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A factorial design study to determine the significant parameters of fresh concrete lateral pressure and initial rate of pressure decay

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ABSTRACT

The design of vertical formwork is governed by the lateral pressure exerted by fresh concrete; the complexity of the problem is due to the large number of factors which affect pressure. This work describes an experimental investigation in columns to determine the variation in lateral pressure and initial rate of pressure drop with the following variables: formwork size and shape, coarse aggregate concentration and concrete temperature.

An 8-run factorial design 2^3 was done to determine the influence of formwork size and shape and coarse aggregate concentration. It was impossible to vary temperature between two levels in the field, so in this analysis this factor was considered as a co-variable. With this objective, square and circular experimental columns 3 m high but with different cross sections were instrumented, and two concrete mixtures with different sand to total aggregate ratios were used.

Afterwards, two tests were done to determine the influence in pressure of concrete impact, changing the method for filling the columns.

Formwork shape, coarse aggregate concentration and concrete impact have a minor effect in maximum lateral pressure, while temperature shows an inverse relationship with the pressure, but not to a sufficient degree to be considered a significant parameter. On the other hand, formwork size has a major effect on the pressure, narrow sections generate less lateral pressure than higher ones. This is attributed to the friction forces between concrete and formwork which are much more important in small sections.

Formwork shape and size present a major influence in the initial rate of pressure decay. While circular formworks present a higher value than squares ones, smaller cross sections present a lower value than larger ones. On the other hand, coarse aggregate concentration has a minor effect on this parameter.

1. Introduction

The key issue for designing vertical formwork is to determine the maximum horizontal pressure exerted by fresh concrete during casting since an overestimation of this value results in an increase of formwork cost, which Hurd [1] showed can be up to 60% of the concrete structure cost.

On the other hand, an underestimation of the pressure generates pieces made of poor quality, which may delay construction causing economic and time losses. Post [2] states that many failures in vertical formwork only produced excessive deflection and were therefore never documented. While maximum lateral pressure is important for formwork design, the kinetics of drops in lateral pressure are important for determining formwork removal time.

Numerous studies were carried out with the objective of understanding the influence of different variables in the phenomena. Examples were those performed by Adam et al. [3], Gardner and Quereshi [4], CIRIA Report 108 [5], ACI Committee 347 [6], Arslan et al. [7] and Hurd [8].

Generally, these variables can be grouped into three categories: concrete characteristics, formwork characteristics and placing method. The large number of factors explains the complexity of the problem.

For example, vibration and rate of placement are significant factors in fresh concrete lateral pressure but have been extensively studied in the literature. Gardner and Quereshi [4] studied 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 lateral pressure. Santilli et al. [9] analysed the influence of rate of placement on maximum lateral pressure. The authors established that this parameter has a variable effect on lateral pressure. While a linear relationship is shown at low rates, this relationship becomes weak at higher rates.

On the other hand, not all the factors were well studied in the bibliography, and some of them present inconsistencies between

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different researcher's conclusions, pointing out the need for further research. The objective of this work is to determine the influence of five factors on fresh concrete maximum lateral pressure: formwork size and shape, coarse aggregate concentration, concrete temperature and concrete impact, and also the influence of the first four in the initial rate of pressure decay.

After casting, as fresh concrete starts to gain shear strength, the total lateral pressure may decrease because the internal friction of the material increase. Andriamanantsilavo and Amziane [10] state that the lateral pressure on formwork walls steadily decreases during a period of time after casting, when the hydration process has not yet started, or may be considered negligible. Assaad et al. [11] and Khayat et al. [12] state for self-compacting concrete (SCC) that the only phenomenon that can occur at this time in fresh concrete is flocculation. Accordingly, the initial rate of pressure decay is associated with concrete flocculation and the increase of concrete shear resistance. (Internal friction and cohesion.)

In the bibliography on vertical formwork, in general, pressure drop is only determined by sensors during a short period of time after casting. In this way, the initial rate of pressure decay is determined. In most cases, the time needed to decrease the maximum lateral pressure by a certain percentage of hydrostatic pressure has been determined by researchers. In this work, a standardised method is presented for determining the initial rate of pressure decay.

2. Influence of the variables

2.1. Formwork size

For vertical formwork CIRIA Report 108 [5] and ACI Committee 347 [6] 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 concrete to be placed in a relatively short time, resulting in a maximum pressure greater than in walls. Furthermore, Palanca [13] states that unless the rate of placement can be controlled to a design specified rate, friction between formwork and concrete is much more important in columns than in walls, due the smaller cross section.

Gardner and Ho [14] demonstrated experimentally that for conventional vibrated concrete, an increase in formwork dimension produces an increase in lateral pressure.

On the other hand, CIRIA Report 108 [5] states that vibration of fresh concrete has a major influence on narrow formwork, which could cause greater lateral pressure.

More recently, Khayat et al. [12] studied the effect of column diameter on maximum lateral pressure for self-consolidating concrete (SCC) using a 200 mm column and a 920 mm column. The authors concluded that the larger column had slightly higher pressure, and higher rate of pressure decay.

In the larger column, the time required to reduce lateral pressure by 5% of the hydrostatic value was 20 min. On the other hand, for the smaller column this time was 38 min.

2.2. Formwork shape

Limited data exist regarding the effect of formwork shape on maximum lateral pressure. Researchers performed their experimental program only in circular formwork like Perrot et al. [15] or only in rectangular ones like Arslan et al. [7]. This makes it difficult to compare different geometries.

In this work, circular and square formwork have been tested with the objective of observing the influence of formwork shape on the two parameters studied.

2.3. Coarse aggregate concentration

Several approaches have been adopted to assess the effect of the granular phase on the development of lateral pressure. Amziane and Baudeau [16] identify concrete as a two-phase heterogeneous material composed of cement paste and coarse aggregate. While the paste follows exclusively viscous rheological behaviour, the granular phase contributes to resistance to shear stress through aggregate friction.

The authors prepared different concrete mixtures with a water–cement ratio of 0.5, and tested the lateral pressure in a formwork 1650 mm high, 1350 mm long and 200 mm wide. Cement paste was reported to initially develop full hydrostatic pressure.

