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Rate of placement discussion for the validation of experimental models of fresh concrete lateral pressure in columns

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ABSTRACT

An analysis of experimental models for predicting fresh concrete lateral pressure in columns was carried, raising the issue of a fundamental parameter like the rate of placement.

Experimental data obtained from different authors were utilised for comparing the adequacy of the different theories making a division into three zones: rates of placement under 3 m/h, between 3 m/h and 10 m/h and over 10 m/h.

The results were established not only in the different zones but also taking into account safety and adequacy. To determine the most suitable model according to rate of placement, level of control, vigilance, planning and inspection of the construction, eight models proposed under different standards or by different authors were compared with respect to the hydrostatic pressure produced by a liquid with concrete density.

The influence of concrete yield stress, evaluated from slump test is also analyzed; the study shows a low correlation between concrete yield stress and the maximum pressure vs. hydrostatic pressure ratio.

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1. Introduction

The components and mechanics of fresh concrete lateral pressure are not completely understood which creates problems for vertical formwork design. Hurd [1] states that the objectives in this process should be: safety, quality and cost, which makes knowing the lateral pressure a necessity.

Fig. 1 shows the generally accepted pressure envelopes of vibrated concrete which is hydrostatic up to a certain depth. Gardner [2] states that as depth and time increase concrete develops internal shear strength and friction with the form. This process makes the pressure to increase at a lower rate with depth than hydrostatic. For depths greater than 2 m Gardner [2] established that the magnitude of lateral pressure decreases near the base of the form.

Two main ways of solving the problem have been developed: to formulate a conceptual model using the mechanical and rheological properties of fresh concrete or to formulate an empirical equation from data obtained in laboratories and/or real construction.

Schjödt [3] and Levitsky [4] give examples of the first way of solving the problem but the large number of factors related to concrete characteristics, formwork and placement methods, which affect lateral pressure, generate very complex models which can not be used in practice for formwork design.

Therefore, experimental models are currently used to predict lateral pressure. Different envelope diagrams have been established by researchers; a typical shape is shown in Fig. 1.

The magnitude of the maximum design pressure is needed for designing formworks since an overestimation increases construction costs. According to Hanna and Senouci [5] this increase can amount to as much as 60% of the concrete structure cost, a fact that is reaffirmed by Hurd [1].

On the other hand, an underestimation of the pressure can generate pieces made with poor dimensional quality. Post [6] states that many failures in vertical formwork only produced excessive deflection and were therefore never documented.

For vertical formwork CIRIA Report 108 [7] and ACI Committee 347 [8] divided the experimental models applied to walls and bases and those used in columns into separate cases. A wall or a base is defined as having sections where either the width or the breadth exceeds 2 m, while for a column both magnitudes are less than 2 m.

Hurd [1] noted that in many types of construction, column dimensions are small enough to allow the concrete to be placed in a relatively short time, resulting in a maximum pressure greater than in walls. Furthermore, Palanca [9] states that unless the rate of placement can be controlled to a design specified rate, friction between formwork and concrete, which in columns is much more important than in walls, due the smaller cross section.

Therefore only columns are analyzed in this work, using the experimental data of others authors, obtained from instrumented

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formwork, which determine concrete lateral pressure on a set of discrete points.

These values were used to validate the column experimental models, making a discussion based on the rate of placement, a fundamental parameter in concrete lateral pressure.

2. Experimental models

The most traditional and conservative approach is to consider fresh concrete having the same characteristics as a fluid. In this way, a hydrostatic pressure distribution on the form walls should be considered.

Rodin [10] collected and reviewed published experimental data up to his time and tried to explain the lateral pressure of fresh concrete against formwork as best as he could with the available data. He obtained the lateral pressure envelope for internal vibration given in Fig. 2a, where P_m and H_m are expressed in Eqs. (1) and (2), respectively. Those equations are valid for a 1:2:4 concrete, with 150 mm slump at a temperature of 21 °C and concrete density is assumed to be 2400 kg/m^3.

$$H_m = 1.63R^{1/3} \quad (1)$$

$$P_m = 23.4H_m \quad (2)$$

where H_m is the head at which the maximum lateral pressure occurs (m), P_m is the maximum lateral pressure against formwork (kPa) and R is the rate of placement (m/h).

As the equations are developed for a given mix, temperature, density and slump, the author proposes correction curves when the parameters are different.

Adam et al. [11] conducted laboratory tests performed on a formwork 3 m high, 2.5 m wide, and with thickness ranging from 8 to 30 cm, suggesting a pressure distribution according to Fig. 2b where the value of P_{max} is expressed in Eq. (3). This value can never be greater than 23.54H, which is equivalent to the hydrostatic pressure produced by a liquid with a 2400 kg/m^3 density.

When $R < 2$ m/h.

$$P_{max} = 19.62 + 12.26R \quad \text{When } T \leqslant 5^\circ\text{C} \quad (3a)$$

$$P_{max} = 19.62 + 9.81R \quad \text{When } T = 15^\circ\text{C} \quad (3b)$$

$$P_{max} = 19.62 + 8.34R \quad \text{When } T \geqslant 25^\circ\text{C} \quad (3c)$$

When R > 2 m/h.

$$P_{max} = 40.22 + 1.96R \quad \text{When } T \leqslant 5^\circ\text{C} \quad (3d)$$

$$P_{max} = 35.32 + 1.96R \quad \text{When } T = 15^\circ\text{C} \quad (3e)$$

$$P_{max} = 32.37 + 1.96R \quad \text{When } T \geqslant 25^\circ\text{C} \quad (3f)$$

where P_{max} is the maximum lateral pressure against formwork (kPa), R is the rate of placement (m/h), H is the concrete depth (m) and T is the concrete temperature (°C).

Gardner [12] after performing several experimental works, proposed a pressure envelope according to Fig. 2b where the value of P_{max} is given by Eq. (4). The maximum pressure can never be greater than the hydrostatic pressure produced by a fluid with concrete density.

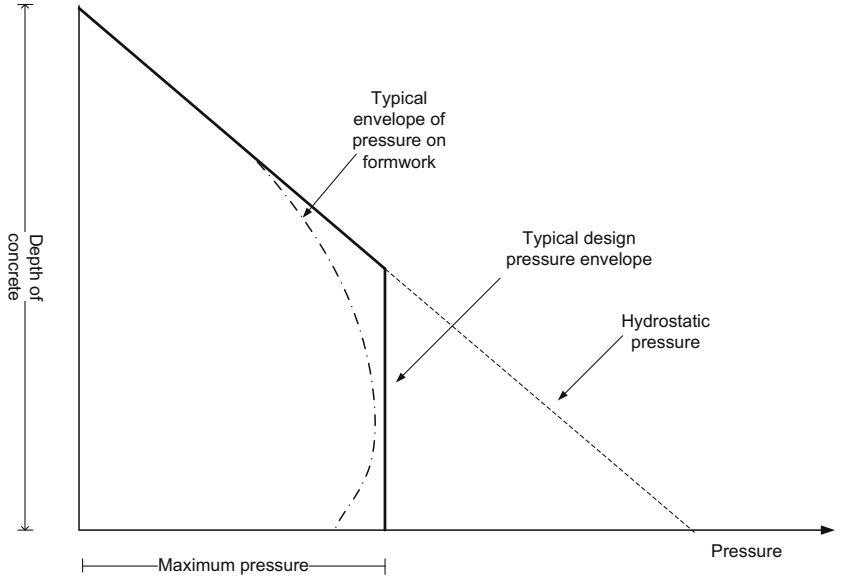


Fig. 1. Typical concrete pressure envelop and experimental model.

