behaves as a Bingham fluid whereas water characteristically behaves as a Newtonian fluid.

Rheology is the study of the deformation and flow of slurry, whose flow is considered to be a function of the relationship between stress and the rate of strain [72]. It is generally agreed that fresh concrete has Bingham flow behaviour for its plastic viscosity and yield stress [41]. The equation (3) can be expressed as follows:

$$\tau = \tau_o + \mu_p . \dot{\gamma} \qquad (3)$$

where τ is the shear stress (Pa); τ_o is yield stress **(**Pa); μ_p is plastic viscosity (Bingham) (Pa s); $\dot{\gamma}$ is the shear rate (s^{-1}).

Fig.7 shows the differences in lateral pressure distribution shapes and shear stress-shear strain rate of concrete in the three categories of normal concrete, SCC and advanced SCC. As shown in **Fig.7** with advanced SCC, the particle sizes of the concrete are usually smaller and contain a higher amount of fluid in the concrete mix. These cause a significant increase in pressure on the formwork and also changes the thixotropic behaviour of the materials, particularly in the shear thinning and thickening of the materials in the concrete mix. Shear thinning is defined as an apparent viscosity reduction with an increase in shear rate, whereas shear thickening is defined as an apparent viscosity increase with an increase in shear rate [73]. The study of Yahia [74] explained that the shear thinning of SCC happened when the w/c ratio was greater than 0.4. Therefore, due to the high content of the fluid in the mix of advanced self-compacting concrete, the shear stress of concrete becomes thinner and causes a higher flow of the materials on the formwork panel. So in shear thinning (pseudoplastic) behaviour to increase shear stresses required less shear rating.

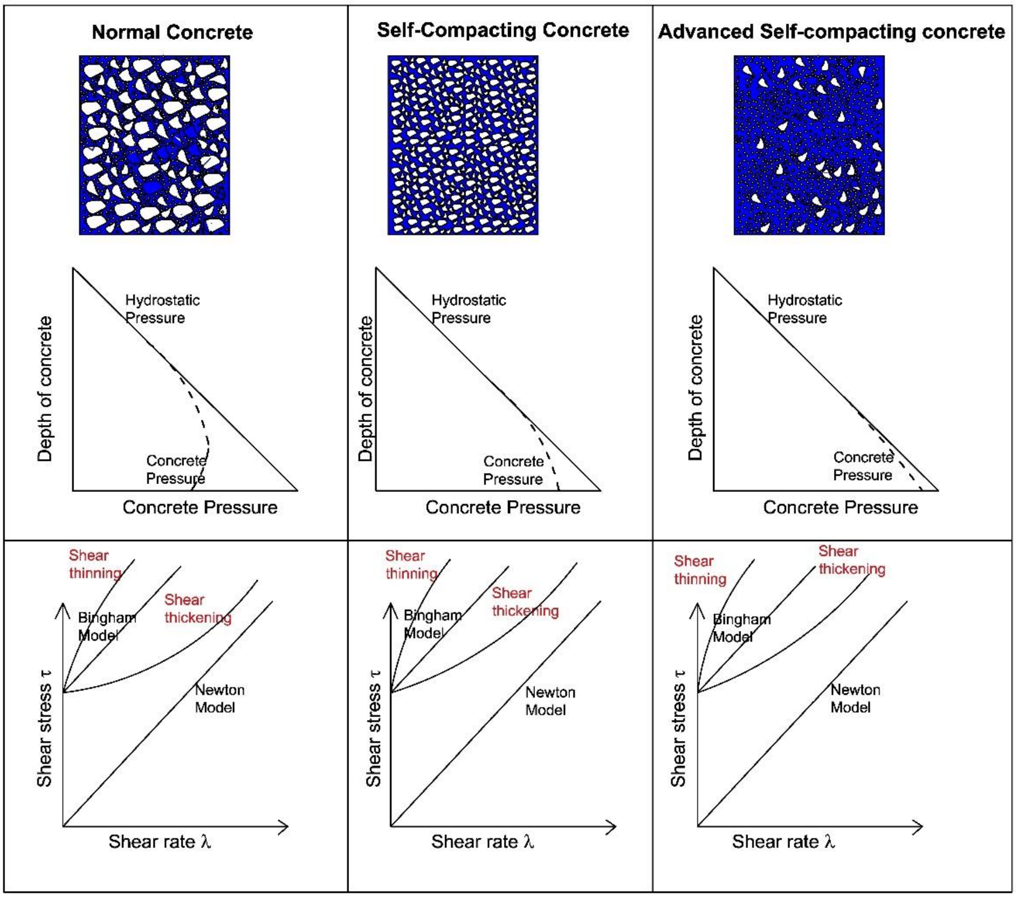

Fig. 7 Differences of pressure, shear stress and shear strain behaviours in normal concrete, self-compacting concrete and advanced self-compacting concrete

The RILEMCommittee (2008) and De Schutter (2010) defined SCC as concrete that flows under its own weight, having high flow properties, and is able to spread smoothly through the congested reinforced zones of the concrete. Self-compacting can be referred to as the ability to self-level [75]. The wide range of mixed proportions to produce SCC results in different rates of exerted pressure on the formwork (RILEMCommittee 2008). For example, a coarse aggregate volume of 30~34% in SCC is lower than that of normal workable concrete with a coarse aggregate volume of 40~45%.

Megid and Khayat [76] assessed the surface quality of self-compacting concrete using different formwork materials (permeable liner, steel, PVC and plywood formwork). They concluded that a permeable liner had a better quality surface finish and fewer pores on the surface of the casted concrete. However, using different types of materials in the formwork significantly varied the transmission of the pressure exerted on the formwork. Some of the formwork has a smooth surface and some less smooth, this is causing a reduction or increasing frictional contact with placed concrete in the formwork. Indirectly, therefore, the voids and surface quality of the concrete were correlated to the exerted pressure on the constrained form. Besides, the rheology and mix design characterization of the materials are major factors.

Previous studies have stated that thixotropic behaviour is responsible for reducing the lateral pressure acting on the formwork. This has been confirmed by the earlier work of Assaad, Khayat, Mesbah and Billberg [33, 77]. The progression of strength and elastic modulus at early ages depends on the rate of flocculation in the paste matrix due to thixotropy and cement hydration [78, 79]. Roussel (2006) proposed a flocculation rate of SCC in different values such as less than 0.1 as non-thixotropic, in a range of 0.1-0.5 thixotropic and higher than 0.5 highly thixotropic behaviour.

Khayat and Omran [2] compared the lateral pressure of three theoretical models (DIN 18218, CIRIA 108, and NF P93-350) [80-82] of conventionally vibrated concrete with flowable consistency. They found that an increase in the casting rate from 1 m/h to 25 m/h would lead to linear pressure which was almost equal to the hydrostatic pressure in the wall. These values were similar to the values given by CIRIA 108 [81] model.

In another study of Assaad and Khayat [31] and Khayat and Omran [2] stated that a highly flowable mix (slump flow of 650±15 mm) with a high coarse aggregate content, showed a decrease in lateral pressure and an increase in the rate of pressure drop after casting. These are due to an increase in internal friction due to a greater coarse aggregate content which reduces the mobility of concrete.

Other researchers have claimed that the degree of internal friction increases when a mix is made with a relatively low sand/coarse aggregate ratio (S/A). This results in a lower magnitude of initial lateral pressure and a faster drop of pressure with time. They found that in a high value of S/A (with a low total aggregate content), aggregate particles had greater freedom for translational and rotational movements within the matrix. This caused an increase in the full mobility of the concrete and vertical stress was transferred to lateral pressure. When the S/A value was low, however, the aggregate particles achieved a greater degree of interlock and interparticle bridging increased, causing the formation of an arching (heterogenous) phenomenon [83].