When coarse aggregate volume increases, hydrostatic pressure is still obtained until the volumetric fraction of the ratio paste-to-coarse aggregate is approximately one. On the other hand, with a value lower than one, the pressure diagram was reported to be bilinear. The lateral pressure is hydrostatic from the free surface to a maximum value at 450 mm from the base of the formwork, making the pressure envelope diverge from the hydrostatic one.

Finally, Assaad and Khayat [17] found that for self-compacting concrete (SCC) the increase in coarse aggregate concentration can reduce maximum lateral pressure.

The authors prepared different concrete mixtures changing the sand to total aggregate ratio (S/A) from 1.0 to 0.3 in a PVC column 2800 mm high and 200 mm in diameter, measuring the lateral pressure with pressure sensors mounted at different heights above the base.

The results show that the initial lateral pressure decreases from 99% to 77% of the hydrostatic pressure when S/A decreases from 1.0 to 0.3.

The authors also determined the initial rate of pressure drop near the bottom of the PVC column. For example, for S/A ratios between 0.5 and 0.3 the time required to reduce lateral pressure by 10% of the hydrostatic value was 145 and 80 min, respectively, pointing out that a mixture with more coarse aggregate has a faster rate of pressure decay.

2.4. Concrete temperature

Concrete temperature is difficult to study because constructors and researchers can have very little influence on temperature in the field. Therefore temperature variation studies are limited in real practice.

Rodin [18] considered concrete temperature as a fundamental parameter in fresh concrete lateral pressure. The author states that an appreciable rise in maximum pressure is shown when temperature decreases, the lower rate of concrete hardening being the most probable cause.

Gardner [19] evaluated the effect of concrete temperature varying from 2 °C to 27 °C. The lateral pressure was found to increase when concrete temperature decreased. The author states that for lower temperatures, the hydration process is slower. The author also reported that the critical temperature that governed the phenomena is the concrete one and not the ambient one.

Concrete temperature is one of the most important parameters in the models which predict the maximum lateral pressure. For example the model proposed by the German Standard DIN 18218 [20], for normal vibrated concrete considered a variation of 3% on pressure prediction for each °C.

Assaad and Khayat [21] filled a column 2800 mm in height and 200 mm in diameter, with SCC at three different temperatures: 10, 20 and 30 °C. The rate of pressure drop determined by a pressure sensor mounted 50 mm above the base was significantly affected by concrete temperature.

The time required to reduce lateral pressure by 25% of the hydrostatic pressure decreases from 400 to 250 and 160 min for 10, 20 and 30 °C, respectively.

In this case, due to the long time recorded by the authors in the rate of pressure decay, both the flocculation process and the concrete hydration are considered, being difficult to differentiate one from the other.

2.5. Impact of concrete

CIRIA Report 108 [5] determined that height of discharge affects the magnitude of the impact forces, which affect lateral pressure in fresh concrete.

The most common process of casting a wall or a column consists of placing concrete in lifts, which are subsequently vibrated, to guarantee a correct consolidation. Harrison [22,23] states that during the placing of initial layers the particle structure will take such a small proportion of the load that the horizontal pressure is almost equal to the hydrostatic pressure of a fluid with concrete density.

As the particle structure can develop shear stress between layers, the horizontal pressure decreases, but each new layer can cause the particle structure to collapse due to the impact force, thereby causing a rise in the lateral pressure.

3. Experimental program

3.1. Experimental design methodology

A Design of Experiment (DoE) methodology (Montgomery [24], and Box et al. [25]) was used to design and analyse the experiments. DoE provides a quick and cost-effective method to understand and optimise products and processes as established by Antony [26].

A full factorial design 2^3 was used initially to determine the influence of formwork size and shape and coarse aggregate concentration in maximum lateral pressure and in the initial rate of pressure decay. The factorial design 2^k is one of the most used designs to research the effects of different factors on a particular response, where k is the number of factors and the base 2 represents the level of treatment for each factor considered (or variable).

Moreover, temperature was analysed as a co-variable, since it was difficult to control in the field. Introducing this factor in the full factorial design does not allow estimating all interactions and makes the design not completely orthogonal. However, the design is able to estimate each of the main effects independently, even if the interaction among them becomes convoluted.

In all cases concrete was pumped with the end of the hose coinciding with the upper edge of the formwork.

Finally, two tests were performed in which the end of the hose level increases with concrete level. The objective of these tests was to determine the influence of concrete impact on maximum lateral pressure.

Since the factorial design uses two levels for each of the selected factors, the next step after choosing the experimental design was to determine the different levels of treatment for each factor to be used in the experimentation.

Experimental design technique suggests that levels could be coded into a unitless value, typically within the −1 and +1 range, in such a way that an experimenter can pick an experimental design from a catalogue of designs.

For formwork shape, the higher level was circular and the lower level was square. In both cases steel formwork was used.

In the case of formwork size the levels were determined by the interior area of the formwork. The lower level was considered an area of 931 ± 31 cm^2, and the higher level an area of 2664 ± 164 cm^2. The variations in the area are due to the commercial formworks that were used, which made it impossible to achieve a perfect coincidence between square and circular areas.

For square formworks, the lower level had 30 cm sides, which represents an area of 900 cm^2, and the higher level had 50 cm sides, which represents an area of 2500 cm^2.

For circular formworks the lower level had a 35 cm diameter, which represents an area of 962 cm^2, and the higher level had a 60 cm diameter, which represents an area of 2827 cm^2.

In the case of coarse aggregate concentration, two different sand to total aggregate ratios (S/A) were used. The lower level presented a ratio S/A equal to 0.7, while the higher level had a ratio equal to 0.56.

The limit for the higher level was imposed by pump limitations since it is extremely difficult to pump concrete with a higher volume of coarse aggregate.

It was very difficult to vary concrete temperature between two levels, due the influence of this parameter on fresh concrete lateral pressure. Temperature was measured in each test, considering the value for the analysis as a co-variable.

The design implemented is presented in Table 1, which summarises the factors studied and their variation levels.

3.2. Formworks

As already mentioned, two square and two circular steel formworks were used in this study, all of them 3 m high.

Square formworks were composed of four panels, each one 3 m high by 0.56 m wide, with a metal sheet 3 mm thick and 13 ribs, including the ones at the top and the bottom. A not-to-scale plot of one panel is shown in Fig. 1a.

Four ribs have six holes spaced 5 cm apart, as shown in Fig. 1a, which allows moulding columns with sides that range from 25 cm to 50 cm. These ribs have a security bolt on one end to connect with the hole of the adjacent panel. A wedge is used to secure the bolt into position during the filling process.