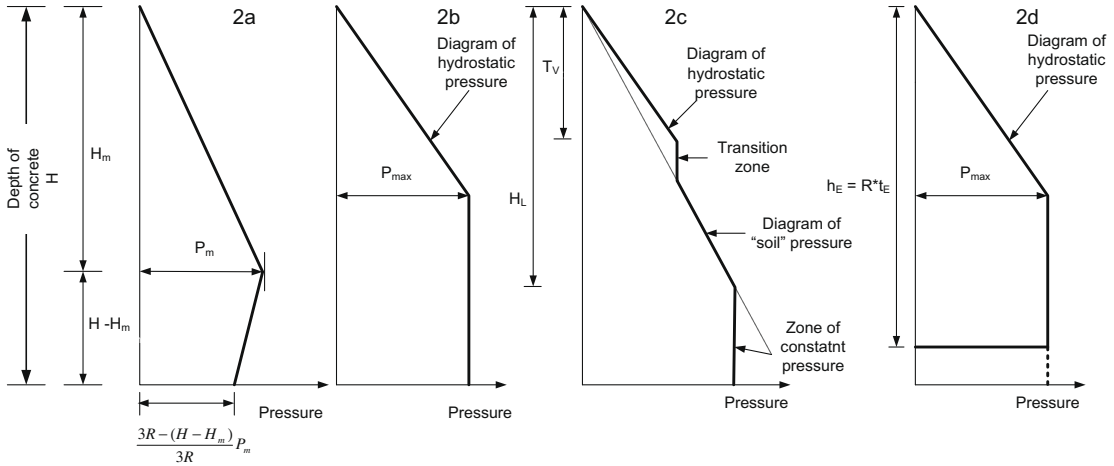


Fig. 2. Different experimental diagrams of pressure envelopes.

$$P_{max} = 24h_i + \frac{3000\,HP}{d} + \frac{d}{40} + \frac{400R^{1/2}}{17.8+T}\left(\frac{100}{100-\%F}\right) + \frac{\alpha-75}{10} \quad (4)$$

where P_{max} is the maximum lateral pressure against formwork (kPa), h_i is the immersed depth of vibrator (m), HP is the vibrator's power (HP), d is the minimum form dimension (mm), R is the rate of placement (m/h), T is the concrete temperature (°C), $\%F$ is the percentage fly ash or slag and α is the concrete slump (mm).

Gardner [2] states that to simplify the equation for formwork design the power of the vibrator can be assumed as 3/4 HP per 30.5 cm of smaller form section. The Canadian Standard CAN/CSA S 269.3 [13] recommended the application of this simplification when all parameters presented in Eq. (4) were known in advance.

Palanca [9], based on experimental data of CERA Report No. 1 [14] and Gardner [15] proposed a law of pressure distribution with four different zones as shown in Fig. 2c. The first zone, with hydrostatic pressure up to a variable height (T_V), depends on the vibration methods and the depth of each lift. Palanca [9] recommended assuming T_V as the height of the last lift or the vibrator depth immersion with a maximum of 1.0 m.

Subsequently, there is a transition zone where the pressure is constant until granular zone. In this zone hydrostatic pressure is affected by a coefficient of active pressure (K_a), which relations vertical and horizontal pressure. This coefficient depends on internal friction between particles and the inclination of the form wall as is given in

$$K_a = \frac{\sin^2\left(\frac{\pi}{4}-\frac{\varphi-\varepsilon}{2}\right)}{\cos^2\left(\frac{\pi}{4}-\frac{\varphi+\varepsilon}{2}\right)} \quad (5)$$

where φ is the concrete angle of internal friction. (Palanca [9], based on experimental data in CERA Report No. 1 [14] considers the value given by Eq. (6).) ε is the inclination of the form wall, from the vertical

$$tg\varphi = \frac{260-\alpha}{1400} \quad (6)$$

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

This distribution is maintained at a depth of pressure limits (H_L) as shown in Fig. 2c, or until the end of the formwork, being determined by two factors: concrete hardening or formwork thickness, the lower depth is the used. Lows rates of placement or reduces thickness leads to the fourth zone of constant pressure until the entire form is covered.

The depth H_L determined by concrete hardening, considering continues the placement is expressed in

$$H_L = T_V + Rt_0 \quad (7)$$

where H_L is the transition depth between the third and fourth zone (m), T_V is the transition depth between the first and second zone (m), R is the rate of placement (m/h) and t_0 is the time up to the initialization of concrete setting time, which the author considers its determination by Eq. (8) based on the experimental data of CERA Report No. 1 [14].

$$t_0 = \frac{70+0.3\alpha-2T}{25+T} \quad (8)$$

where t_0 is the time up to the initialization of concrete setting time (h), α is the concrete slump (mm) and T is the concrete temperature (°C).

The depth H_L determined by formwork thickness is expressed in Eq. (9), which was formulated by the author taking into account the Janssen theory.

$$H_L = 21 * 10^3\left(\frac{43-T}{(165-\alpha)(303+\alpha)}\right)\frac{d}{1+\eta} \quad (9)$$

where H_L is the transition depth between the third and fourth zone (m), T is the concrete temperature (°C), α is the concrete slump (mm), d is the minimum form dimension (m) and η is the ratio between cross section dimensions, always equal to or less than one.

CIRIA Report 108 [7] proposed a pressure curve according to Fig. 2b where the value of P_{max} is determined by Eq. (10) and is never greater than the hydrostatic pressure produced by a fluid with concrete density.

$$P_{max} = \left[C_1\sqrt{R} + C_2K\sqrt{H_1 - C_1\sqrt{R}}\right]\gamma \quad (10)$$

where P_{max} is the maximum lateral pressure against formwork (kPa), C_1 is the coefficient that depends on the size and shape of the formwork, for columns $C_1 = 1.5$, C_2 is the coefficient that depends on the constituent materials of the concrete, γ is the concrete specific weight (kN/m^3), H_1 is the vertical form height (m), K is the coefficient that depends on the concrete temperature given in Eq. (11) and R is the rate of placement (m/h)

$$K = \left(\frac{36}{T+16}\right)^2 \quad (11)$$

where T is the concrete temperature (°C).

The French Standard NFP 93-350 [16] considers the application of hydrostatic distribution for formwork design up to 3 m high.