Assaad and Khayat [31] stated that the increase in the maximum size of aggregate from 10 to 14 mm reduced lateral hydrostatic pressure after casting from 98% to 85% and increased the rate of the drop with time. It was observed that a maximum particle size of 14mm had the highest packing density of 62% and the maximum size of 10mm and 20 mm had packing densities of 56% and 60%, respectively. Higher densities increased the contact value between particles, thereby reducing both the mobility of the concrete and lateral pressure. They claimed that the effect of hydrogen and ionic bonds between adjacent molecules led to variations in cohesiveness.

Assaad and Khayat [31] also showed that the pore water pressure affected the lateral pressure despite the relatively coarse aggregate size and maximum size aggregate. The lateral pressure occurs mainly as a result of pore water pressure during the period where the concrete is still at the plastic stage.

Domone [84] reviewed earlier, publications regarding the setting and strength development of SCC. The results showed that the lowest compressive strength value in SCC has a higher value than normal concrete at 28 days. It was also found that the proportion of tensile to compressive strength for SCC was similar to that of normal concrete. In another study [85], recycled rubber (rubberised aggregate) was used instead of the natural aggregate in SCC. They used rubberised aggregate at 30% of the total volume instead of normal aggregate and retained an acceptable level of stiffness and strength for rubberised concrete. These factors such as mechanical strength and stiffness of materials were indirectly related to lateral pressure exertion. At fresh stated concrete, achieving higher strength means a quick reaction between particles occurred, as a result, the cohesiveness of particles causes a released attachment from the formwork panel.

Kim, Beacraft and Shah [27], using a mineral admixture such as processed clay (metakaolin), significantly reduced the lateral pressure on formwork. The correlation between the formwork pressure responses and the loss of slump flow was also derived, thereby providing a method to estimate the reduction in formwork pressure. They found that a small ratio of processed clay metakaolin (MK) (2~10%), Magniusum alumina-silicate (MA) (0.33~1%) and Silica fume (5~10%) could effectively enhance shear resistance and lead to reduce lateral pressure on the formwork. Loss of slump flow of the mix at rest had a good correlation with the instantaneous response, but the spreading rate did not have those desirable properties. A similar study by Kim, Noemi and Shah [86] were conducted. Replacing fly ash and limestone filler with Portland cement increased the flowability, slump flow and decreased the dynamic yield stress. Therefore, incrementing flow resulted in a higher exerted pressure on the formwork. This is showed that using different mixed matrix has the main influence on changing the design of the structural formwork.

Assaad and Khayat [29] discussed the slump flow consistency effect on formwork pressure exerted by flowable concrete. For the slump of 550 mm, the SCC mix with a 0.46 w/c ratio slightly had a higher initial pressure and lower thixotropy compared to the SCC mix with 0.4 and 0.36 w/c ratio. This is obviously due to high water content and less coarse aggregate volume in the mix, which causes less shear strength behaviour in the concrete. However, over time (after approximately 25 minutes of casting), they found that the rate of drop in lateral pressure for the 0.4 w/c ratios was greater than the SCC of 0.36 w/c ratio. This was due to the lower content of HRWRA in the higher w/c ratio which causes less rate of structural build-up and develops proper cohesiveness in lower w/c ratio.

Assaad and Khayat [29] concluded that flowable concrete and SCC were affected by their initial consistency levels. They also confirmed that a higher level of consistency exerted higher pressure at the initial stage.

Gregori, Ferron, Sun and Shah [35] used numerical simulation to calculate lateral pressure for a column with a height of 14 m. They used four different mix designs and different binder compositions. For a mix with a w/c ratio of 0.32, they found that the pressure reached up to 50% of hydrostatic pressure when the rate of casting was 7 m/hr. They also found that the use of fly ash in the SCC mix reduced the pressure exertion on the formwork. When class F fly ash was used in the mix design the pressure was reduced whereas the use of class C fly ash did not affect the lateral pressure. However, the reasons for the reduced pressure by adding class F fly ash were not clearly given by the authors but it might be due to the cohesiveness of the class F fly ash acting as a filler to bind materials. On the other hand, this could be controversial because fly ash has spherical particles generally and could assist concrete to be more workable. It also reduces the strength development of cementitious materials at early ages. Therefore, these two factors might increase lateral pressure on the formwork while using fly ash in the SCC mix. They also found that the parameter most affecting the peak pressure was the casting rate. Reduced rate of casting exerted reduced pressure on the formwork. Further, the mixed design of the materials plays a major role in controlling the pressure exerted on the formwork and also reducing the w/c ratio would cause lower peak values.

Assaad and Khayat [30] claimed that the binder content influenced the lateral and pore water pressures of self-compacting concrete at early ages. They found that increasing binder content caused a sharper drop in pressure on the formwork. These occurred due to hydration reactions after the end of the dormant period when the rate of hydration is accelerated. At the end of the plastic stage, the pore water pressure decreased sharply to a negative value as a result of the self-desiccation process. Increasing binder content caused an increase in the initial lateral pressure (coarse aggregate content reduced). Nevertheless, the lateral pressure decreased over time with a higher binder content in the mix.

Khayat and Assaad [32] studied the field and laboratory evaluation of lateral pressure exerted by flowable concrete and self-compacting concrete (SCC). Pore-water pressure sensors were attached to the rigid formwork. They also recommended that sono-tube (formatube) formwork made of cardboard was not suitable for measuring and monitoring pressure because of its flexibility and erroneous values. For this type of formwork, to confine the formwork, external straps were used which interfered with the pressure values. Therefore, they preferred to use a rigid PVC tube to evaluate the pressure envelope exerted by SCC. For example, they used a 10mm thick PVC pipe as a column of 2800 mm high, which was sufficient to provide rigidity.

Assaad, Khayat and Mesbah [87] investigated on time-dependent properties of the mix composition of SCC which had a dominant impact on formwork. However, Billberg [77] stated that the casting rate was the major influence on pressure development, not mixed composition. Another study by Brameshuber and Uebachs [88] claimed that the SCC lateral pressure became extremely close to the hydrostatic pressure while increasing the rate of casting and placing concrete from the bottom of the formwork.

Tejeda-Dominguez, Lange and D'Ambrosia [7] stated that the SCC pressure on the formwork is a time-dependent phenomenon that is affected by the rate of concrete casting. They found that the pressure started to decrease as soon as the concrete materials were at rest and that this was due neither to hydration nor the setting time of the concrete but due to completion of casting rate. They found that if the SCC was vibrated even after casting, the pressure on the formwork would, potentially, be activated irrespective of the rate of hydration of the SCC material. Indeed, this is a controversial aspect, hydration and setting time of materials are major part to reduce the duration of lateral pressure but not the peak value of the pressure.

Proske, Khayat, Omran and Leitzbach [38] claimed that specific regulations for flowable concrete and SCC are not included in the standards. Some standards, such as Standard DIN 18218:2010-01, ACI-347 and CSA S 269, have explained flowable concrete. They stated that the current methods to calculate the maximum lateral pressure of flowable concrete and SCC were based on the shear strength of concrete depending on various concepts such as thixotropy and setting time of concrete. Moreover, they stated that the concrete casting at the field is required to validate and prove the current models of lateral pressure by SCC on formwork. However, to have a safe design for lateral pressure on formwork, three parameters should be considered, namely, the casting rate, unit weight of mix compositions and height of formwork. They have also proposed a method for measuring the formwork pressure of flowable concrete based on measuring shear strength using different concepts such as structural build-up at rest and the setting time of concrete. Knowledge of those data would be beneficial for improving formwork production.

Lomboy, Wang and Wang [89] observed that the thixotropy magnitude of SCC for pre-sheared concrete was lower than concrete not pre-sheared. This is due to the breakdown of partially hydrated cement particles from the rest of the matrix. However, they confirmed that the thixotropy value and shear rate stress increased with and without pre-sheared concrete being applied to the material's matrix. They found that having an internal vibrator during casting can cause full hydrostatic pressure on the formwork.