Setting up the formwork starts by standing up one panel, which is stabilised by a tensor, fixed to the floor. Then, the other panels are mounted joining one to another with the security bolts and the wedges.

Fig. 1b and c represents how to join the panels to form the square formworks with 50 and 30 cm sides, respectively.

Circular formworks were composed by four semicircular panels of which two are 2 m high, while the other two are only 1 m high. The shorter ones were mounted above the taller ones to complete a 3 m mould.

All formwork panels were composed of a metal sheet of 3 mm thick. The longer ones have five ribs including the top and the bottom ribs, while the shorter have only three ribs including the top and the bottom. A not-to-scale plot of a 2 m panel is shown in Fig. 2.

The upper and bottom ribs have holes, as shown in Fig. 2. These holes allow the shorter panel to be joined to the taller panel to complete the formwork height. The pieces are joined by means of security bolts, which get stuck, thanks to the hole's shape.

Setting up the formwork starts by joining the 1 m and 2 m panels. One panel is then stood up and stabilised by a tensor, which is fixed to the floor. Then, the other panel is mounted, joining one to another by means of the security bolts.

Fig. 3 shows an image of the rectangular and circular formwork.

3.3. Formwork instrumentation

The lateral pressure was determined using four pressure sensors mounted at 100, 360, 650, 1120 mm from the base. Omega PX 102-025GV pressure cells were chosen because of their size and pressure range. The pressure range was between 0 and 172 kPa. In this case the sensors used allow measuring the hydrostatic value, of a liquid with the same density as concrete for a column up to 7 m high. Therefore, the sensors were appropriate for this experimental program.

Khayat and Assaad [27], established that the sensor diameter should be greater than the maximum aggregate size used in the concrete to prevent any interference during measurements. Each pressure sensor has an active diameter of 19 mm, which allows the use of aggregate up to this size.

Sensors were fitted to formwork with two steel parts. The first part works like a threaded washer holding the sensor, as shown in Fig. 4a. While the second part was welded to the formwork, which permit tightening the screws into the washers, as shown in Fig. 4b, ensuring the proper fastening of the sensor. In accordance with Khayat and Assaad [27] sensors were aligned flush with the inner surface of the formwork.

The calibration was carried out by comparing the sensor signal with another sensor calibrated using air pressure. Then the sensor was mounted in a PVC column 3.6 m high and a re-calibration was carried out using water as a live load. The difference between both calibrations for all the sensors used in this work was less than 2.5%, which was considered acceptable.

Concrete temperature was monitored using two T-type thermocouples placed 2000 mm from formwork base.

3.4. Mixture proportions

Two different concrete mixtures were used in this work, both with cement CEM II/A-M(V-L) 42.5R according to UNE – EN 197-1 [28] similar to ASTM C 150 [29]

Table 1
Levels of factor of the design of experiments.

Factor	Low level (−1)	High level (+1)
Formwork shape	Square	Circular
Formwork size	931 ± 31 cm^2	2664 ± 164 cm^2
Coarse aggregate concentration	S/A = 0.7	S/A = 0.56
Concrete temperature	Real variation	

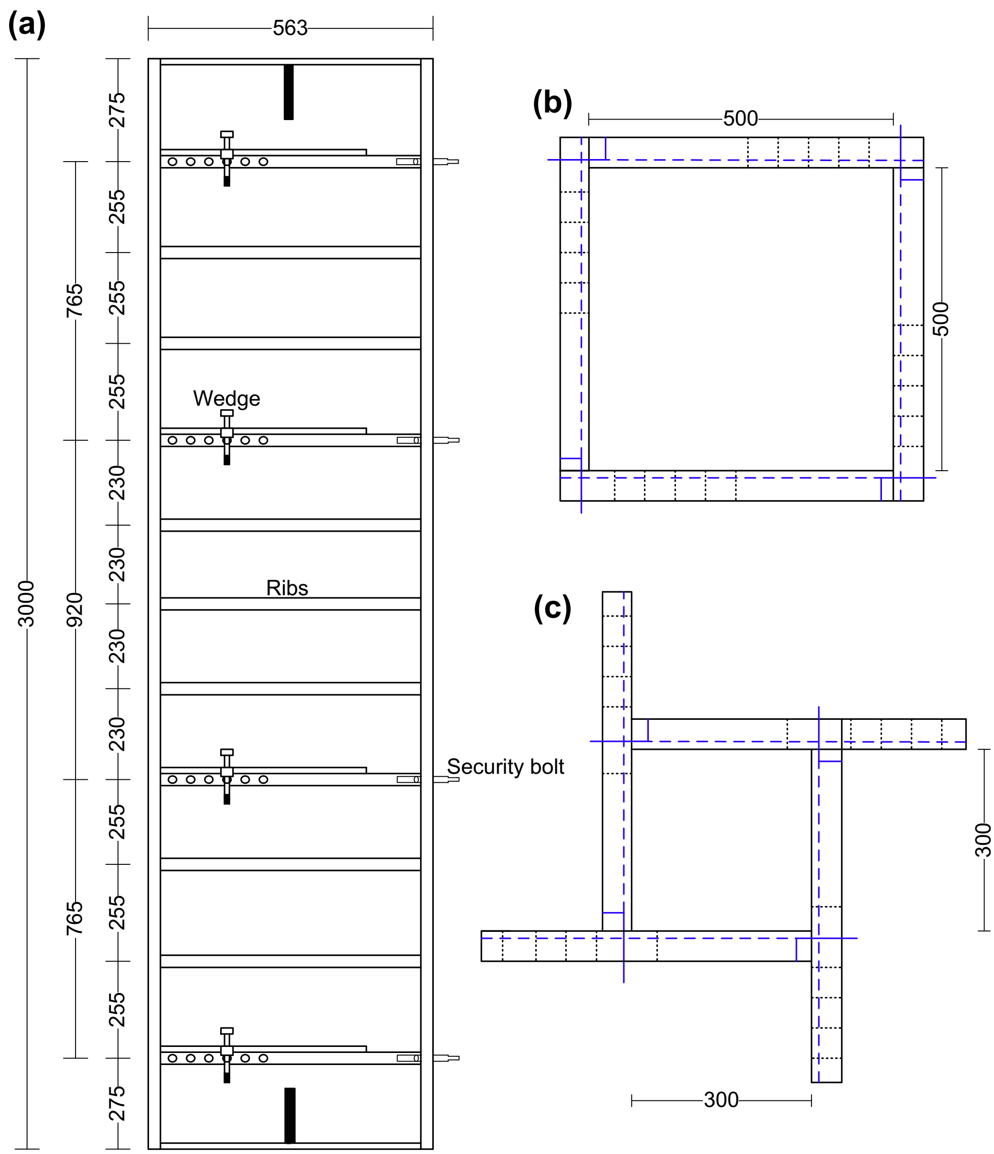

Fig. 1. Square formwork plot (mm).