Yu [17], compiling historical data, formulated an equation for predicting concrete lateral pressure using multiple linear regression techniques. The model appears in Fig. 2b, where the value of P_{max} is determined in Eq. (12) and is never greater than the hydrostatic pressure produced by a fluid with concrete density.

$$P_{max} = C_mC_f\lfloor 31.1 + 7.8H - 0.5(T+17.8) + 0.8(\alpha)^{1/2} - 14.8\log(t)\rfloor \quad (12)$$

where P_{max} is the maximum lateral pressure against formwork (kPa), C_m is the coefficient that depends on the constituent materials of the concrete, C_f is the coefficient that depends on the size and shape of the formwork, for column 1.2, H is the concrete depth (m), T is the concrete temperature (°C), is α is the concrete slump (mm) and t is the time of concrete placement (h).

The ACI Committee 347 [8] proposes a pressure envelope according to Fig. 2b where the maximum pressure is determined by Eq. (13). Two coefficients should be used to correct the mix specific weight (C_W) and chemical composition and additives (C_C).

$$P_{max} = C_WC_C\left[7.2 + \frac{785R}{T+17.8}\right]. \quad (13)$$

where P_{max} is the maximum lateral pressure against formwork (kPa), C_W is the unit weight coefficient, C_C is the chemistry coefficient, R is the rate of placement (m/h) and T is the concrete temperature (°C).

In all cases P_{max} should be greater than $30C_W$, but no higher than the hydrostatic pressure produced by a fluid with concrete density.

ASCE 37 [18] recommends the application of the previous ACI Committee 347R [19] model, which consisted of the same equations without the unit weight and chemistry coefficients. Barnes and Johnston [20] recommended the implementation of coefficients C_W and C_C.

The European Standard EN 12812 [21] states that fresh concrete lateral pressure shall be calculated from one of the following models: CIRIA Report 108 [7] or DIN 18218 [22].

A new draft of the German standard E DIN 18218 [23] provides the pressure envelope according to Fig. 2d, when the pressure value must be assumed hydrostatic until the value of P_{max} is reached. Thereafter the pressure is constant until the minimum value between form height or concrete hardening depth which is determined by the product between concrete setting time (t_E) and rate of placement.

The value of P_{max} is expressed in Eq. (14) according to the consistency categories established by UNE-EN 206-1 [24], based on the flow table tests. This pressure envelope is only valid for a temperature of 15 °C, a concrete specific weight of 25 kN/m^3 and for classes F1–F4 for rate of placement below 7.0 m/h.

$$\text{Class F1}: P_{max} = (5R+21)K_D \geqslant 25 \quad (14a)$$
$$\text{Class F2}: P_{max} = (10R+19)K_D \geqslant 25 \quad (14b)$$
$$\text{Class F3}: P_{max} = (14R+18)K_D \geqslant 25 \quad (14c)$$
$$\text{Class F4}: P_{max} = (17R+17)K_D \geqslant 25 \quad (14d)$$
$$\text{Class F5}: P_{max} = 44RK_D \geqslant 30 \quad (14e)$$
$$\text{Class F6}: P_{max} = 65.5RK_D \geqslant 30 \quad (14f)$$

where P_{max} is the maximum lateral pressure against formwork (kPa), R is the rate of placement (m/h) and K_D is a coefficient which depends on concrete setting time (t_E).

This standard provides that the value of P_{max} should increase by 3% for each °C under 15 °C, and decrease by 3% for each °C over 15 °C up to a maximum reduction of 30%. Furthermore, a correction factor as a function of the specific weight of the mixture is proposed.

The most common envelope proposed by the models for concrete lateral pressure is shown in Fig. 2b. Extreme cases like concrete with a retarder, or a superplasticiser, cold weather or a high rate of placement, produced the value of maximum pressure to be placed at a depth greater than the height of the column. As this was not high enough to reach this value, the distribution proposed by the model is therefore the same as the hydrostatic one.

For self-compacting concrete (SCC) the distribution was studied by Ovarlez and Roussel [25] and Proske and Graubner [26], who established envelopes for this type of concrete that are close to the hydrostatic one.

3. Discussion of the phenomena

Numerous field and laboratory investigations have been carried out by different researchers to provide a better understanding of variables that can affect concrete lateral pressure. Concrete and formwork characteristics and placement methods, are the source of the large number of factors that explain the complexity of the problem. Key factors that have been identified which can influence concrete lateral pressure are gathered in Table 1.

Table 1
Key factors that can influence concrete lateral pressure.

Concrete characteristics	Formwork characteristics	Placing method
Cement type	Cross section minimum dimension	Rate of placement
Use of supplementary cementitious materials	Cross section shape	Height of placement
	Formwork reinforcement	Placement method: lifts or continuous
Size, type, roughness and concentration of coarse aggregate	Formwork material	Vibration: time, depth of immersion and power
Relation W/C	Formwork permeability	Impact during placement
Use of retarders or superplasticisers	Formwork roughness	Consolidation form
Concrete density	Height of the concrete piece and formwork	
Concrete mix	Formwork slope	
Workability		
Concrete temperature		

Despite the many factors that influence on concrete lateral pressure, according to the equations given above, rate of placement and temperature are the fundamental ones, since they appear either implicitly or explicitly in all the equations.

The main difference between those two factors is that the designer of the formwork can not affect concrete temperature in normal column practice, but they can control the rate of placement, which has considerable effect on the maximum lateral pressure value.

The influence of rate of placement on different experimental models applied to a column with a height of 3 m height, with a rectangular cross section of 0.3 * 0.4 m, concrete type I with a density of 2400 kg/m^3, 120 mm slump and a temperature of 20 °C, is shown in Fig. 3.

The critical nature of rate of placement with respect to maximum lateral pressure has been established in the bibliography: the effect of rate of placement on its value is different. While a linear relationship is shown at low rates, this relationship becomes weak at higher rates.

This work present a determination of concrete lateral pressure from experimental model into three zones according to the variable effect of rate of placement, and compares those models with experimental data obtained in the bibliography.

First zone is the one with rates of placement under 3 m/h. Peurifoy [27] confirmed a linear relationship between rate of placement and maximum lateral pressure in this region. Fig. 3 shows that all the experimental models in the study case behave quite differently, but all of them predict a pressure below the hydrostatic standard.

The second zone is the one with rates of placement range from 3 to 10 m/h. Gardner and Ho [28] concluded that the maximum pressure increases by a lower proportion than the rate of placement. Fig. 3 shows that for the study case, some experimental model establish a hydrostatic distribution and others do not.

The last zone is for high rate of placement (over 10 m/h). O'Janpa III [29], states that rapid rates of placement are becoming a modern construction technique and an adequate equation is needed by designers, to quantify the pressure in this region.

4. Experimental data considered for discussion

4.1. Rates of placement under 3 m/h

The experimental data considered for rates of placement under 3 m/h were those supplied by Jackson [30], Ritchie [31,32], Ore and Straugham [33], Gardner [12,15], Arslan [34] and Arslan et al. [35].

Jackson [30] studied cylindrical formwork with a high of 2.4 m and 3.6 m and a 40.5 cm diameter. In each formwork a 30.5 cm in high test section was mounted. This section consisted of two semi cylindrical steel plates united with bolts. Two strain gages were mounted 180° apart on the long axis of the bolt, to compensate the effect of bending. Calibration was carried out using water as a live load.