Another study on the flow rate and viscosity of SCC concluded that the flow rate of SCC affects the pressure loss in a linear relationship according to the law of fluid mechanics, namely, with increasing flow rate, pressure loss increases [90]. They also found that concrete viscosity highly affected by the pressure loss in SCC and they had a good linear relationship with each other. The findings of Drewniok, Cygan and Gołaszewski [91] confirmed a similar slump flow and flow rate. They stated that low dynamic yield stress could cause higher lateral pressure on the formwork panel.

Ferron [92] claimed that the lateral pressure was highly dependent on the mixture proportion of the concrete matrix. Therefore, having a proper mix design would possibly reduce formwork pressure by as much as 30%. Furthermore, higher structural build-up and higher shear strength of concrete provided more resistance to applied vertical stresses and less initial pressure might develop on the formwork.

Roussel [13] explained a detailed study on the rheology of concrete, including SCC. It was revealed that the concrete usually placed as a layer over layers due to being cast in stages. Therefore, having stages of casting and lack of vibration in SCC, the layers of casting would not mix properly and resulted in a weak interface in the hardened concrete. In contrast, this is not a major issue in casting SCC due to having a continuous pumping and high slump value in materials, the bonding between layers can be eliminated.

5. Types of pressure sensors used for measurement

It is crucial to comprehend the differences in the type of pressure sensors and the calibration process because it significantly affects the result of the pressure readings. Electronic calibration units such as Vector Network Analyzers (VNA) have been designed to make calibration quicker, easier, and simpler to use than traditional mechanical calibration. Electronic gauges add fewer connections which potentially reduces the number of errors in the connection systems [93]. Nevertheless, the calibration should be verified regularly with mechanical sensors and empirical calculation because the sensitivity of the sensors might result in large differences in the tolerance of the calibration.

Fig.8 is an illustration of the transducer sensors which are usually used to measure the pressure of concrete on the formwork. Pressure transducers transform applied pressure into an electrical signal when a force is applied to the sensing element [94]. Many types of pressure transducer could be utilised with the assistance of various technologies such as thin/thick film, bonded foil and semi-conductor strain gauges. These transducers have good stability and frequency response performances. Some other pressure transducers are used without electronic compensation, for example, pressure capsules that are typically used in Original Equipment Manufacturer (OEM) applications. These transducer sensors are small in size, easy to calibrate and perfect for most construction applications. Most of the earlier studies by Assaad, Khayat and Mesbah [33] and Billberg, Roussel, Amziane, Beitzel, Charitou, Freund, Gardner, Grampeix, Graubner, Keller, Khayat, Lange, Omran, Perrot, Proske, Quattrociocchi and Vanhove [36] have been used this type of transducers.

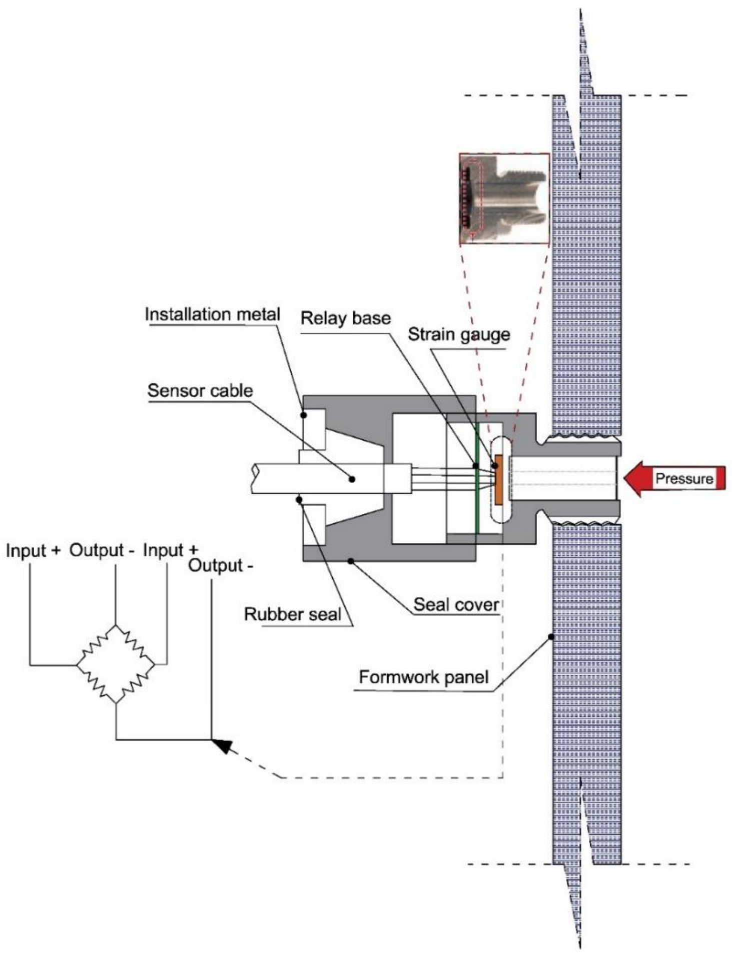

Fig. 8 Transducer sensor detailed sketch

Despite the advantages of transducers, they also have drawbacks. These sensors could be easily damaged if the sharp edge of concrete aggregate hits the head of the sensor or if the sensor is not properly placed or protected. Furthermore, unless the end of the sensors is properly lubricated to avoid sticking to the concrete, it would be difficult to later remove the concrete from the end of the sensors. Moreover, these sensors are expensive. Fibre Bragg Grating (FBG) sensors could be an alternative and cost-effective sensor compared with transducer sensors. These sensors could be embedded on the formwork panel to measure the precise lateral pressure of concrete. FBG sensors could be reusable if handled properly.

6. Effect of geometry and dimensions of formwork on lateral pressure

The shape and size of the formwork greatly affect the pressure on the formwork. For example, if the column shape is circular or square, the pressure distribution will greatly depend on the reaction of the formwork structure to resist concrete flow. **Fig.9** shows the difference between a circular and a square column. The formwork design and material types are also major factors to be considered.

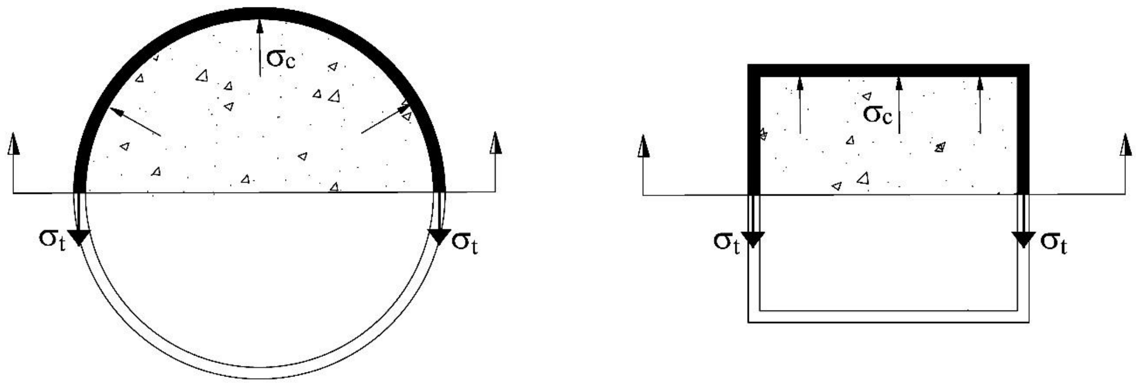

Fig. 9 Difference in stress distribution for square and circular columns

However, according to the active pressure of concrete and reaction pressure of the formwork, the pressure distribution could be represented by the following equation (4):

$$\sigma_c * D = 2 * \sigma_t * T \quad (4)$$

where σ_c is pressure on the form, *D* is the diameter of the member cast, σ_t is the hoop stress in the formwork and *T* is the thickness of the formwork. According to equation 4, the reaction pressure of the formwork panel should be equal to the pressure side of the concrete. In this case, the same formula would apply to the geometries of the square and the circular formworks. Overall, the reaction and force distribution on the formwork would not be the same. Further investigation is required to determine how the formwork geometry affects the pressure distribution on the formwork panel.

