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# Correlation between L-box test and rheological parameters of a homogeneous yield stress fluid

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**Abstract**

In this paper, a theoretical analysis of the L-box test is proposed in the case where no heterogeneity is induced by the flow. It is first demonstrated that if the standard procedure is followed and the L-box gate promptly lifted, the flow is dominated by inertia effects, depending on the lifting speed of the gate and thus on the operator. When the gate is slowly lifted, the flow and flow stoppage of a homogeneous yield stress fluid in a bounded channel are first studied. The obtained theoretical shape of the sample at stoppage is successfully correlated to the experimental results in the case of limestone powder suspensions. Then, the influence of steel bars was included in both the theoretical and the experimental study. Finally, practical applications of the present work to the case of real self-compacting concrete are suggested.


*Keywords:* Fresh concrete; Rheology; Workability; Yield stress

## 1. Introduction

The L-box test is used in many countries as an acceptance test for Self-Compacting Concretes (SCC). It displays all the phenomena that occur during concrete casting: it is a three-dimensional free surface flow of a non-Newtonian fluid between steel bars as obstacles. Moreover, the fact that the gap between the bars is of the same order as the largest particle makes the test sensitive to a possible dynamic segregation (as opposed to static segregation that is due to gravity). The result of the test thus depends both on the rheological behaviour of the concrete and on its capacity to stay homogeneous. That is why, despite the simplicity of the initial flow pattern (L-shape), the complexity of its analysis greatly increases because of the steel bars. The description of the tested concrete as a homogeneous "fluid" may prove wrong if the confined zone induces heterogeneity.

If the presence of the steel bars is for now left aside, the L-box test may be considered as the Cartesian version of the slump flow. Instead of lifting a mould, a gate is opened. Just like the slump test, a geometrical quantity is then measured to describe the shape at stoppage of the tested material. As for the slump test, it can be admitted that the flow stops when the shear stress in the tested sample becomes equal to or smaller than the yield stress (Schowalter and Christensen [1]). Consequently, the shape at stoppage is directly linked to the material yield stress. In the case of the slump test, several attempts to relate the measured slump to the tested material yield stress may be found in literature. Murata first established a relation between the final height of the cone and the yield stress [2]. Subsequent works established analogous relations either for conical (Schowalter and Christensen [1]) or cylindrical moulds (Pashias et al. [3]). These results were successfully validated by Clayton et al. [4] and Saak et al. [5] in the case of cylindrical moulds. Recently, Roussel et al. [6] proposed an analytical correlation between spread and yield stress of cement pastes for the ASTM mini cone test based on the work of Coussot et al. [7]. Roussel and Coussot [8] correlated the yield stress to the slump or the spread over a large range of yield stresses for any conical geometry. Moreover, they quantify the influence of secondary phenomena such as surface forces, inertia of the flow and initial shape of the cone on the meaningfulness of the test. The present work tries to reach the same two objectives in the case of the L-box test: to correlate the test result to physical parameters and to analyse the limitations of the test.

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In this paper, we will try to dissociate and isolate all the physical phenomena listed in the first paragraph (free surface flow and stoppage of a non-Newtonian fluid, influence of the steel bars, potential induced heterogeneity). First, the flow and flow stoppage of a homogeneous yield stress fluid in a semi-infinite channel will be studied; the studied area will then be bounded by an additional wall to obtain the standard L-box shape. The obtained theoretical solution will be compared to experimental results in the case of limestone powder suspensions. The effect of the steel bars will then be added to the analysis and experimentally measured in the case of limestone powder suspensions (homogeneous flow). Finally, practical applications of the present work in the case of real concrete are described.

It has to be noted that the theoretical approach proposed here is rigorously validated only in the case of fine particles suspensions. The reason why the approach proposed here is not compared to real SCC experimental measurements is because there is no concrete rheometer that gives an absolute value of the rheological parameters of the tested concrete [9,10]. Because of this limitation in the civil engineering community's ability to measure the rheological behaviour of SCC, the approach proposed here is validated on fine particles suspension suitable with traditional rheometry and then extrapolated to homogeneous concrete.