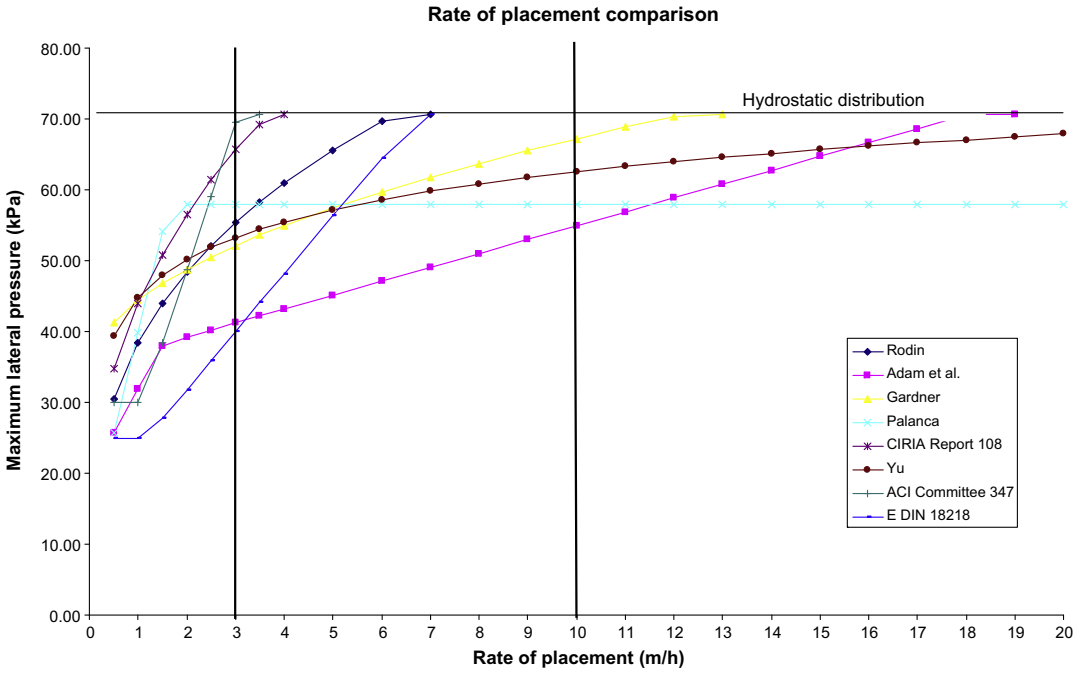


Fig. 3. Influence of rate of placement on different experimental models.

Cement type I, and a mix 1.0:2.6:3.6 mix was used while varying the rate of placement from 0.6 m/h to 2.7 m/h.

Ritchie [31,32] studied the effect of rate of placement, mode of compaction, workability and mix composition on the lateral pressure envelope in a square column 2.4 m high with a side of 15.3 cm.

The author used four measuring device, located at heights of 7.6 cm, 45.2 cm, 82.9 cm and 120 cm from the base. Concrete temperature and slump were estimated to validate the experimental equations.

Ore and Straugham [33] studied the effect of cement hydration on limiting concrete lateral pressure by comparing the behaviour of concrete with and without a water reducing agent, a set retarding agent, and a mixture containing fly ash. The form used was 3.05 m high, 0.9 m wide and 0.3 m thick.

The authors used 15.2 cm diameter oil-filled pressure cells. Calibration was performed using water as a live load and the cells were located 53.3 cm apart starting with a pair of cells centred 30.5 cm from the bottom of the form.

Gardner [15] studied the pressure of fresh concrete in an instrumented steel formwork with 4.6 m high, 0.91 m wide and either 27.9 cm, 29.2 cm or 53.3 cm between faces, constructed as rigid as possible. The lateral pressure was measured by means of five pressure cells mounted at 0.31 m, 0.92 m, 1.52 m, 2.13 m and 2.74 m, above the base of the form.

Gardner [12] analyzed the effect of superplasticisers and fly ash on formwork lateral pressure using the same device.

Arslan [34] studied the effects of permeable formwork on lateral pressure. He instrumented seven formworks that were 2 m high, 1 m width and 15 cm thick. The formworks were made of *Populus nigra* timber, *Pinus silvestris* timber, steel and plywood. The author used concrete type I and measurement was taken by means of strain gages connected in a full bridge configuration placed in plates mounted on each bottom side of the formworks. Arslan et al. [35] used the same formwork to check the influence of the surface on concrete lateral pressure.

For Arslan [34] and Arslan et al. [35] only the maximum value has been used in this work.

In order to make the validation of the models when the power of the vibration is unknown, the simplification proposed for Gardner [2] is assumed. When the immersion depth of the vibrator is unknown a value of 0.5 m is assumed.

4.2. Rates of placement between 3 m/h and 10 m/h

The experimental data considered for rates of placement between 3 m/h and 10 m/h were those supplied by Ritchie [31,32], Gardner and Quereshi [36], Gardner and Ho [28] and Gardner [12,15].

Gardner and Quereshi [36] used the same formwork described by Gardner [15] in his research on the influence on lateral pressure of immersion depth, power and duration of the vibration. They concluded that depth of immersion and power of vibrators are critical parameters for the lateral pressure.

Gardner and Ho [28] studied the variation in concrete lateral pressure with: rate of placement, concrete strength, slump and consistency. They used a steel formwork 5 m high, 0.9 m wide with thickness ranging from 15 cm to 45 cm. The authors used pressure measuring devices at 0.3 m, 0.91 m, 1.52 m, 2.13 m, 2.74 m, 3.35 m and 3.96 m above the base. Calibration of the load cells was carried using water as live load.

The estimation expressed above for power and vibrator immersion depth is also used.

4.3. Rates of placement over 10 m/h

The experimental data considered for rates of placement over 10 m/h were those proposed by Ritchie [31,32], Gardner and Ho [28], Gardner [15] and O'Janpa III [29].

O'Janpa III [29] performed field data experimentation mainly on walls, but also in a column 3.66 m tall, that was instrumented with five pressure cells inserted in tapped holes at elevations of 15.2 cm, 76.2 cm, 121.9 cm, 182.9 cm and 254.0 cm from the bottom.

The estimations expressed above for power and vibrator depth are also used.

5. Pressures envelopes considered in the analyses

The comparison between different models was carried out considering the maximum lateral pressure for nine different models: the hydrostatic pressure of a fluid with the same density as concrete, Rodin [10], Adam et al. [11], Gardner [12], Palanca [9], CIRIA Report 108 [7], Yu [17], ACI Committee 347 [8] and E DIN 18218 [23].

For E DIN 18218 [23] as the value of concrete setting time is a new consideration of the standard, an estimative value was considered based on the concrete temperature and composition (use of retarders). For rate of placement over 7 m/h for classes F1–F4 a hydrostatic distribution was used.

As the above mentioned standard bases the differentiation of the different admixtures on the flow table test, the relationship proposed by Mor and Ravina [37], was utilised for determining the classes of different experimental data from the slump test. This assumption could take an error in the class determination because many parameters may affect the constants as was pointed out by some authors. Nevertheless, if a linear relationship is accepted the equation has a correlation coefficient of 0.94, which provides a very good estimation.