7. Effect of pumping procedure on lateral pressure

When SCC is pumped from the base to the top of the formwork, any interruptions during pumping should be avoided, otherwise, the high pump pressure required to control the agglomeration of materials may cause build-up during resting of the SCC and its thixotropic behaviour. However, a wall with a height of 9 m has been successfully cast using robust panels and using a continuous pumping procedure without any problems [46].

Kaplan [95] found that the casting of conventional concrete did not cause pressure loss at bends while pumping. Feys, De Schutter and Verhoeven [41] found that the pumping of SCC into bends causes loss of pressure which can be larger than the rule of thumb (guidelines stated that 90˚bends will be equal to 3 m of the straight pipeline) [96]. They also found that the length of the bend can be reduced with increasing viscosity and discharge rate. The results of another study by Geert De and Dimitri [97] was consistent with their earlier study in terms of the effect of bending pipelines which caused a pressure loss. However, highly packed materials such as Ultra-high Performance Concrete require lubrication layers until it can be easily pumped. This is quite the opposite of SCC that does not require any lubrication due to its high flowability mix.

With SCC, excessive pressures, sometimes approaching hydrostatic pressures, were recorded due to the high fluidity of the concrete. While pumping and placing the SCC, there is a possibility of excessive formwork deformation or even failure [46]. Therefore, further studies in understanding the details of lateral pressure distributions of SCC are vital.

Details of the SCC requirements in terms of measurement of the slump flow, T500 and passing ability are provided in **Table 3** (Australian Vicroads [98]). According to **Table 3**, T500 is the time taken for the flow to reach 500mm diameter from the base of the slump cone. This is considered as a measure of the viscosity of the SCC. Flowability, the viscosity of materials and passing ability measurements of SCC in the formwork would be valuable while casting SCC in the field. However, most of the concrete plants are neither providing the same mix proportions nor having the same procedure to produce the concrete. Therefore, the workability and pumping requirements of the SCC would be difficult to assess for each site.

Table 3. Slump flow, T500 and passing ability requirements of SCC

Properties of SCC	Measurement	Observations
Slump Flow (Filling ability/flowability)	550-650 mm spread	The aggregate shall be evenly distributed throughout the concrete paste within the spread and shall not exhibit signs of segregation

T500 time (measure of viscosity)	3.5 ± 1 seconds to achieve a spread of 500 mm	The final spread shall not exceed 650 mm in diameter
Passing Ability	≤ 10 mm	The concrete shall not exhibit signs of segregation

Table 4 shows the mounting points of the pressure sensors from earlier studies with the results of the maximum exerted pressure. In the study by Kim, Beacraft and Shah [27], external pressure was applied on the top surface of a short column. Therefore, the maximum lateral pressure results of this study are potentially higher compared with the other studies.

Table 4. Mounted heights for pressure gauges on the formwork of SCC

Height in the column (m)	Maximum lateral pressure (kPa)	Total height (m)	Sensor capacity (kPa)	References
0.55, 1.95, 3.36	NG	10	NG	[23]
0.15	345	0.3	NG	[27]
0.05, 0.25, 0.45, 0.85, 1.55	49, 49, 50, 38, 27	2.8	100	[29]
0.05, 0.25, 0.45, 0.85, 1.55	49, 49, 50, 38, 27	2.8	100	[31]
0.15	NG	0.3	NG	[35]
0.05, 0.25, 0.45	23	1.1	100	[30]
0.05, 0.25, 0.45, 0.85, 1.55	58, 53, 49, 42, 36	1.3	50 to 500	[32]
0.2, 0.4	NG	2	NG	[42]
1, 2, 3, 4, 7	156.8, 186.2, 166.6, 176.4, 117.6	12	NG	[44]
0.25, 0.7, 1.5, 2, 2.5	98, 78, 58, 39, 27	2.8	NG	[45]
0.2, 0.9, 1.7, 2.5, 3.3 (Field)	98, 78, 58, 39, 27	4.9	NG	[46]
0.15, 0.75, 2.55 (Lab)	NG	2.7		
0.075, 0.25, 0.43, 0.65, 0.77 (lab)	NG	0.97		
0.05,0.25,0.45, 0.85, 0.125	45, 40, 38, 24, 19	2.1	100	[33]
0.5, 1.4, 2.5, 4	89, 65, 47, 31	6.6	689	[36]
0.5, 1.0, 2.0, 3.1	71, 40, 33, 20	4.2		
0.61, 1.83, 3.05, 4.27, 5.49, 6.71, 7.93	20.68, 34.47, 20.68, 19.10, 34.47, 18.80, 0.20	8.53	NG	[7]
0.3, 1.3, 2.3, 3.3	NG	4.3	NG	[99]

NG: Not Given

Fig.10 illustrates the maximum lateral pressures found in previous work. Measurements are shown with respect to different mixed design and various heights. These studies used different types of pressure gauges, different material types of formwork and different casting rates to measure the maximum lateral pressure on the formwork. The highest pressure would be at the lowest point of the formwork panel, however, this is not the case because each study used different types of sensor and different mix designs. Therefore, the maximum measured pressures vary dramatically. The red dot describes the normal placement while casting, however, the blue dot in **Fig. 10** describes the applied force on the fresh confined SCC in the formwork.

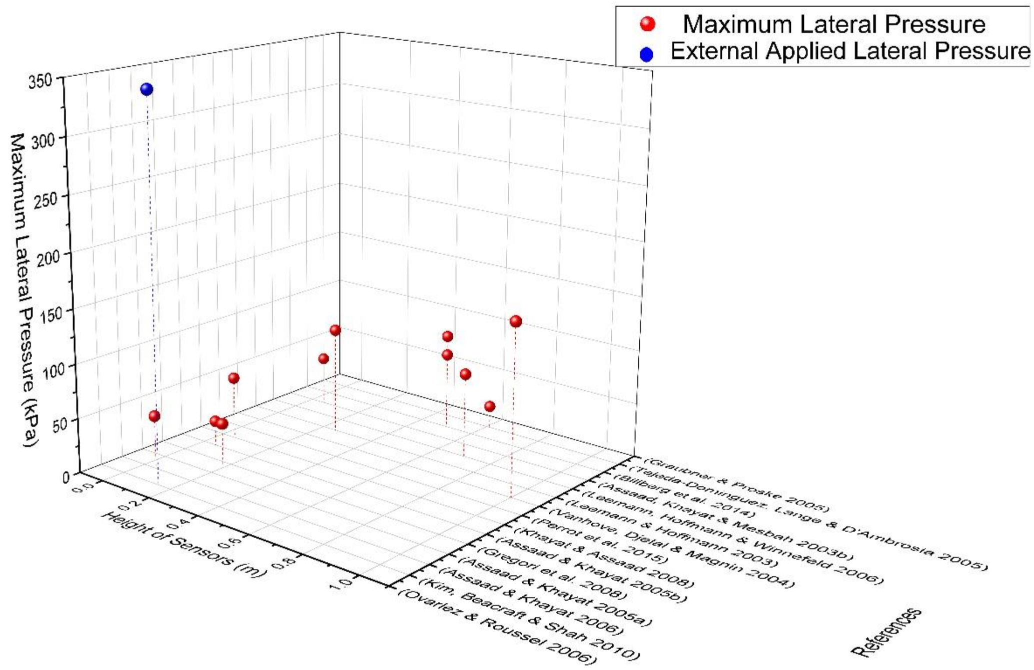

Fig. 10 Relationship of maximum lateral pressure and the height of the sensors in the formwork in different studies from the literature [7, 23, 27, 29-33, 35, 36, 42, 44-46, 99]

Feys, Khayat and Khatib [90] confirmed that increasing the pipe radius from 100 to 125 mm would lead to a decrease in pressure loss by a ratio of 2.2, however, this is slightly lower than the ratio of 2.4 required for Newtonian fluid materials.