## 2. The L-box test

Two L-boxes were used in this research. They consist of a "chimney" section closed by a sliding gate and a "channel" section. The first L-box (standard one) had dimensions according to Fig. 1(a). The steel bars that were used in this work are shown in Fig. 1(b). The second one was 1.20 m long instead of 0.70 m. Once the test was completed, the height of concrete in the chimney was recorded as $h_1$ and the height of concrete at the opposite end of the channel was recorded as $h_2$. The L-box value (also referred to as the "L-box ratio", "blocking value", or "blocking ratio") is simply $h_2/h_1$. If the concrete is perfectly levelled at the end of the test, the L-box value is then equal to 1. Conversely, if the concrete is too stiff to reach the end of the channel, the L-box value is equal to 0. The regulations regarding acceptance L-box values in the case with steel bars vary from one country to another in the range of 0.60 to 1.

The procedure for running the L-box test is as follows [11]:

1. *Dampen all surfaces of the box that will be in contact with concrete.*
2. *Make sure that the gate is completely shut as to avoid premature flow of concrete through the L-box.*
3. *Continuously fill the vertical section of the L-box with a representative sample concrete.*
4. *Screed the concrete from the top of the box as to ensure the proper amount of concrete is within the apparatus.*
5. *Promptly lift the gate to allow flow of concrete.*
6. *Once the concrete has ceased flowing (no later than one minute after lifting the gate) measure the height of concrete at the "channel end" ($h_2$) and at the "chimney end" ($h_1$) to the nearest 1/2 in.*
7. *The L-box ratio is calculated as $h_2/h_1$.*

## 3. Theoretical analysis of the flow

### 3.1. SCC flow behaviour law

Any thixotropic aspect of the rheological behaviour is neglected in this work as the resting time between L-box filling and beginning of the test is short (about 1 min). The concrete does not have enough time to flocculate and develop an apparent yield stress [12]. The Bingham model is used here to describe the flow behaviour of the fresh concrete. It involves two parameters: the yield stress and the plastic viscosity. If the L-box test is representative of the rheological behaviour and if no segregation of the sample occurs, the test result should only depend on these two parameters. Moreover, as the L-box test is similar to the slump test, it can be expected that the final shape, if no segregation occurs, only depends on the yield stress. It is showed in this investigation that this is not the case if the standard procedure is followed. It should be noted that, as far as stoppage is concerned here, there is no point in discussing whether a Herschel–Bulkley model is more suitable than a Bingham model or so forth. Indeed, when flow is about to stop, the shear rate tends towards zero and the part of behaviour law concerned by the above discussion

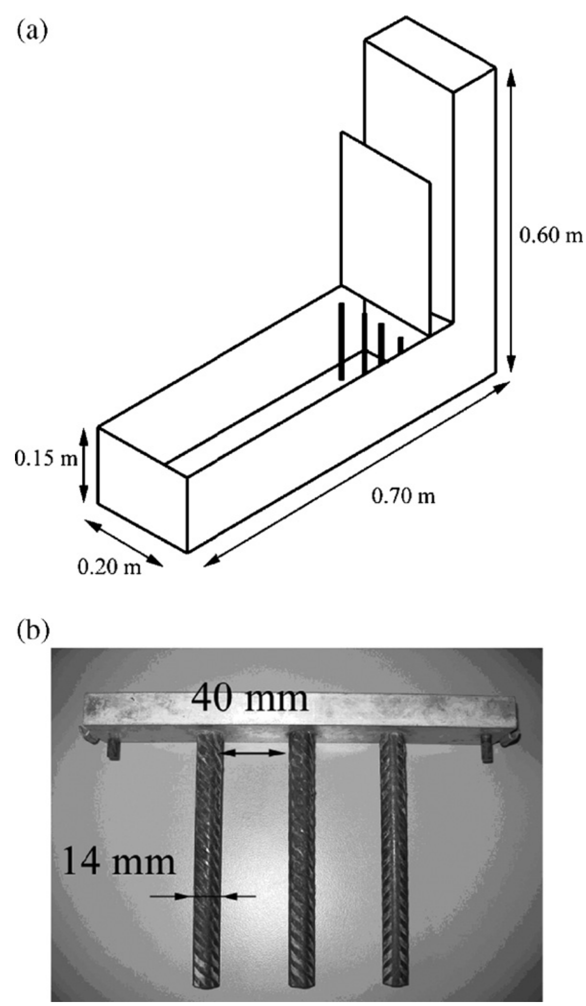


Fig. 1. The standard L-box geometry (a) and the steel bars (b).

vanishes. The important point here is that we are using a yield stress model.