Type III. In all cases, the concrete has 330 kg of cement per cubic meter and a ratio of water to cement of 0.5 by weight.

A continuously graded coarse aggregate with a maximum size of 12 mm was employed in both concrete mixtures. With the objective of meeting the recommendation proposed by Khayat and Assaad [27]. As already mentioned, the difference between the mixtures was in the sand to total aggregate ratio.

3.5. Testing program

The tests were carried out in a concrete plant, with the objective of reducing to a minimum the time the concrete remains in the pump-truck. Concrete was pumped into formwork in three layers each 1 m high, which were subsequently vibrated. The 1 HP power vibrator was submerged into the concrete a length equal to the height of the lift to guarantee a correct consolidation, during a period of 30 s. The rate of placement for all test was 12 m/h, which is guaranteed controlling the waiting time between lifts after vibration. The data obtained by the sensors was almost continuously recorded in order to obtain the maximum value for this parameter. The pressure data was stored every 5 s.

Once the design has been chosen, it is desirable to perform experimental runs in random order to minimise the effects of extraneous sources of variability, and to validate the statistical procedures for analysing the results. Table 2 presents the standard order (the order picked from an experimental design from a catalogue of designs) and the run order (the real order in which the test were made, to minimise the effects of extraneous sources of variability) of the 10 runs. Tests designated with letter A, are part of the design of experiments, while tests designated with letter B are the two extra tests to determine the influence of impact. The number after the letter identifies the test characteristic. For example, test A6 and B6 have the same characteristics (formwork shape, formwork size and coarse aggregate concentration), but A6 had been used for the factorial design and B6 for the analysis of the influence of impact.

4. Results

4.1. Maximum lateral pressure

A typical diagram showing the envelope of lateral pressure along the 3000 mm height of the experimental columns for two of the test is given in Fig. 5.

Fig. 5 shows two different shapes for the envelope of fresh concrete maximum lateral pressure. One of them presents the maximum lateral pressure in the second sensor, as in test A1. However, other tests present an envelope like test A3, in which the maximum pressure is reached at the lower sensor. In summary, depending on the test, the maximum pressure was registered in the lower sensor (S1) or in the second one from the bottom (S2), all the pressure data was gathered in Table 3. The sensors were counting from the bottom.

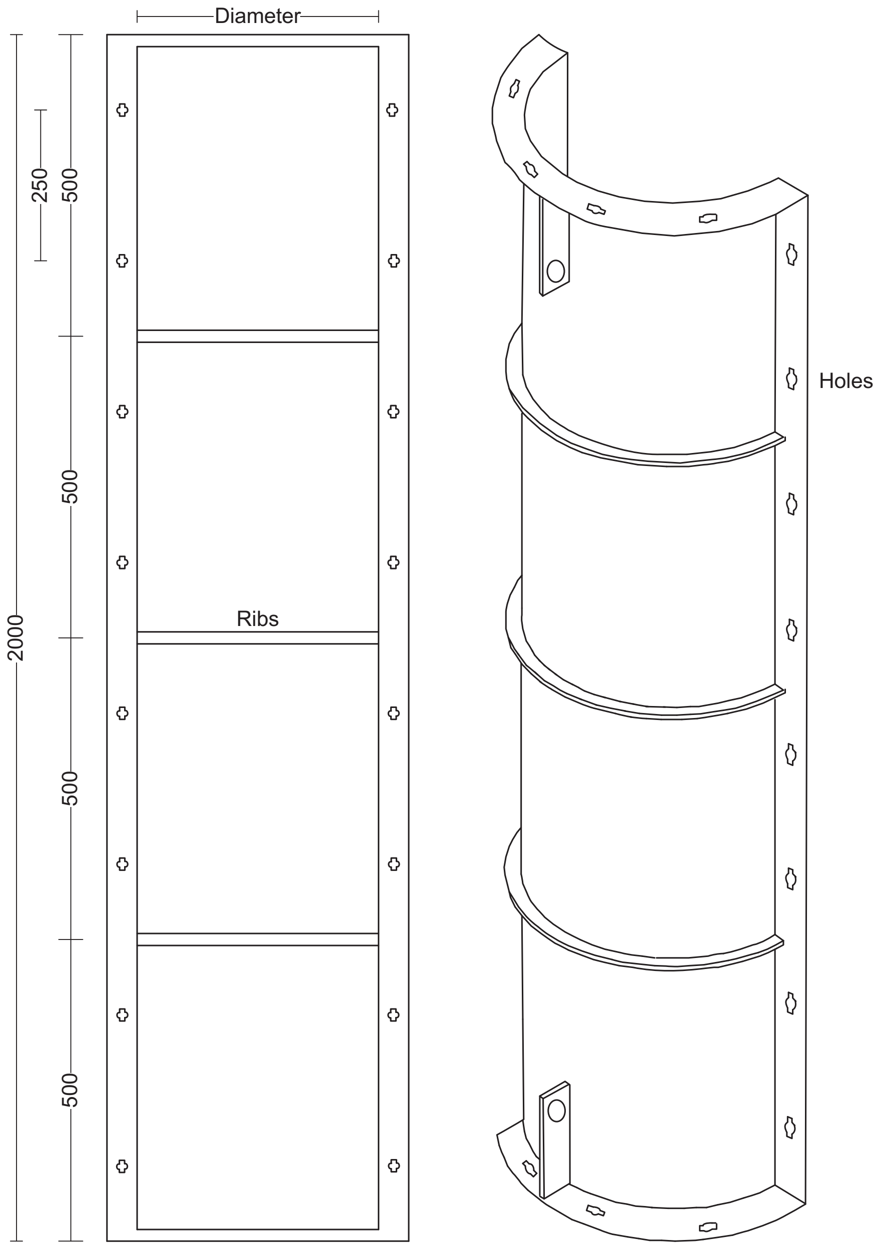

Fig. 2. Circular formwork plot (mm).