Feys [100] gave a lot of information regarding the pumping of SCC. The study found that the pressure loss and discharge output have a non-linear relationship in SCC, however, in conventional concrete exists a linear relationship. Further, the study explained that the air content introduced into the pumping system resulted in an increase in yield stress and a decrease in the viscosity of the materials. The study also noticed that temperature rose while discharging concrete. The increasing temperature was linearly related to the pressure loss per unit length of concrete.

8. Theoretical prediction of SCC pressure on formwork

Predicting pressure on the formwork exerted by SCC could be achieved by using a theoretical model and related mathematical analysis. Few studies have used this approach to predict the pressure exerted by SCC on formwork. To provide a general idea of the lateral pressure of conventional concrete and SCC, **Fig.11** displays the schematic explanation of lateral pressure exerted by both types of concrete on the formwork. Each type of concrete represents a different shape of lateral pressure on the panel. It is obvious that, compared with conventional concrete, SCC exerts a high pressure in the bottom of the panel.

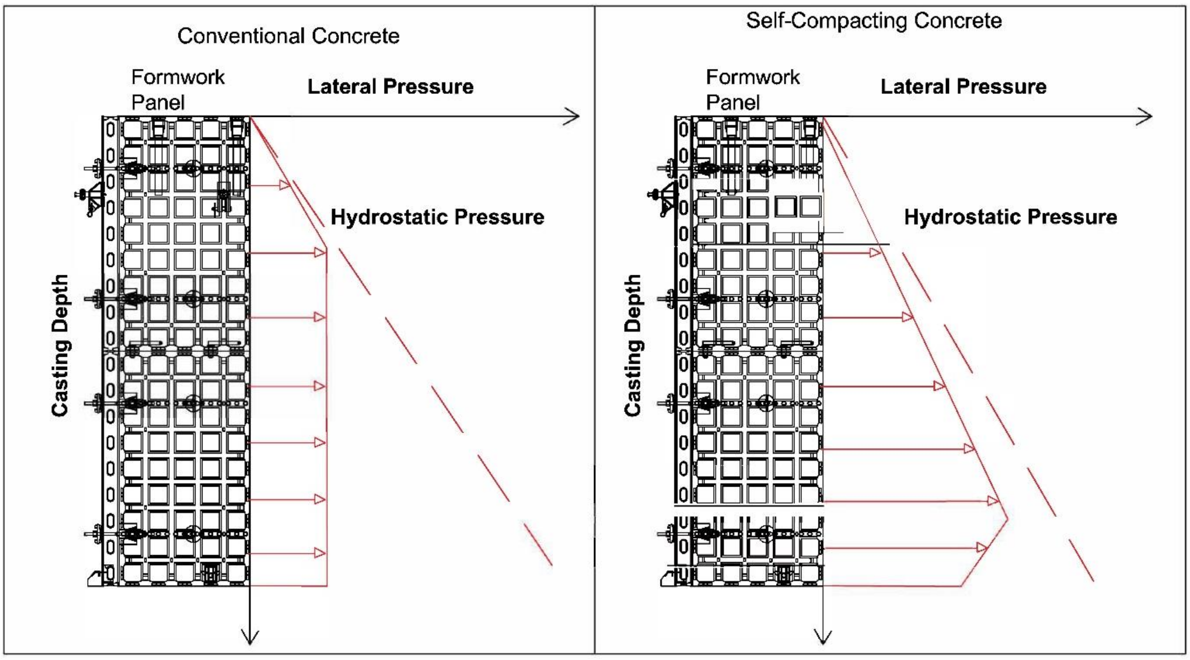

Fig. 11 Schematic explanation of lateral pressure generally in conventional concrete and SCC

Tah and Price [25] studied concrete lateral pressure magnitudes as changes occurred in the temperature and casting rate of concrete. Their study modified the equation proposed in the Construction Industry Research and Information Association (CIRIA) Report[81]. They presented a complex-shaped wall that considered the different coefficients of shape and size of the form C_1 and the coefficient of the constituent materials of concrete C_2. Computation analysis was performed using the ProCAD software. The formwork was divided into different sub-sections *i* and levels *j*. The maximum pressure at each point on the complex-shaped formwork was determined according to equation 5:

$$P_{\max i,j} = D[C_1\sqrt{R_{i,j}} + C_2K\sqrt{H - C_1\sqrt{R_{i,j}}}] \quad (\text{kN/m}^2) \qquad (5)$$

where $P_{\max i,j}$ is the maximum pressure at level *j* in subsection *i*, *H* is the height of the form, C_1 represents the coefficient of the shape and size of the form, C_2 is the coefficient of constituent materials, $R_{i,j}$ is the rate of rising at each level of *j* and the subsection *i*, when the rate of rising (casting rate) is equal to the uniform volume supply rate (m^3/h) divided by the plan area at each level (m^2), D is the weight density of concrete kN/m^3, K is the temperature coefficient $(36/(T+16))^2$, T is the concrete temperature at placing (°C).

According to the ACI-Committee237R [101], the formwork is designed using the hydrostatic pressure of concrete according to the equation;

$$P = wh \quad (6)$$

where *P* is the lateral pressure, *w* is the unit weight and *h* is the depth of the fresh-state concrete. This makes the formwork thicker and heavier.

ACI-Committee347 [102] also suggested calculating the lateral pressure on the formwork, according to the following equations :

when R < 2.1 m/h and H < 4.2 m (where R: rate of placement in m/h and H: head of concrete in m), for columns and walls.

$$P_{max} = C_w C_c \left(7.2 + \frac{785R}{T+17.8}\right) \quad (7)$$

where P_{max} is maximum lateral pressure, kPa,

R: rate of placement, m/h;

T: temperature of concrete during placing, °C;

C_C = chemistry coefficient; and C_W = unit weight coefficient

when R < 2.1 m/h and H > 4.2 m (for columns and walls) and

for all walls with 2.1 m/h < R < 4.5 m/h

$$P_{max} = C_w C_c \left(7.2 + \frac{1156}{T+17.8} + \frac{244R}{T+17.8}\right) \quad (8)$$

Most of the guidance and standard codes recommend the use of traditional vibrated concrete to measure lateral pressure [81, 102]. Usually, conventional vibrated concrete is used to represent SCC for measuring lateral pressure. This, however, might not be the best representation of SCC.

Silo geometry has been originally used for soil mechanics applications by Janssen [103]. Vanhove, Djelal and Magnin [44] used silo geometry for a model aimed to predict the formwork pressure of fresh concrete. They used a tribometer to measure the friction coefficient between the metal surface of formwork and concrete. They modified Janssen's equation, which is used in soil mechanics, by introducing the α coefficient (Amontons-Coulomb) which is dependent on the rheological properties, agent release and casting techniques of concrete. Their results clearly showed that Janssen's model underestimated the lateral pressure of the materials and overestimated internal friction and friction on the walls.