## 3.2. Inertia effects and gate lifting rate

Two cases can be distinguished:

If the gate is lifted quickly (around 0.5 s to reach full opening [13]), the typical inertia stress is $\rho(v)^2 \cong 100$ Pa as the average flowing distance of the tested concrete is approximately equal to 0.8 m and the flow generally stops after no more than a few seconds. In this case, the order of magnitude of the average flowing velocity ($v$) may thus be estimated as 0.2 m/s. The typical inertia stress is then of the same order as the yield stress of the stiffest SCC [14]. The final shape of the sample is dictated of course by the yield stress but also by the kinetic energy of the flow that depends on the plastic viscosity and on the rate of gate lifting. Of course, as the rate of gate lifting does not vary much between two operators for these high lifting rates, this kinetic energy and thus the result of the test will mainly depend on the plastic viscosity of the tested concrete whereas the yield stress is the most interesting value when filling or passing ability is concerned. Moreover, this prevents any theoretical analysis and thus comprehension of the test without a proper measurement of the gate lifting speed combined with complex numerical simulations [14]. Finally, for low plastic viscosity concretes, a "wave phenomenon" can appear. In this case, the concrete will flow until the extreme end of the box and, because of its kinetic energy, will bounce back before stoppage. In this particular case, of course, the meaning of the test in terms of passing and filling ability of the tested material can be questioned.

If the gate is slowly lifted, the kinetic energy is spread over the gate lifting duration. Its value is low and does not play any role in the Navier–Stokes equations. The flow tends slowly towards stoppage. The lifting speed of the gate that influences the inertia effects does not matter, as inertia itself does not play any role. In this case, the rate of gate lifting is not a parameter of the test and the final shape will only depend on the yield stress. As a very rough approximation, it can be assumed that the inertia stress is reduced proportionally to the gate lifting duration. In order to reach an inertia stress that does not influence the quantification of the rheological behaviour, this stress has to be one order of magnitude lower than the yield stress itself. In the case of the SCC with the lowest yield stresses (20 Pa), this means that the lifting rate of the gate should be divided by 20. A critical low gate lifting duration is thus found around 10 s. Of course, in this case, it is very difficult to keep the same rate of lifting for such a low value but this does not matter as the kinetic energy, and hence, the inertia stress can be neglected in front of the yield stress as long as the gate lifting rate is lower than the above critical value.

In the following theoretical analysis, it will be considered that the gate is slowly lifted and that inertia effects are negligible. We will also consider this point in the experimental part of this paper.

## 3.3. Theoretical study of the flow stoppage

Close to the walls (bottom and lateral walls), the stress tensor simplifies and turns into a scalar: the shear stress. Moreover, when the flow stops, it is because the shear stress equals the yield stress in these zones. By writing the force equilibrium on the elementary volume in Fig. 2, one obtains

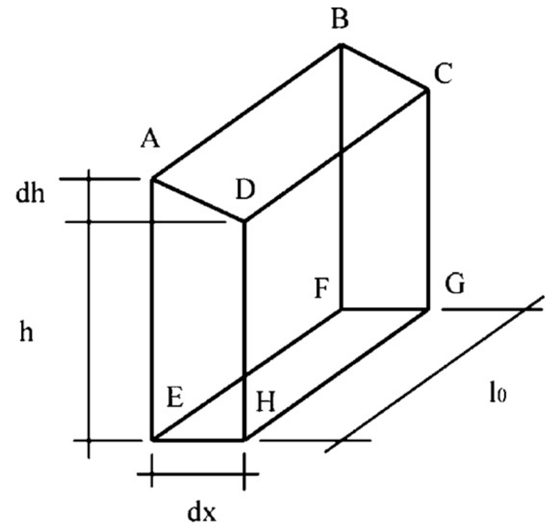


Fig. 2. An elementary volume in the sample at stoppage.

$$\left(\rho g l_0 \frac{(h+\mathrm{d}h)^2}{2}\right)_{ABFE} - \left(\rho g l_0 \frac{h^2}{2}\right)_{DCGH} + (\tau_0 l_0 \mathrm{d}x)_{EFGH} + (2\tau_0 h \mathrm{d}x)_{ADHE+BCGF} = 0 \quad (1)$$