A possible reason for those different shapes may be the large number of factors that influence fresh concrete lateral pressure, such as vibration. For example, the vibrator may be closer to sensors in one test than in another, obtaining as a result variations in pressure envelopes.

For the analysis of the variables, the maximum formwork pressure has been used, without taking into account at which sensor it was measured. Table 3 also presents the results of concrete temperature and slump cone for the 10 tests that were carried out.

4.2. Initial rate of pressure decay

In the bibliography, as shown above, the initial rate of pressure decay is determined considering the time needed to reduce a given percentage of hydrostatic pressure. This is a simplified manner to resolve the problem, because only two data were used: the maximum pressure and the limit pressure.

Another problem is the impossibility of making a comparison between different researches projects, because, for the same experimental test, the consideration of two different percentages of hydrostatic pressure reduction could produce important variations in the initial rate of pressure decay.

In order to demonstrate this, for tests A4 and A6, the rate of pressure decay was determined considering two different times required to reduce the maximum pressure in 5–15% of the hydrostatic pressure, similar values to those considered in the literature. The results show that the rates of pressure decay for the two considered test are different depending on the percentage of reduction considered. The variations in the rate of pressure decay that changed the percentage of lateral pressure reduction from 5% to 15% of the maximum hydrostatic value are 21–15%, respectively.

Due to this problem in this work the initial rate of pressure decay is going to be determined from a cubic spline with a smoothing

Fig. 3. Formworks placed at construction site.

parameter. A cubic spline passes through all the data, but in all experimental research, noise is present in the measurements. Therefore, the problem is how to eliminate noise from the data without suppressing the main signal.

Meizoso [30] recommended the cubic spline with a smoothing coefficient for data leakage, because it is a technique which combines the polynomial adjustment by means of maximum likelihood method, with the spline technique. A natural measure of smoothness associated with a function f according to Meizoso [30] is $\int f''(t)^2 dt$, while a standard measure of data fitting is the residual sum of squares: $n^{-1}\sum(y_i - f(t_i))^2$. Therefore, an assessment of the quality of a candidate estimator f is provided by the following equation:

$$S = pn^{-1}\sum(y_i - f(t_i))^2 + (1-p)\int f''(t)^2 dt \quad (1)$$

Table 2
Testing program.

Test number	Standard order	Run order	Formwork shape	Formwork size (cm^2)	Coarse aggregate concentration
A1	1	5	Square	931 ± 31	S/A = 0.7
A2	2	9	Circular	931 ± 31	S/A = 0.7
A3	3	1	Square	2664 ± 164	S/A = 0.7
A4	4	3	Circular	2664 ± 164	S/A = 0.7
A5	5	2	Square	931 ± 31	S/A = 0.56
A6	6	6	Circular	931 ± 31	S/A = 0.56
A7	7	7	Square	2664 ± 164	S/A = 0.56
A8	8	8	Circular	2664 ± 164	S/A = 0.56
B6	–	4	Circular	931 ± 31	S/A = 0.56
B7	–	10	Square	2664 ± 164	S/A = 0.56

where $p \in [0;1]$, is the smoothing parameter. For $p = 0$ the result is a linear regression, while for $p = 1$ the result is the natural cubic spline which interpolates the data. An optimal estimator can be obtained by minimising the function presented in Eq. (1).

The final problem is to select a suitable level of smoothing for a set of data. Eubank [31] established that there are different ways to choose a value for the smoothing parameter (p). One way is a trial and error procedure where arbitrary values of p are tried until one gives a visually satisfactory fit to the experimental data. Throughout the entire analysis the Matlab R2008b Spline Toolbox was used.

Fig. 6 shows for the sensor mounted 100 mm above the base for test A5, the experimental data and the cubic spline with four different smoothing parameters: 0.01; 0.1; 0.5 and 0.8.

As Fig. 6 shows, the curves presented for $p = 0.01$ and 0.1 do not present a good fit with the experimental data, therefore a higher value of p needs to be considered. On the other hand, curves with $p = 0.5$ and 0.8 have a very similar behaviour and are visually satisfactory. Therefore, a value of the smoothing parameter equal to 0.5 has been selected for this work, to determine the rate of pressure decay. Afterwards, this smoothing parameter was verified in the entire test, presenting in all cases a visually satisfactory result, similar to the one shown in Fig. 6 for test A5.

For the entire test realized the results is visually satisfactory. Therefore, a smoothing parameter equal to 0.5 has been used to determine the rate of pressure decay.

The derivate over time of the cubic spline with the smoothing parameter represents the rate of pressure decay at each instant of time; in all cases this value is constant for a variable time after casting (15 min). Therefore, this value will be considered as the initial rate of pressure decay for the factorial design.

Researchers tend to compeer the initial rate of pressure decay between various tests in the lower sensor. Examples of that are the works presented by Khayat et al. [12], Perrot et al. [15] and

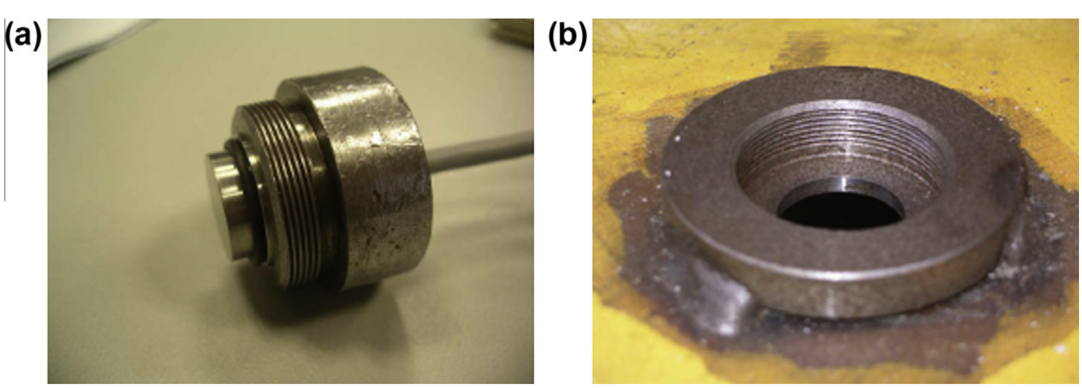

Fig. 4. Pressure cell with the washer and the socket welded to the formwork.