The studies of Vanhove, Djelal and Magnin [44] and Vanhove, Djelal and Magnin [104] explained the horizontal pressure P'(h) and vertical pressure P(h). These pressures can be linked by the phenomenological coefficient of K which relies on the frictional angle of the internal materials.

$$P'(h) = K.P(h) \quad (9)$$

Janssen's model assumed that the pressure at a point is at the slip threshold, which is derived from the Coulomb formula.

$$\tau(h) = \mu.P'(h) \quad (10)$$

where τ(h) is the friction stress and assumes μ as constant (coefficient of friction). From this equation, it is acceptable to evaluate the equilibrium force employed by the wall on the materials and vertical forces, as shown in **Fig.12**, using the following equation:

$$AdP' + \mu\, KP'(2e + 2L)dh = \rho gAdh \quad (11)$$

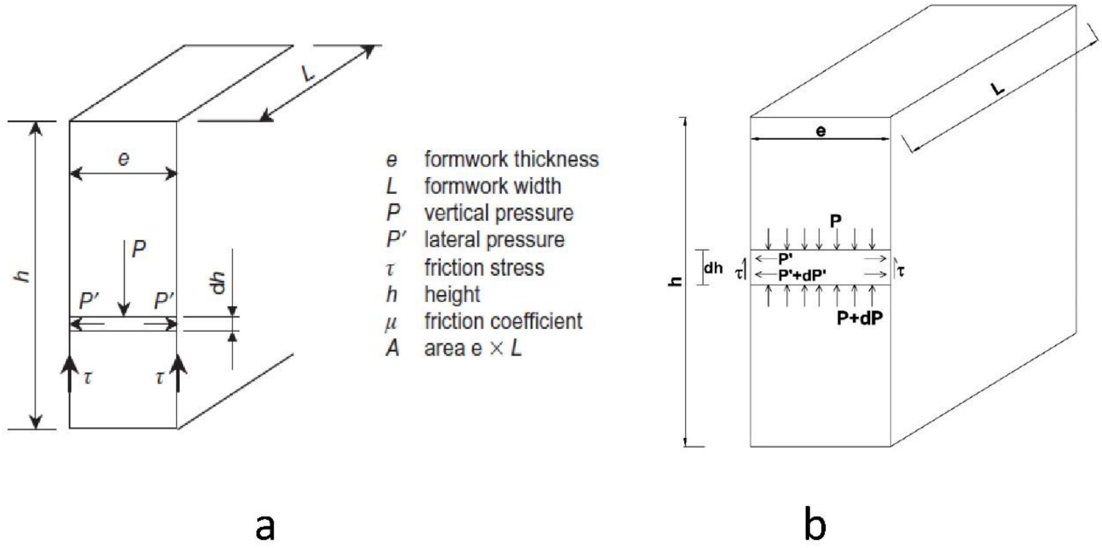

Fig. 12 (a). Stress schematic representation in formwork reproduced after [44], (b) Stress distribution in the formwork further detail

The equation was modified according to Janssen's assumption as pressure has a slip threshold. Thus, the equation is formed according to the Coulomb form approach, by considering initial shear stress, $\tau_{\circ}$.

$$\tau(h)=\mu.P'(h)+\tau_{\circ} \qquad (12)$$

Therefore, the equilibrium formula can be developed further to account for the exerted forces on the form of walls and vertical forces.

$$A(P+dP)+\mu.K.P'.(2e+2L)dh=\rho.g.A.dh+A.P \qquad (13)$$

where *A* is the area, *e* is the thickness, *L* is the width, ρ is the density of the granular materials, and *g* is the gravity acceleration as is shown in **Fig.12**.

To clarify **Fig.12 (a)** in more details, an explanation of the forces distribution have explained in **Fig.12 (b)**. Each of equation 7 and 9 are also derived from the forces shown in **Fig.12 (b)**.

Ovarlez and Roussel [23] proposed a physical model which defined the evolution of the lateral stress exerted by SCC on formwork. Their theoretical model was compared with previous work in the literature and they demonstrated an excellent match and acceptable prediction. Their results showed that the lateral stress was equal to the hydrostatic pressure when the casting concrete happen at the bottom of the formwork because the material is not able to flocculate and, therefore, is maintained as a fluid. They assumed the yield stress at rest was linear with time at the resting state:

$$\tau_{\circ}(t) = A_{thix}t \qquad (14)$$

where A_{thix} is the flocculation coefficient, t is the resting time, typically A_{thix} is a value between 0.1-0.2 Pa/s. This value in other studies [23, 105] was confirmed to be between (0.1-0.2 Pa/s). Billberg [106], however, predicted an unusually higher value for A_{thix} of 0.6 Pa/s (from a model) for SCC.

Ovarlez and Roussel [23] also expressed the critical rate of casting as follows:

$$R_{crit} = \frac{2HA_{thix}}{e\rho g} \qquad (15)$$

where R_{crit} is the critical casting rate, e is the cross-sectional width and H is the height of the formwork.

In contrast to casting from the bottom of the formwork, casting from the top of the formwork does not reach the hydrostatic pressure, because the concrete slowly flocculates at the bottom of the formwork [23]. Furthermore, they found that lateral stress decreases abruptly after the end of the casting, which can develop higher yield stress and starts behaving as if in a solid-state condition. Thus, they developed an equation for the maximum pressure P_{max}, based on static yield stress at rest A_{thix} (Pa/s), height H (m), the width e (m), casting rate R (m/h) and concrete density ρ (kg/m^3).

$$P_{max} = \rho gH - \frac{H^2 A_{thix}}{eR} \qquad (16)$$

Perrot, Amziane, Ovarlez and Roussel [24] further developed the equation obtained in the previous study [23] for maximum lateral pressure of SCC. Perrot's equation included the cross-sectional area of steel bars in the formula to calculate the maximum pressure. As a result of this change, the maximal horizontal pressure can be calculated according to the following equation.

$$P_{max} = [\rho gH - \left(\frac{\emptyset_b+2S_b}{(e-S_b)\emptyset_b}\right)\frac{A_{thix}\,H^2}{R}] \qquad (17)$$

where S_b is the horizontal steel section per linear meter of the form length (m^2), and $\emptyset_b$ is the average diameter of the vertical rebars (m).

In the study by Khayat and Omran [107], the maximum pressure was measured using a 0.7 m high column and their design was used to simulate a 13 m high concrete column using air overpressure [36]. They have obtained the dataset which established a formula to predict the maximum pressure.

$$P_{max} = \frac{\gamma_c H}{100}(98 - 3.82\mathrm{H} + 0.63\mathrm{R} + 11\mathrm{D}_{min}) \qquad (18)$$

where γ is the unit weight of SCC (kN/m^3), R is a casting rate (m/h), D_{min} is the minimum formwork dimension (m), ($0.2 \le Dmin \le 0.4$ m).

Gardner, Keller, Quattrociocchi and Charitou [108] based on the slump flow of concrete to reach zero. Therefore, P_{max} could be found as follows:

$$P_{max} = wRt_o/2 \qquad (19)$$

where w=unit weight of SCC (kN/m^3), R=casting rate (m/h) and t_o=intial time (this parameter obtained by concluding the slump loss from the slump flow (when inverted cone) to drop to reach 400 mm from the initial value (h) t_o = $\boldsymbol{t_{400}}$ [initial slump flow/(initial slump flow – 400 mm)]). This equation is valid where the time is more than half of t_0 ($t>t_0/2$), t= after the start of placement time (h).

However, if the time is less than half of t_o ($t<t_o$), the following equation will apply:

$$P = wR(t - \frac{t^2}{2t_0}) \qquad (20)$$

The German standard of DIN18218 [80] has a series of equations for calculating the lateral pressure of concrete while vibrating at various levels of consistency and taking account of the temperature.

For concrete cast at T=15 ˚C

$$P_{max} = \gamma_c C_2 K_t(0.48R + 0.74) \qquad (21)$$

P_{max}=21+5R *for the stiff mixture*

P_{max}=19+10R *for the soft mixture*

P_{max}=18+14R *for the fluid mixture*

Where

P_{max} is the maximum lateral pressure kPa,

γ_c unit weight of concrete in kg/m^3.

C_2 is the added coefficient,

K_t is a temperature coefficient given by (145-3T)/100,

R is the rate of placement, m/h and

T is the concrete temperature, °C.