By conserving only first order terms,

$$\rho g h \frac{\mathrm{d}h}{\mathrm{d}x} = -\tau_0 - 2\tau_0 \frac{h}{l_0} \quad (2)$$

By replacing $A = \dfrac{2\tau_0}{\rho g l_0}$ and $u = \dfrac{2h}{l_0}$, Eq. (2) becomes

$$\frac{u}{1+u}\frac{\mathrm{d}u}{\mathrm{d}x} = -\frac{2A}{l_0} \quad (3)$$

The solution of this differential equation is

$$h_0 - h + \frac{l_0}{2}\ln\left(\frac{l_0+2h}{l_0+2h_0}\right) = Ax \quad (4)$$

with $h_0$ the thickness of the deposit at $x=0$.

According to the volume and the yield stress of the tested material, two cases may occur as shown in Fig. 3(a) and (b).

It can be noted that, in the ideal 2D case (no influence of the lateral walls), Eq. (2) simplifies to

$$\rho g h \frac{\mathrm{d}h}{\mathrm{d}x} = -\tau_0 \quad (5)$$

This relation is similar to the one obtained in cylindrical coordinates for the spread flow of a given volume of a yield stress fluid [6–8].

**Case (a).** $L < L_0$

By writing that the total volume $V$ of the sample is equal to

$$V = l_0 \int_0^{h_0} x\mathrm{d}h = \frac{l_0^3}{4A}\left(\ln(l+u_0) + \frac{u_0(u_0-2)}{2}\right) \quad (6)$$

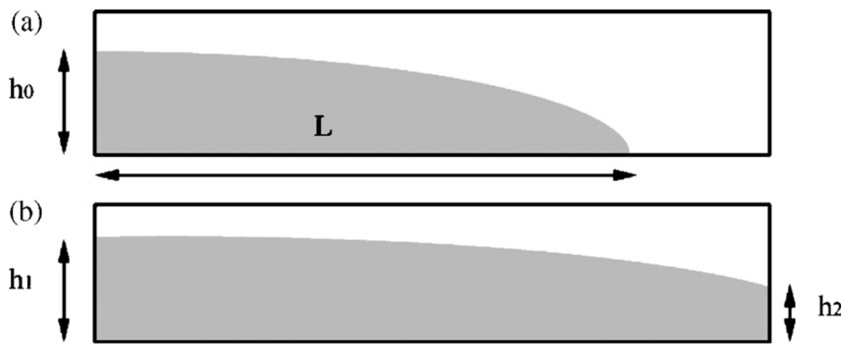


Fig. 3. The two possible cases in which Eq. (5) has to be solved. (a) L<L0; (b) L=L0 Traditional L-box test give deposit profiles similar to case (b).

with $u_0=2h_0/l_0$, Eq. (6) allows the computation of $h_0$ for a given tested volume $V$. The spread length may then be calculated using

$$L=\frac{h_0}{A}+\frac{l_0}{2A}\ln\left(\frac{l_0}{l_0+2h_0}\right) \quad (7)$$

This relation allows the prediction of $L$ (spread length) when the yield stress is known for a given fluid.

**Case (b).** $L=L_0$

To be rigorously correct, Eq. (4) is licit in this case only when $h_2 \ll l_0$. It is assumed here that this condition is fulfilled. In this case, the relation between the thicknesses ($h_1$ at $x=0$ and $h_2$ at $x=L_0$) of the deposit at the extreme sides of the box writes:

$$L_0=\frac{h_l-h_2}{A}+\frac{l_0}{2A}\ln\left(\frac{l_0+2h_2}{l_0+2h_1}\right) \quad (8)$$

By approximating the total volume sample $V$ by $l_0L_0(h_1+h_2)/2$ and introducing the ratio $r=h_2/h_1$ and the dimensionless volume $V'=V/(l_0^2L_0)$, the following dimensionless equation is obtained:

$$4V'\frac{l-r}{l+r}-\ln\left(\frac{l+r+4V'}{l+r+4rV'}\right)=\frac{2AL_0}{l_0} \quad (9)$$

This equation allows the prediction of the ratio $h_2/h_1$ for a given yield stress. It will be shown further in this paper that the approximation of the sample volume used here to obtain Eq. (9) is licit as, in the case ($L=L_0$), the thickness of the sample decreases almost linearly with $x$.