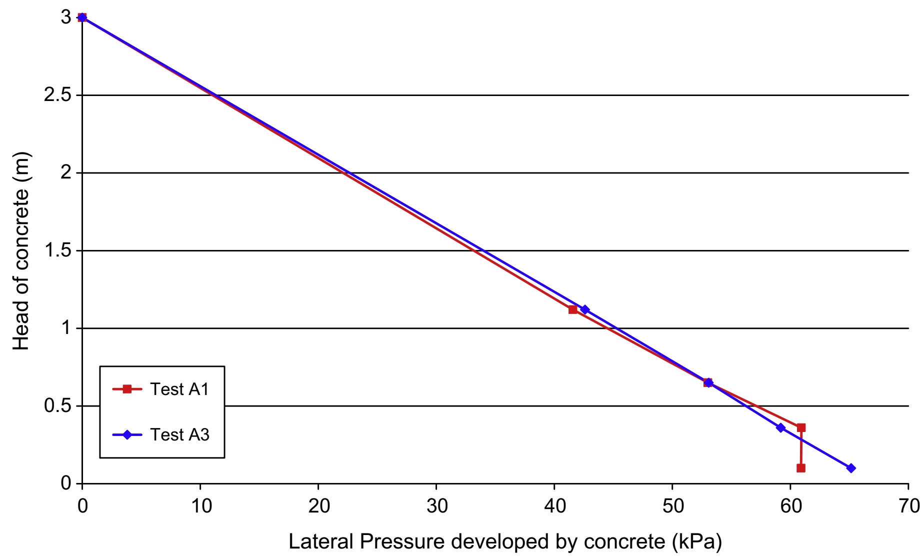

Fig. 5. Envelope of concrete lateral pressure.

Table 3
Experimental results.

Test number	Temperature (°C)	Slump (mm)	Lateral pressure (kPa)				Pressure decay (kPa/hr)
			S1	S2	S3	S4	
A1	11.3	260	60.90	60.93	53.02	41.58	15.6
A2	16.7	160	59.43	55.32	50.03	40.66	19.1
A3	15.7	240	65.15	59.18	53.08	42.60	19.5
A4	15.3	220	65.20	59.42	53.35	42.34	33.9
A5	17.5	240	58.38	55.31	50.02	40.09	10.5
A6	11.7	230	62.37	57.57	53.68	43.26	31.7
A7	12.7	260	65.48	60.30	–	–	17.6
A8	14.9	230	65.29	59.36	53.12	43.53	28.3
B6	16.2	220	61.14	59.89	53.46	43.36	–
B7	16.5	210	65.19	59.84	51.71	42.40	–

Assaad and Khayat [21]. Therefore, in this work the factorial design is carried out only for the sensor placed in the lower position, as has been done by others authors. The results of the initial rate of pressure decay for the lower sensor is also presented in Table 3.

The selection of the smoothing coefficient, as established by Eubank [31], has been performed in an arbitrary manner. Therefore, a sensitivity analysis is needed to ascertain the robustness of the method, and the ability to establish consistent conclusions. The sensitivity analysis shows that the method to determined the initial rate of pressure decay has a high degree of robustness in the coefficient selection. Important variation in the initial rate of pressure decay is observed only when the order of magnitude of the smoothing coefficient changes. In conclusion, it is clear that definitive conclusions can be established with this method.

5. Analysis and discussion

5.1. Hydrostatic distribution

Very few data were presented in the bibliography for pumped concrete. For all the tests, as shown in Table 3, despite the high value of the slump cone, the lateral pressure is lower than the one made by a liquid with concrete density.

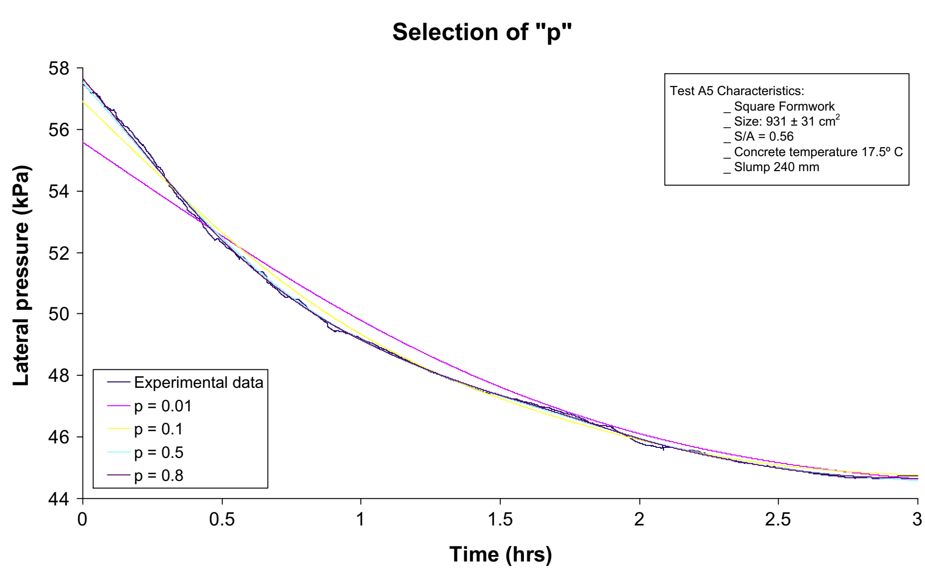

Fig. 6. Selection of the smoothing parameter.

What is more, the lowest pressure registered (test A5) represents 84% of the hydrostatic distribution, and the mean value for all the tests represents 91% of the hydrostatic pressure of a liquid with concrete density. Those data demonstrate that hydrostatic distribution is conservative for pumped concrete. This result was in good agreement with the recompilation made by Santilli et al. [32], for rates of placement over 10 m/h.

The main cause for this difference could be that, with vibration, not all the concrete mass fluidised since deeper layers are not affected and, therefore, develop shear strength, which allows them to support vertical loads, and to develop friction between concrete and the formwork wall, thereby generating lateral pressure lower than the hydrostatic one.