However, contrary to the above studies, Puente et al. 2010 [109] divided the lateral pressure of concrete into four major parts. For the first model, they proposed an equation for the P_{max} when the concrete mix is 1:2:4 with a slump of 150 mm, an ambient temperature of 21°C and the concrete density is assumed to be 2400 kg/m^3. The equation (22) is expressed as follows:

$$P_{max} = 23.4H_m \tag{22}$$

H_m is the height at which maximum lateral pressure occurred (m)

P_{max} is the maximum lateral pressure on the formwork (kPa)

R is the casting rate (m/h)

The same study proposed another model for calculating the concrete lateral pressure by using the internal friction and slump of concrete, equation (23):

$$tg\varphi = \frac{260-\alpha}{1400} \tag{23}$$

where φ is the internal friction of the concrete angle, α is a concrete slump (mm).

The other model is the French standard NFP 93-350 [110], which is similar to equation (5) (CIRIA model).

$$P_{max} = \left(C_1\sqrt{R} + C_2\,K_1\,\sqrt{H_1 - \sqrt{R}C_1}\right)\gamma \tag{24}$$

Where P_{max} is the maximum lateral pressure (kPa)

C_1 is the coefficient that depends on the size and shape of the formwork. For walls and bases C_1=1

C_2 is the coefficient that depends on the constituent materials of the concrete

γ is the concrete density (kN/m^3)

H_1 is the vertical height (m)

K_1 is the coefficient that depends on the concrete temperature

R is the casting rate (m/h)

Puente et al. (2010) [109] explained that the vertical pressure was directly related to the horizontal pressure, explaining the theoretical relationship in the following equation (25):

$$P = \lambda_C \gamma H \tag{25}$$

Where λ_C is the relationship between vertical and horizontal pressure, γ is concrete density, and H is the height of the concrete. They explained that λ_C is a crucial factor that does not have a constant value. This value ranges from one to zero, where the number one represents a fluid concrete like water.

However, the collected data of previous studies showed that the water ratio in the concrete matrix has a significant effect on the lateral pressure of SCC on the formwork panel. **Fig.13** showed the relation between water content to lateral pressure almost linear with increasing water the lateral pressure increases. Therefore, having a high water content significantly increases pressure on the formwork panel. Overall, most studies showed increased water extremely affect the lateral pressure on formwork, except a study showed high water content in the matrix with a lower value of lateral pressure, which this is might not mean the maximum pressure. Some study has a limited number of sensors in the formwork and the allocation of mounted sensor highly significant to achieve the right value of maximum lateral pressure. Despite water content, dormant period and casting rate which are listed in this paper, they are other factors that should be considered.

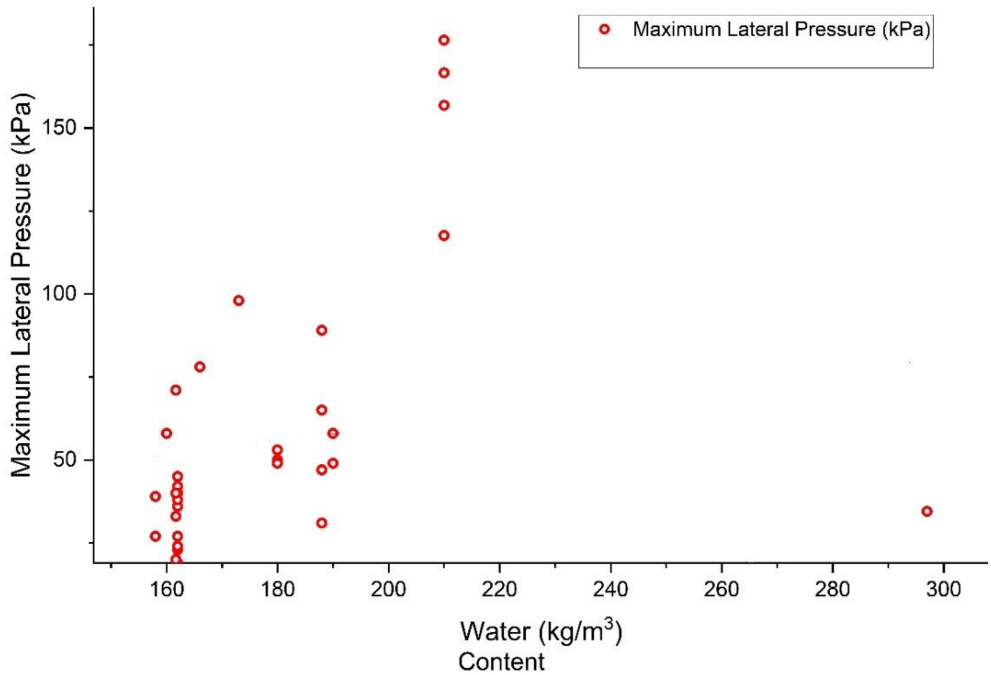

Fig.13. Relationship between water content to maximum lateral pressure exerted of SCC

Table 5 presented rheology models and parameters of concrete, it also shows all parameters that should be included in a fluid-like concrete. Liu, Cheng, Chen, Pan and Liu [111] stated that the value of rheology can be achieved by rheometer as a direct method of testing or indirectly through slump flow.

Table 5. Rheology models and properties for concrete

Model	**Equation**	**Properties**	**References**
Bingham	$\tau = \tau o + \eta\dot{\gamma}$	Practical, unsuitable for low water/cement ratio	[112, 113]
Herschel-bulkley	$\tau = \tau o + a\dot{\gamma}^{b}$	Suitable for shear-thinning and shear-thickening, restricted for low shear rate region	[114]
Modified Bingham	$\tau = \tau o + \eta\dot{\gamma} + c.\dot{\gamma}^{2}$	Suitable for non-linear behaviour of cement materials (high shear-thickening not included)	[115, 116]
Thixotropic model	$\tau = (1+\lambda)\tau o + \eta\dot{\gamma}$ $\frac{\partial\lambda}{\partial t} = \frac{1}{T} - \alpha\lambda\dot{\gamma}$	Complex, suitable for viscous additive such as silica fume	[79, 117]
Casson	$\sqrt{\tau} = \sqrt{\tau o} + \sqrt{\eta\dot{\gamma}}$	Complex, suitable for viscous supplementary cementitious mix such as silica fume	[115, 118]
De Kee	$\tau = \tau o + \eta\dot{\gamma}e^{-a\dot{\gamma}}$	Suitable for cement paste and modifying admixture	[115]
Yahia and Khayat	$\tau = \tau o + 2\sqrt{\tau o\eta\dot{\gamma}}e^{-a\dot{\gamma}}$	Unsuitable for high shear-thickening concrete	[115]
Quemada	$\tau = (\frac{1+\sqrt{a\gamma}}{b+c\sqrt{a\gamma}})^{2}\dot{\gamma}$	Suitable for pseudoplastic (shear-thinning) materials	[119]

Vom Berg	$\tau = \tau o + a\, Sinh^{-1}(b\dot{\gamma})$	Suitable for a mix of both shear thinning and thickening behaviour	[120]
Powers	$\tau = \tau o + Ptan\emptyset$	Suitable to calculate the internal friction	[121]
Tattersall	$\tau = \tau o + \eta N$	Unsuitable for low water/cement ratio	[121, 122]
Note: a, b and c are constant parameters; generally, $\boldsymbol{\tau}$ (Pa) is shear stress, $\boldsymbol{\tau o}$ (Pa) is yield shear stress, $\boldsymbol{\eta}$ (Pa s) is plastic viscosity, $\dot{\boldsymbol{\gamma}}$ (1/s) is shear rate, **k** is a flocculation state of concrete, **a** is a thixotropic parameter and **T** is a characteristic time of flocculation, ***P*** is normal stress, ***tan***$\emptyset$ is an internal friction coefficient, ***N*** is the rotating speed of the impeller			

Table 5 shows major parameters in the shear stress equations which always exist the value of yield shear stress, shear rate and plastic viscosity. Besides, the flocculation of the concrete and thixotropic parameters is also considered a major contribution to the matrix. These values are contributing to creating a high or low ratio of an exerted lateral pressure.