6. Comparison between models and experimental data

6.1. Rates of placement under 3 m/h

A total of 54 experimental data of maximum pressure of fresh concrete has been used to make the comparison with the experimental models.

Fig. 4 shows the experimental data plotted vs. the predictions made by the different models considered. A 1:1 line also appears in each plot. Data points that fall below the line represents experimental data lower than the predicted, meaning that the equation for this value is conservative.

Validation of any experimental model of concrete lateral pressure is difficult due to a safety problem with points that are over the 1:1 line. Four statistical parameters were considered in this work for the ratio of measured pressure vs. calculated pressure: the mean value ($\mu_{M/C}$), the standard deviation ($\sigma_{M/C}$), the maximum value max(M/C) and the percentage of the experimental data with ratios higher than one ($\%_{M/C} > 1$).

Table 2, shows the statistical parameters for all the models considered for rates of placement under 3 m/h.

6.2. Rates of placement between 3 m/h and 10 m/h

A total of 55 experimental data of maximum pressure of fresh concrete has been used to make the comparison with the experimental models.

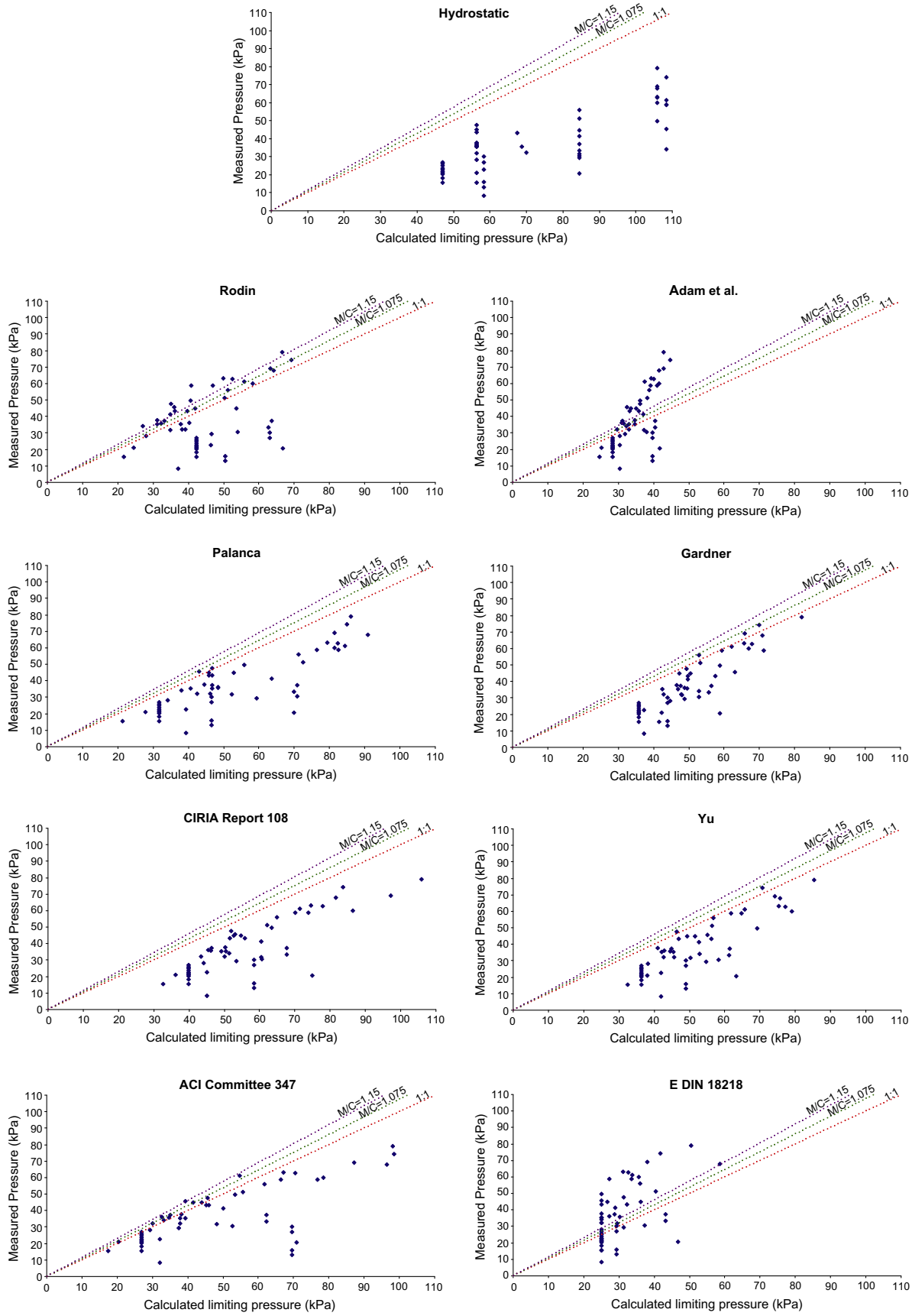


Fig. 4. Comparison between experimental and predictive pressures for rates of placement under 3 m/h.

Table 2
Statistical parameters for rates of placement under 3 m/h.

Model	Statistical parameter			
	$\mu_{M/C}$	$\sigma_{M/C}$	max(M/C)	$\%_{M/C} > 1$
Hydrostatic	0.51	0.1499	0.85	0.0
Rodin	0.85	0.3340	1.44	46.3
Adam et al.	1.06	0.3721	1.84	51.9
Palanca	0.71	0.1835	1.06	3.7
Gardner	0.72	0.2019	1.06	5.5
CIRIA Report 108	0.65	0.1797	0.92	0.0
Yu	0.71	0.1977	1.05	3.7
ACI Committee 347	0.81	0.2352	1.15	24.1
EDIN 18218	1.22	0.4469	2.15	66.7

Fig. 5 shows the experimental data plotted vs. the predictions made by the different models expressed above with the 1:1 line. Table 3 shows the statistical parameters for all the models considered for rates of placement between 3 m/h and 10 m/h.

6.3. Rates of placement over 10 m/h

A total of 10 experimental data of maximum pressure of fresh concrete has been used to make the comparison with the experimental models.

Fig. 6 shows the experimental data plotted vs. the predictions made by the different models expressed above with the 1:1 line. Table 4 shows the statistical parameters for all the models considered for rates of placement over 10 m/h.

CIRIA Report 108 [7], ACI Committee 347 [8] and the new draft of the German Standard E DIN 18218 [23] are not present in Fig. 6 and Table 4, because in all cases the maximum values are equal to the one predictive by the hydrostatic distribution.

7. Discussion

It is difficult to establish a comparison between different methods using only statistical parameters, without some kind of normalization. Due the complex nature of the phenomena, future research should be based on a design of experiments technique (DoE) with the objective of establishing the interaction between variables which allow an optimum analysis of the data.

Moreover, the graphs presented in Figs. 4–6 have an implicit safety factor, which make the comparison even more difficult. This is due to the fact that typical distribution of pressure were taken as hydrostatic pressure up to a maximum value that is maintained constant down to the bottom of concrete depth. The actual pressure distribution is known to have the form shown in Fig. 1.