5.2. Design of experiment

For two-level factorial design, the main effect of a factor may be defined as the change in the response produced by a change in the level of that factor averaged over the other level of the factor. Eq. (2) shows that the effect can be calculated by the sum of the values when the factor was at high level (+1), minus the sum of the values of the response when the factor was at low level (−1), divided by half of the total number of experiments done.

$$\text{Effect A} = \frac{\sum \text{Response with } A = (+1) - \sum \text{Response with } A = (-1)}{(\text{Numbers of experiments})/2} \quad (2)$$

The effect of the factors show the variation in the response caused by changing the factor from low level (−1) to high level (+1). If the effect is shown as positive, its change will cause an increase in the response value. In this work the calculations for the analysis were done with Design Expert v8R, which is software specifically for implementing factorial designs.

After determining all the possible effects, an analysis of which ones are statistically significant has to be done. This means determining with certainty (a low probability of error) which factors have a real influence on the initial rate of pressure decay.

An analysis of variance (ANOVA) was carried out to look for significant effects in the initial rate of pressure decay. Lorenzen and Anderson [33] established that the ANOVA is the most accurate method to carry out this kind of analysis. This is a formal and accurate method which basically consists of looking at the total of the variation in the data, breaking it into its various components and running statistical tests in order to find out which components have an important influence on the experiment.

An effect is usually considered significant when the p-value is less than 0.05, as suggested by Tanco et al. [34]. The p-value is the probability of obtaining a test at least as extreme as the one that was actually observed, assuming that the null hypothesis is true.

Initially, since temperature was considered as a co-variable, it was necessary to analyse the results with an ANCOVA (Analysis of the Covariance) in order not to lose precision in the conclusion as established by Silknitter et al. [35]. Fortunately, Design Expert v8R, which was the software used in this analysis is able to analyse DoE with co-variables by recalculating the analysis after the model selection.

5.2.1. Maximum lateral pressure

Table 4 summarises the p-value for the model and for the four individual factors studied for fresh concrete maximum lateral pressure. The p-value for the model states that there is only a 0.65% probability that this result could occur due to noise.

In the ANOVA analysis, Graham [36] established that a signal to noise ratio higher than four is desirable, for the study case, the ratio was 8.736 which indicates an adequate signal. Therefore this model is valid for establishing conclusions.

Table 4
ANOVA p-values for maximum lateral pressure.

Source	p-Value
Model	0.0065
Formwork shape	0.185
Formwork size	0.005
Coarse aggregate concentration	0.922
Concrete temperature	0.065

The only factor that has a p-value lower than 0.05 is formwork size, being a significant parameter in fresh concrete lateral pressure. Fig. 7a shows the main effect plot for this factor. The main reason for this influence could be attributed to the friction forces between formwork and fresh concrete, which are much more important in small sections. This result is consistent with the results presented by Gardner and Ho [14], and Khayat et al. [12] for SCC.

Fig. 7b shows the main effect plot for concrete temperature. This factor, presents a p-value of 0.065. One reason for the insignificance of this factor may be that the studied range data could only be obtained from experiments between 11.3 and 16.5 °C. Further research is needed for expanding the temperature range because it is considered a very important factor in the principal models which predict maximum lateral pressure (ACI Committee 347 [6] and DIN 18218 [20]).

Formwork shape and coarse aggregate concentration are clearly not significant parameters in the phenomena, because they present p-values of 0.185 and 0.922, respectively.

Coarse aggregate concentration in the studied range shows a low influence on fresh concrete lateral pressure, based on Table 4. In theory, fresh concrete lateral pressure has to reduce when coarse aggregate increases, as established by Amziane and Baudeau [16], due to the capacity of coarse aggregate to form a structure capable of supporting vertical loads, thereby reducing the lateral pressure. Due the limitation presented by the pump, more research is needed to study in a more complete form the effect of this parameter, with the objective of determining in a clear form its influence.

5.2.2. Initial rate of pressure decay

Table 5 summarises the p-values for the model and the four individual factors studied in the analysis of the initial rate of pressure decay.

The p-value for the model states that there is only a 5.15% probability that this result could occur due to noise. In this type of analysis, Graham [36] established that a signal to noise ratio higher than four is desirable. In the study case the ratio was 11.6 which indicate an adequate signal. Since the p-value is slightly higher to the arbitrary limit of 5%, the model has been considered significant because the limit is an arbitrary selection and it does not make sense to apply it rigidly. Therefore, this analysis is valid for establishing further conclusions.

Fig. 8 shows the main effect plot for each of the significant factors resulting from the ANOVA analysis.

Formwork shape, according to Table 5, presents a p-value lower than 0.05, as a significant parameter. Fig. 8a clearly shows that circular formwork presents higher initial rate of pressure decay than the square ones.

Formwork size, based on Table 5, presents a p-value that is also under 0.05, making it a significant parameter for the initial rate of pressure decay. Fig. 8b shows that bigger cross sections have higher initial rate of pressure decay. This result is in concordance with the results presented by Khayat et al. [11] for SCC.

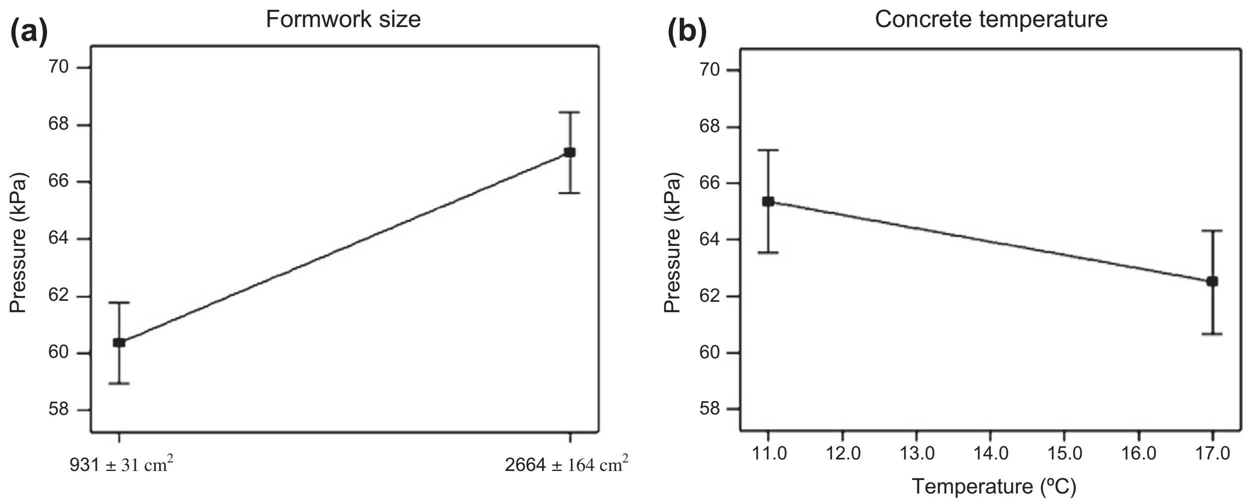

Fig. 7. Main effect plot for lateral pressure significant parameters.