## 4. Experimental study

### 4.1. The studied materials

Suspensions of limestone powder ($P$) PIKETTY© and water ($W$) were prepared as testing homogenous yield stress fluids. The maximum particle size of these powders (100 μm) is largely smaller than the diameter of the steel bars (14 mm) or their spacing (40 mm). The solid volume fraction of the limestone powder suspension was varied between 0.71 and 0.75 ($P/W$ between 0.33 and 0.45) in order to produce mixtures with yield stresses between 15 and 150 Pa. This range covers the various yield stresses of SCC from the most fluid ones to the stiffest [13]. It has to be noted that the mixtures obtained with the lowest solid volume fractions were stable only for a couple hours. This was, however, sufficient to carry out our measurements without any perturbation from sedimentation phenomena. The specific gravity of these suspensions varied from 1.8 to 2.3 depending on their solid fractions.

### 4.2. Rheological measurements

The yield stresses of the limestone powder suspensions were determined independently using a HAAKE ViscoTester® VT550 equipped with a vane-type sensor (HAAKE FL10) and following the procedure described by Nguyen and Boger [15] with a rotation speed of 0.4 rad $\text{min}^{-1}$.

### 4.3. L-box test procedure

The standard procedure was strictly followed except that, in order to prevent inertia effects from dominating the flow and its

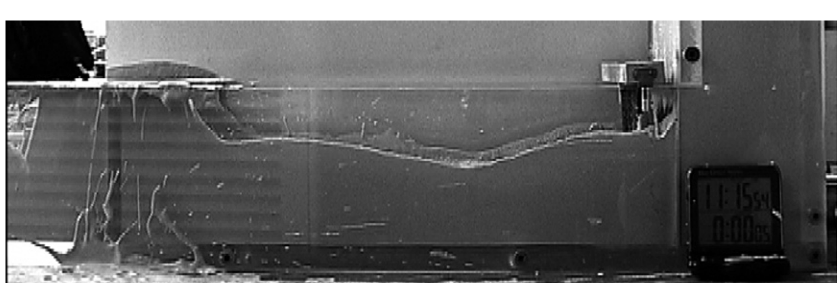


Fig. 4. Effect of inertia in the case of limestone powder suspension.

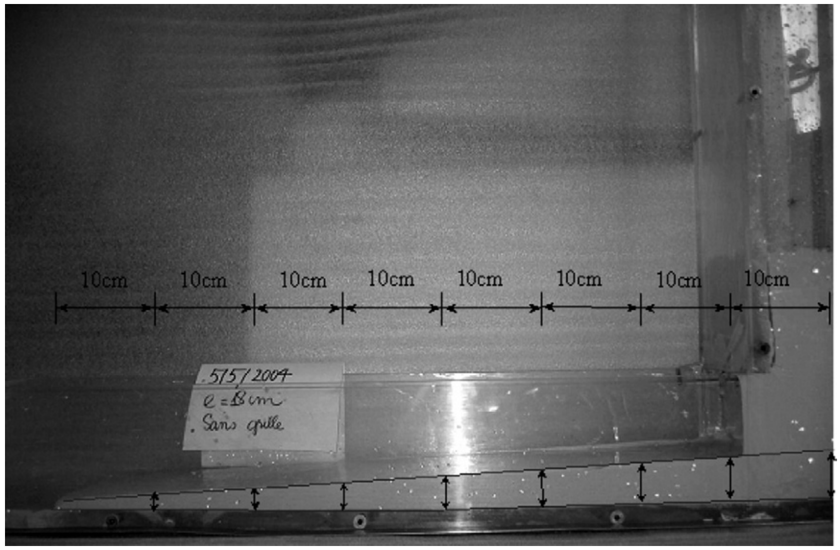


Fig. 5. Digital image processing example in the case of $L<L_0$.

stoppage, it was decided to lift the L-box gate slowly (1.5 cm/s). Anyway, this was mandatory in the case of the limestone powders suspensions because, if the gate was promptly opened, the induced wave could not be contained by the L-box (see Fig. 4). In the case of concrete, this wave phenomenon is not so obvious since the plastic viscosity is far higher and the initial very high kinetic energy of the flow is more quickly dissipated but, as discussed in Section 3.2, it anyway affects the final shape of the deposit. However, this wave phenomenon can even be detected in the case of very fluid SCC. The wave propagates when the gate is lifted and sometimes even "bounces" on the extreme wall. In these cases, the flow is dominated by inertia and no information on the casting ability of the SCC may be obtained as, during casting, the inertia of the flow will be far lower.