So accepting the maximum pressure value of the real envelope is considered as a bi-linear pressure distribution is an intrinsically safe approach, as shown in Fig. 7b.

A comparison considering the most common pressure diagram shown in Fig. 2b is realised in Fig. 7, which represents three different cases of the ratio between measured and calculated pressure.

Case presented in Fig. 7a is conservative because the measured value is less than the calculated one, so in the pressure diagram distribution, the theoretical model adds the safety area to the real value.

On the other hand the case show in Fig. 7c can be unsafe because the measured result is higher than the calculated one, and in terms of diagram the safety area cannot compensate the unsafe one.

Case presented in Fig. 7b represents a measured data equal to the calculated data. This can be an acceptable limit but in terms of pressure diagram, the case is similar to the one shown in Fig. 7a, because there is always a safety area for the distribution that will be considered.

Therefore ratios of measure pressure vs. calculated pressure a little bit higher than one can be adequate in terms of pressure diagrams, because for these values the safety area can compensate the unsafe area in terms of force and moment.

Another issue is the fact that the different studies presented above only establish the maximum absolute pressure. O'Janpa III [29] stated that this value can occur during the filling process. That is, the maximum pressure when the filling is done may be less than the absolute maximum.

It is difficult to quantify these implicit safety factors because they depend on the same parameters as concrete lateral pressure, as established in Table 1. According to the established analysis a value of 5% of the maximum pressure can be considered without risk.

That did not consider the security coefficient used by designers and engineers in the design process. ACI Committee 347 [8], recommends a factor of 2, and E DIN 18218 [23] recommends a factor of 1.5, for formworks.

Paez [38] and Randall [39] believe that structures may show a difference between the theoretical value of the security coefficient and the real one, stating that the real safety factor of a structure may be greater than the projected one when the construction is done with a high degree of planning, vigilance and control. An increase of 10% is going to be assumed for these types of construction.

The European Standard EN 1990 [40], divided the design supervision and the construction inspection into three different levels. With an extended level of inspection, supervision and vigilance, a more refined assessment of the magnitude of actions to be resisted by the structure could be considered in the design process.

With these considerations in mind, three different models are going to be recommended for each range of rates of placement, depending on the assumptions considered by designers and engineers.

Safe recommendation methods will be usable for formworks that are going to have low inspection, planning and vigilance, when a conservative approach is best. For these cases, a model which has a measured pressured to calculated pressure ratio higher than one must be discarded.

A less conservative recommendation will be usable for formworks that are going to have extended inspection, planning and vigilance, which permit considering implicit factors and an increase in the construction security factor. For this recommendation models which have a maximum ratio measured pressure vs. calculated pressure of 1.15, can be considered. Accepting the values of the implicit safety factor and the increase in the security coefficient mentioned above. This means the theoretical safety factor is still present to ensure construction project safety.

Medium recommendation will be usable for formworks that are going to have medium inspection, planning and vigilance. For this recommendation models which have a maximum ratio of measured pressure vs. calculated pressure of 1.075, can be considered. This is the medium value between the maximum ratios acceptable for safe and less conservative recommendations.

In Figs. 4–6 are also draw the lines which represent the ratio measure pressure vs. calculated pressure equal to 1.075 and 1.15, with the objective of make a clearer division between the different recommendations.

7.1. Rates of placement under 3 m/h

7.1.1. Safe recommendation

CIRIA Report 108 [7] and the hydrostatic model were the only two that have no measured pressure vs. calculated pressure ratio

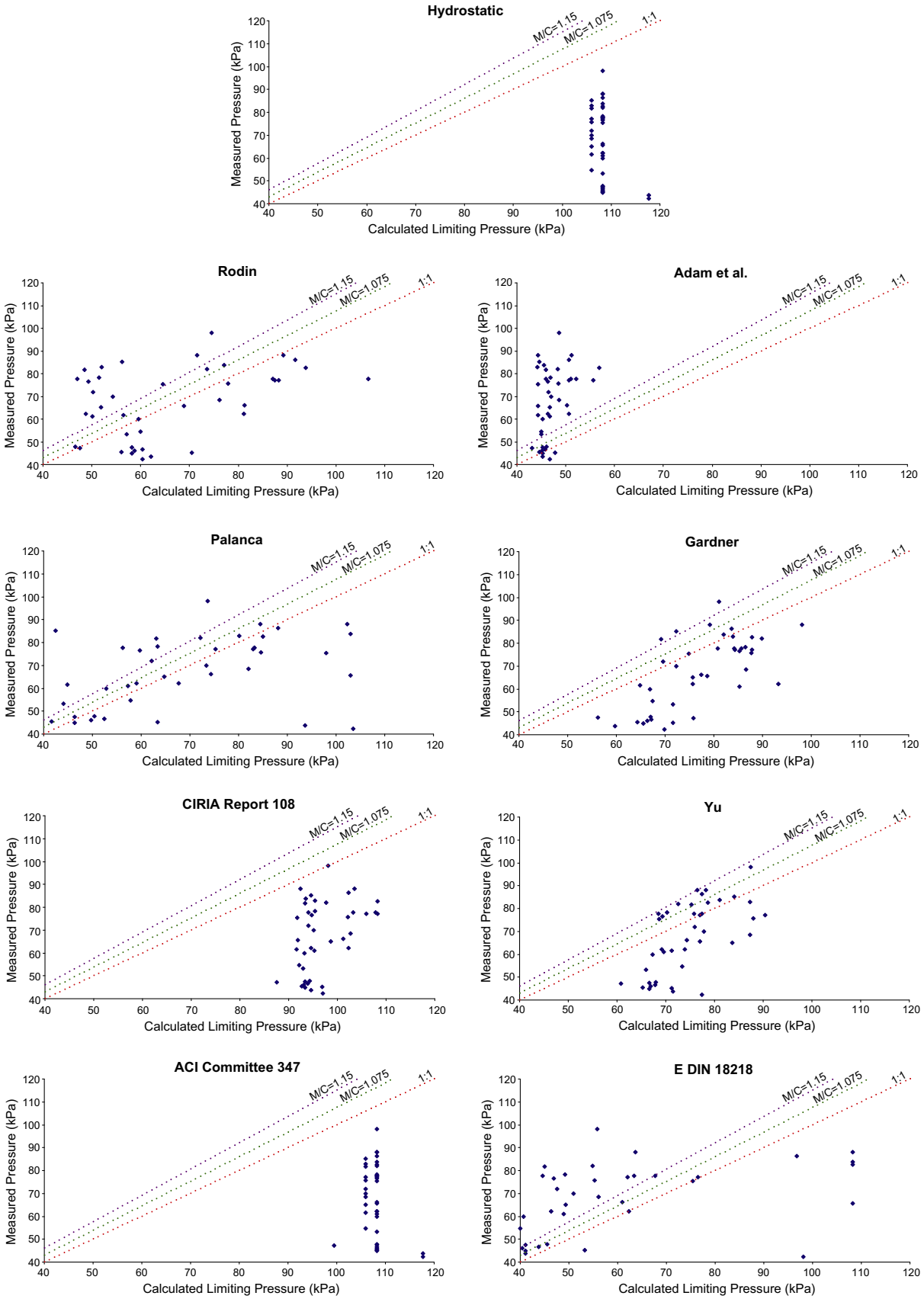


Fig. 5. Comparison between experimental and predictive pressures for rates of placement between 3 m/h and 10 m/h.

higher than one for this range of rate of placement. According to the statistical parameters presented in Table 2, CIRIA Report 108 [7] adjusts the experimental data better than hydrostatic distribution, making it a more adequate model.