Table 5
ANOVA *p*-values for the initial rate of pressure decay.

Source	*p*-Value
Model	0.0515
Formwork shape	0.0132
Formwork size	0.0495
Coarse aggregate concentration	0.1729
Concrete temperature	0.0525

As establish above, the rate of pressure decay in fresh concrete depends on concrete flocculation and on the increase of concrete shear resistance. Therefore, for columns with a smaller cross section, the friction with the form can be much more pronounced. This may affect the rate of the interlocking between aggregates buildup after casting, which may reduce the initial rate of pressure decay.

Coarse aggregate concentration, according to Table 5, presents a *p*-value equal to 0.1729. Therefore, it is not a significant parameter in the initial rate of pressure decay. Due to the limitations presented by the pump used in the filling, more research is needed to study in a more complete form the effect of this parameter.

Finally, temperature, according to Table 5, presents a *p*-value closer to 0.05, which makes the interpretation of the results difficult. Moreover, since temperature was studied as a co-variable, which makes the model non-orthogonal and even more difficult to interpret, the analysis of this parameter is further complicated. As no variation in concrete temperature was recorded in the first hour after casting, and this work analysed the initial rate of pressure decay, hydration can be considered negligible. Therefore, concrete temperature could be considered as a non-significant parameter.

5.3. Concrete impact

As explained above, two extra tests of the full factorial design were performed to study the effect of concrete impact on lateral pressure. Tests B6 and B7, as shown in Table 3 have a maximum pressure of 61.14 and 65.19 kPa, respectively, lower than the 62.37 and 65.48 kPa presented by tests A6 and A7.

The differences between the tests performed with the holes in different positions was 0.4–2.5%, pointing out that when the hole is maintained at the same level of the formwork top the lateral pressure is higher than when the hole level is elevated with concrete. This conclusion is consistent with the results presented by CIRIA Report 108 [5] and Harrison [22].

The differences were too low for this factor to be considered as significant, but in both cases concrete pumped with impact presents higher pressure. One possible reason for the low differences could be the coarse aggregate size. In this work, the maximum aggregate size was 12 mm; bigger aggregate could cause the

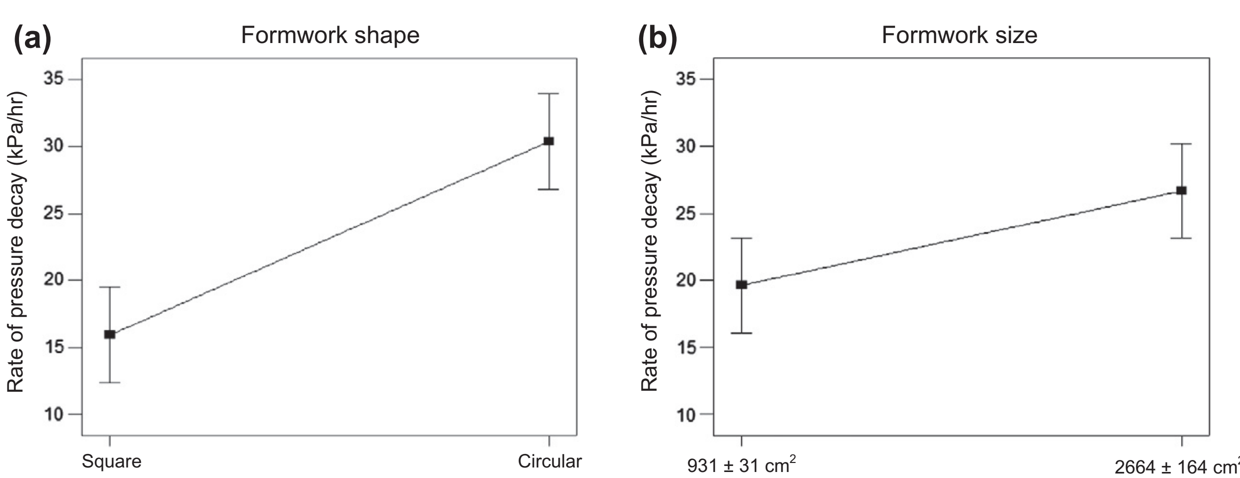

Fig. 8. Main effect plot for initial rate of pressure decay significant parameters.

particle structure of previous layers to collapse more easily than smaller ones.

6. Conclusions

After experimentally obtaining the pressure value of vibrated concrete over time, it was possible to establish the following conclusions:

(1) The hypothesis that pressure exerted by fresh concrete is equal to the hydrostatic pressure of a liquid with the same density of the mix is in general conservative for pumped concrete.
(2) Formwork shape had little influence on fresh concrete lateral pressure. For circular formwork the pressure is slightly higher than for square formwork. On the other hand, this parameter has a major influence on the initial rate of pressure decay. Smaller cross sections exhibit lower rate of pressure decay than larger ones.
(3) Formwork size is a significant factor in fresh concrete lateral pressure and in the initial rate of pressure decay. Small sections exhibit less pressure and lower rates of pressure decay than bigger ones.
(4) Coarse aggregate concentration presented little influence in lateral pressure and in the initial rate of pressure decay in the studied range. More tests will be needed to determine the behaviour of concrete with lower sand to total aggregate ratios.
(5) Concrete temperature has an inverse relationship with fresh concrete lateral pressure, and it is not a significant parameter. As no variation in concrete temperature was registered in the first hour after casting, the hydration process can be considered negligible. Therefore, concrete temperature can be considered as a non-significant parameter with respect to the initial rate of pressure decay.
(6) Concrete impact has very little influence on fresh concrete lateral pressure. In the two tests performed without impact, the pressure recorded was little less than in the test with impact.

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