Shear stress is related to internal materials behaviour, this is possibly related to lateral pressure exerted on the formwork. In the study of Banfill [123], rheological behaviour at different water to cement ratios have been studied at the dormant period. They have observed low shear stress occurred at high water to cement ratio and vice versa. Thus, the internal concrete at a high w/c ratio provide lower internal stress and provide higher external stress out of the boundary of materials. Consequently, this is initiated a high exerted pressure on the formwork in SCC compared to conventional concrete.

In terms of rheology properties of SCC materials concerning exerted lateral pressure, structural build-up of cementitious paste is one of the matters. After approximately 30 minutes from mixing the slope of hydration start slowly and after that period can be extended to 100 minutes, this process has been discussed potentially by [124]. The structural build-up of cementitious material is highly affected by chemical admixtures in the matrix. The most common use of chemical admixture is polycarboxylate ether (PCE) superplasticizer in SCC, this is used to enhance workability and open time [124]. Winnefeld [125] studied that thixotropic structural build-up is set on 30 minutes of mixing cement with water, he displayed the storage modulus G’ (denotes a solid-like property and higher the G’ means higher strength or mechanical rigidity) with different ratios of superplasticizer. It showed that increasing superplasticizer is reduced the storage modulus of materials and possible delaying in hydration time. Several studies confrimed that the concrete can have a high flocculated particles but SCC have a lower degree of flocculation due to using high content of superplasticizer [79, 122, 126]. This is likely delay the hydration process and setting time of SCC. For that purpose, Khayat and Omran [2] determined the relationship between pressure cancelation and initial and final setting time of SCC which designated a linear relationship. To understand further in relate to pressure cancelation and setting time, more investigation in terms of setting time and plastic shrinkage period of SCC are required to attain best relationship between rheology of materials and lateral pressure in the confined formwork.

According to Drewniok, Cygan and Gołaszewski [91], they made a correlation between static and dynamic yield stress and slump flow in relation to lateral pressure of concrete in formwork. In their study showed that higher slump flow with lower yield stress causes a higher lateral pressure; however, they figured out that the main effect is static yield stress in unstabilised concrete stiffening. Banfill [127] confirmed that the SCC has a lower static yield stress by 90% compared to conventional concrete. This causes massive lateral pressure in comparison to conventional concrete.

An example for considering maximum pressure of SCC, CIRIA Report equation (5) used as theory equation and compared with the real casting of SCC on-site, it expects that the percentage of error for maximum pressure would be between (20-30)%. Equation (5) does not consider some factors such as the chemical composition of materials and the internal temperature of concrete which are major roles in controlling maximum pressure. ASTM1064 [128] using a method to measure concrete temperature through a thermometer to depth 7.6 cm. Nevertheless, this would be not enough to determine the temperature of concrete at different positions in the confined formwork.

Fig.14 shows the general explanation of concrete casting in the dormant period time. The figure explained the concrete in the first placement of casting having a maximum pressure, then pressure during first to second hours after casting drops to approximately 1/3 of maximum pressure. After 6-10 hours, which the development of flocculation among materials intensively occurred, pressure drops to about zero. In 10 hours and above, concrete would transit completely to a hardened state.

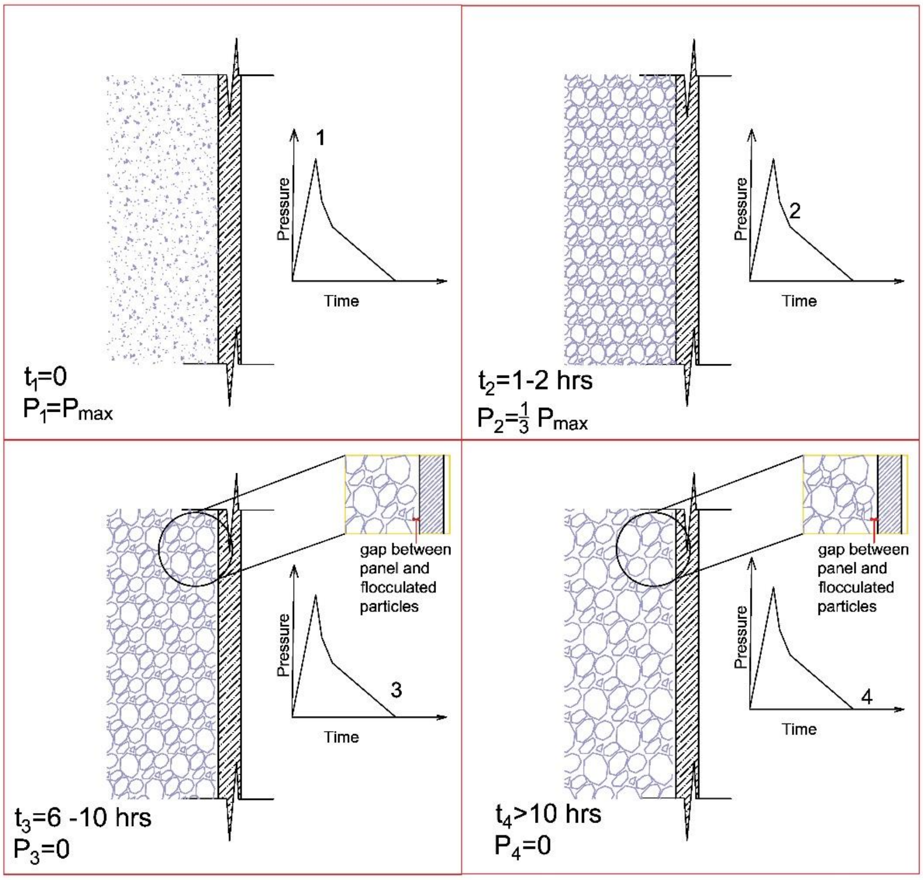

Fig.14. Schematic illustration of fresh concrete lateral pressure on the formwork in a dormant period

Most studies considered several factors relating to SCC pressure on the formwork. However, certain factors have not been considered, such as casting concrete at a different orientational angle, the distance of the formwork from the source of concrete, relative humidity during concrete casting, concrete internal temperature and the delivery system (the type of pipe and pump). In any future investigations, these factors need to be considered if appropriate.

9. Conclusions

Pressure exerted on formwork by SCC at an early age has several significant features. If the formwork panel is not designed properly, the concrete pressure might result in serious damage at the construction site.

The main conclusions of this paper can be summarised as follows:

- The ambient and internal temperatures of SCC have a major impact on the lateral pressure on the formwork panel. There are only a few studies on the ambient temperature conditions of the SCC. On the effect of internal temperatures, there is hardly any research.
- Pressure values in previous studies are different from each other due to the use of different types of pressure sensor. To measure the correct value of the exerted pressure of SCC on the formwork panel, the location of sensors, appropriate sensors and gauges are required.
- Casting rate has been identified as the dominant factor influencing the exerted pressure on the formwork.
- The influence of geometric shape and size of formwork and the types of material used to fabricate the formwork on lateral pressure needs further investigation.
- Overall, the exerted pressure of SCC on formwork contributes to cost-efficiency in the construction industry and formwork rigidity is dependent on the concrete mix and placing rate. Further studies on the measurement of the exerted pressure of SCC are required. They should employ advanced techniques such as fibre optic sensors.
- Further studies are also necessary to investigate plastic shrinkage at the initial time of mixing and certain technologies such as digital image correlation are crucial to map strain contours of the surface and the relationship of plastic shrinkage with lateral pressure on the form need to be discussed.

Acknowledgement

This research is funded through the ARC Research Hub for Nanoscience based Construction Materials Manufacturing (IH150100006) with the support of Holcim Australia, the Industry Partner.

The authors are grateful for the support of Holcim team.

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