Table 3
Statistical parameters for rates of placement between 3 m/h and 10 m/h.

Model	Statistical parameter			
	$\mu_{M/C}$	$\sigma_{M/C}$	max(M/C)	$\%_{M/C} > 1$
Hydrostatic	0.56	0.1779	0.91	0.0
Rodin	0.94	0.3377	1.69	35.0
Adam et al.	1.25	0.4163	2.02	69.0
Palanca	0.94	0.2978	2.01	36.0
Gardner	0.79	0.1978	1.21	15.0
CIRIA Report 108	0.62	0.1879	1.01	1.8
Yu	0.80	0.2302	1.15	29.0
ACI Committee 347	0.56	0.1775	0.91	0.0
E DIN 18218	1.15	0.4277	2.56	60.0

Table 4
Statistical parameters for rates of placement over 10 m/h.

Model	Statistical parameter			
	$\mu_{M/C}$	$\sigma_{M/C}$	max(M/C)	$\%_{M/C} > 1$
Hydrostatic	0.60	0.1920	0.90	0.0
Rodin	0.64	0.2191	0.95	0.0
Adam et al.	0.77	0.3736	1.46	30.0
Palanca	1.38	0.3904	1.86	80.0
Gardner	0.65	0.2177	0.90	0.0
Yu	0.63	0.2013	0.90	0.0

7.1.2. Medium recommendation

Models proposed by Palanca [9], Gardner [12] and Yu [17], have the maximum measured pressure vs. calculated pressure ratio that is appropriate to be used under this recommendation. All of them have a similar adequacy to the experimental results presenting $\mu_{M/C}$ of 0.71, 0.72 and 0.71 respectively and values of 3.7%, 5.6% and 3.7% for the $\%_{M/C}$, respectively. These values make it difficult to discuss which of methods should be applied to the design process.

On the other hand, the three models have different levels of complexity Gardner [12] has the disadvantage of needing many more parameters than the other two, such as vibration power or immersion depth. Palanca [9] presents a more complex distribution. Therefore, the model proposed by Yu [17] may be the most adequate.

7.1.3. Less conservative recommendation

ACI Committee 347 [8] is the method that best fits the experimental results according to the statistical parameters presented in Table 2, and has a maximum measured pressure vs. calculated pressure ratio less than 1.15, which makes it the most adequate for this recommendation.

ACI Committee 347 [8] has a $\mu_{M/C}$ of 0.81 which is higher than the 0.71 presented by Yu [17], which is the model recommended for the medium recommendation.

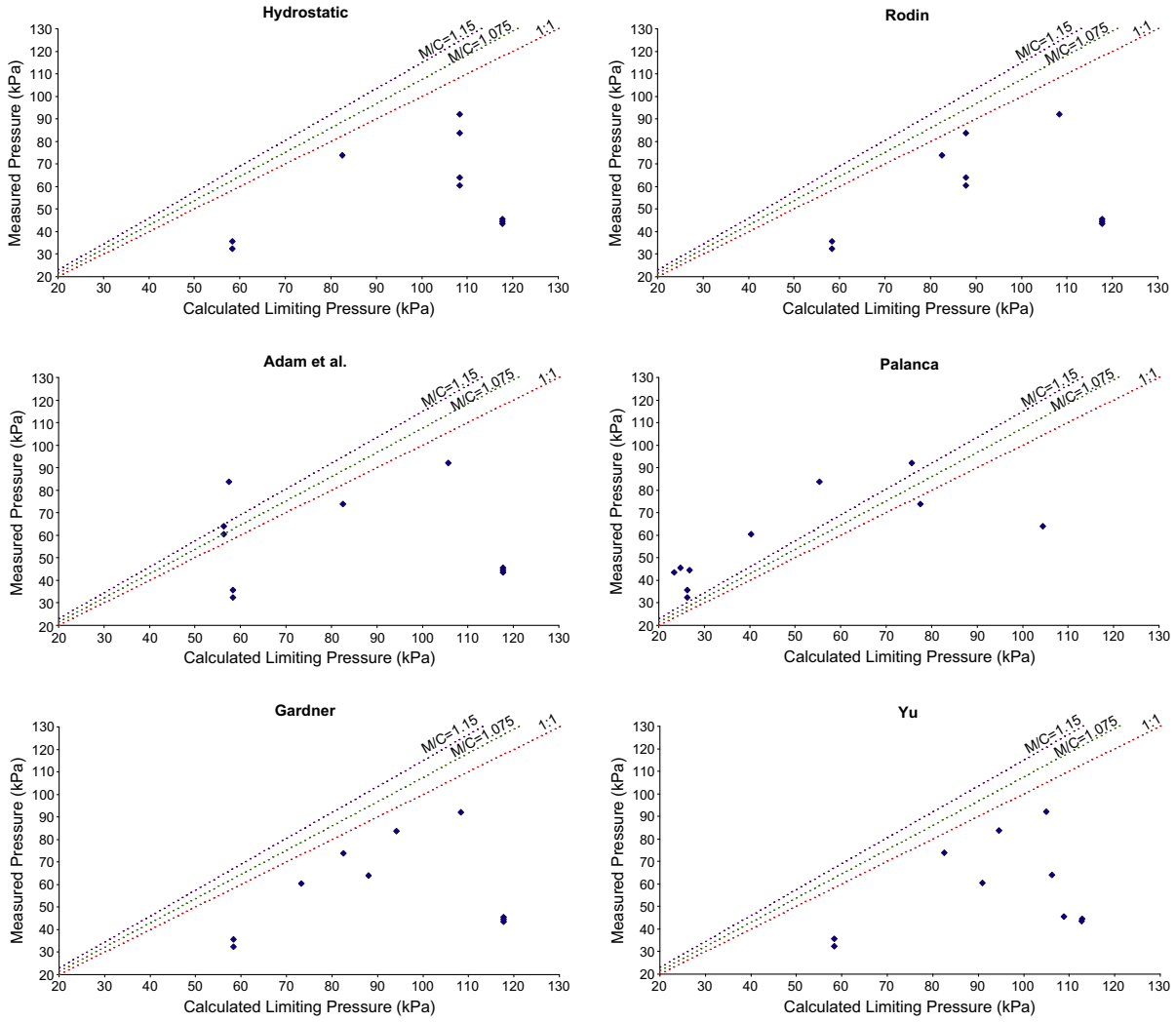
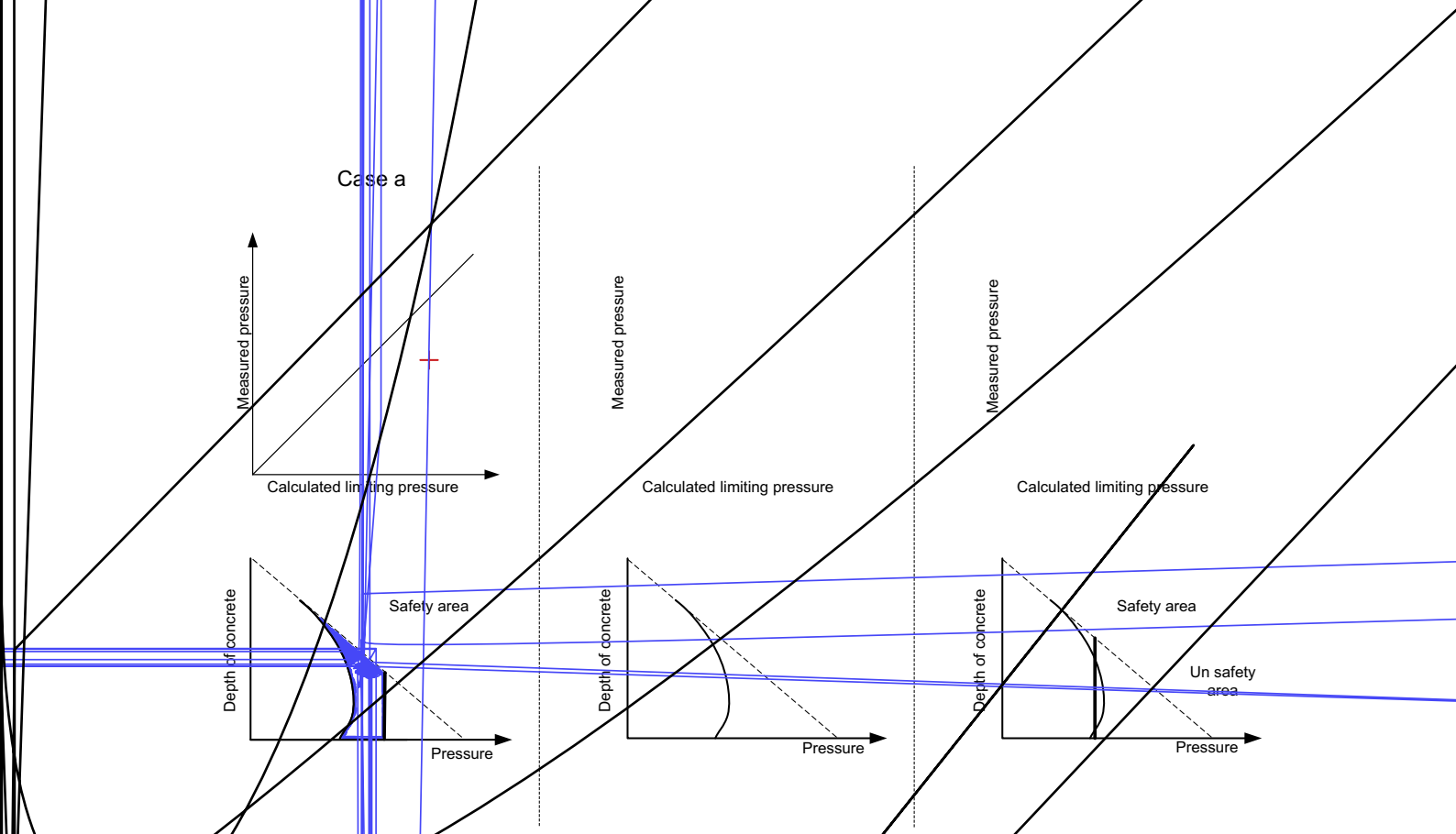


Fig. 6. Comparison between experimental and predictive pressures for rates of placement over 10 m/h.



Other distributions like Rodin [10], Adam et al. [11] or E DIN 18218 [23] underestimate concrete lateral pressure for these range of rate of placement. For all the experimental data with cement containing fly ash, these distributions have a measured pressure vs. calculated pressure ratio higher than one.

7.2. Rates of placement between 3 m/h and 10 m/h

7.2.1. Safe recommendation

ACI Committee 347 [8], and the hydrostatic model were the only two that did not have a measured pressure vs. calculated pressure ratio higher than one for this range of rates of placement. According to the statistical parameters presented in Table 3, both distributions have very similar parameters. The main reason of this coincidence is that ACI Committee 347 [8] assumes the same value for maximum pressure as the hydrostatic distribution in 98% of the data.

ACI Committee 347 [8] presents a $\mu_{M/C}$ of only 0.56 which presents a conservative method but the most suitable for this recommendation.

7.2.2. Medium recommendation

The model proposed by CIRIA Report 108 [7] has the maximum measured pressure vs. calculated pressure ratio appropriate for use with this recommendation. It presents a $\mu_{M/C}$ value equal to 0.62, which indicate a better approximation to the real experimental data than ACI Committee 347 [8], where the difference of the maximum measured pressure vs. calculated pressure ratio is 1.01, which indicates the usefulness of this model.

7.2.3. Less conservative recommendation

Yu [17] has a maximum measured pressure vs. calculated pressure ratio equal to 1.15 and could be used in construction with extended inspections. The main advantage of this model is that it has a $\mu_{M/C}$ of 0.8 higher than 0.62 presented by CIRIA Report 108 [7] and 0.56 presented by ACI Committee 347 [8], which indicates a better fit to the experimental results.

Gardner [12] has a maximum measured pressure vs. calculated pressure ratio of 1.21, higher than the maximum limit but in less proportion, but less adequate than Yu [17] because it presents a $\mu_{M/C}$ of 0.79, being Yu [17] a better distribution less risk and more adequacy.

Other distributions like Rodin [10], Adam et al. [11], Palanca [9] and E DIN 18218 [23] underestimate concrete lateral pressure for this range of rate of placement.

Palanca [9], which has a good fit to the experimental results for rate of placement lower than 3 m/h, presents a maximum measured pressure vs. calculated pressure ratio of 2.01 in this range of rate of placement, which indicate that for higher rate of placement the model is not conservative.

7.3. Rates of placement over 10 m/h

Due to the lack of experimental data presented for this range or rates of placement it is difficult to recommend different models for formwork design.

Hydrostatic distribution with a $\mu_{M/C}$ of 0.6 seems to be a conservative approach to the problem, so that the models proposed by CIRIA Report 108 [7], ACI Committee 347 [8] and E DIN 18218 [23], which proposed a hydrostatic distribution for this range of rate of placement, have to be considered conservative.

Palanca [9] and Adam et al. [11] underestimate the lateral pressure because they present a maximum measured pressure vs. calculated pressure ratio of 1.86 and 1.46 respectively, so none of these methods can be used in this range or rate of placement.

Models proposed by Rodin [10], Gardner [12] or Yu [17], can be applied to formwork design in this range of rates of placement because they have a best fit than hydrostatic distribution and do not under estimate the lateral pressure.

All the models considered have a poor relationship with experimental data in this range. With the objective of improving the