Two minutes after the apparent end of the flow, the thickness of the deposit was measured on the central axis every 10 cm using digital image processing as shown in Fig. 5. A photograph was taken through one of the lateral transparent walls and then pixels were counted to obtain the value of the thickness at a given position in the box.

### 4.4. Results and discussions

#### 4.4.1. L-box without bars

The tests were carried out on limestone powder suspensions of various solid fractions and thus various yield stresses. These tests were also carried out for various volumes. Some examples of measured profiles are plotted in Fig. 6(a) and (b). It has to be noted that these measurements were not easy to carry out as only small thickness variations between the two ends of the box were measurable for low and medium yield stresses. The uncertainty on these thickness variations was estimated to be ±4 mm according to the size of the local surface perturbations in the profile at stoppage. These local perturbations were rather high especially for the highest yield stresses. It can be noted that the thickness variation between the two ends of the box was almost linear with $x$ in the tests where $L=L_0$.

In order to compute the theoretical values, the yield stress was measured independently as described above. Moreover, the volume of the sample was calculated from the weight of material tested and its density. The theoretical model proposed here proves to be able to predict very precisely the final shape of the sample from its yield stress, density and tested volume. It is able to predict both the shape and the spread length $L$ in the case of $L<L_0$ using Eqs. (6) and (7). Likewise, it is able to predict the thickness of the sample at the end of the channel ($h_2$) using Eqs. (8) and (9) in the case of $L=L_0$. However, the thickness measured at $x=0$ is not predicted correctly by the model. In fact, the adhesion of the sample to the internal wall of the chimney generates a local increase of the sample thickness that can reach up to 5 mm in our test. However, this perturbation is less than the uncertainty indicated in the test procedure *"measure […] to the nearest 1/2 in."*

#### 4.4.2. L-box with bars

Bars were then placed in the L-box and carried out the same measurements as above but this time keeping the tested volume equal to the standard one (12.5 L) in the case $L<L_0$. The yield stress of the tested suspensions was varied between 15 and 150 Pa. A difference in thickness was systematically recorded due to the presence of the steel bars along the first 12 cm of the channel, as shown in Fig. 7.

This local difference in thickness increases with the yield stress of the tested suspension. In the yield stress range studied here, there seemed to be a linear relation between the thickness difference and the yield stress/density ratio (cf. Fig. 8). Knowing that, for a homogeneous Newtonian fluid (zero yield stress), the bars should not play any role and the thickness variation should thus be equal to zero, we fitted the experimental results to the following relation between the local thickness variation due to the bars and the yield stress:

$$\Delta h_{\text{bars}} = B\frac{\tau_0}{\rho g} \tag{10}$$

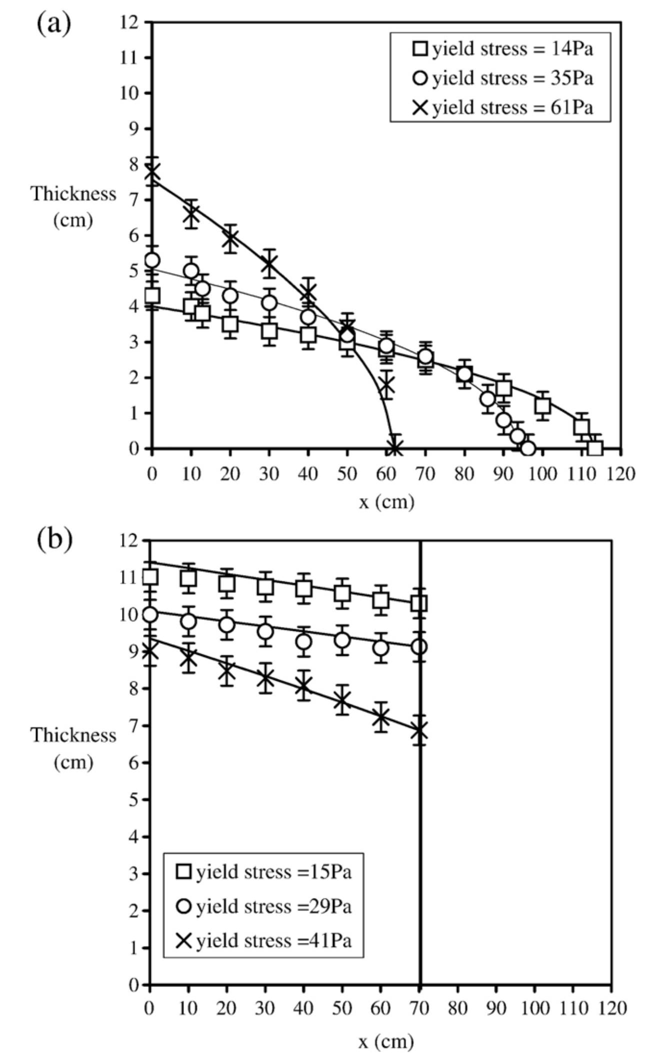


Fig. 6. Final sample shape for various yield stresses and tested volumes. Comparison between experimental measurements and theoretical prediction. (a) $L<L_0$, (b) $L=L_0$.

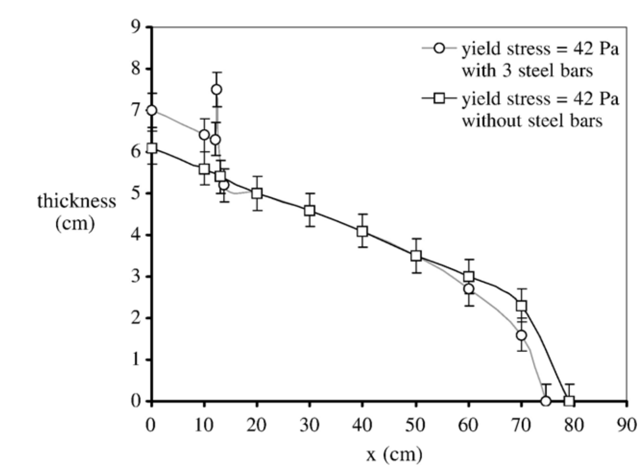


Fig. 7. Final sample shape with and without steel bars in the case $L<L_0$ for a limestone powder suspension with a yield stress of 42 Pa.

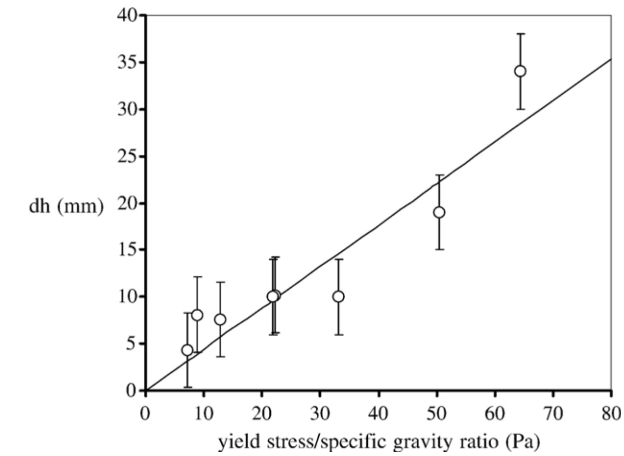


Fig. 8. Local sample thickness difference due to the presence of the steel bars as a function of the yield stress/specific gravity ratio. A linear relation is fitted to the experimental values.

with $\Delta h_{\mathrm{bars}}$ in m, $\tau_0$ in Pa, $\rho$ in kg m$^{-3}$, and $g$ in m s$^{-2}$, whereas B is dimensionless. From a theoretical point of view, this relation is not surprising. Indeed, the suspension thickness variation creates a local pressure gradient proportional to $\rho g \Delta h$. This pressure gradient generates a proportional shear stress between the bars. Flow stops when this shear stress is equal to the yield stress leading to Eq. (10). The coefficient $B$ is linked to the geometry of the obstacles, i.e., the diameter and the spacing of the bars in the L-box test. The value obtained for $B$ here was 4.4.

## 5. Practical use of the proposed approach

Without any further assumptions, Eq. (2) may be rewritten as

$$\frac{\mathrm{d}h}{\mathrm{d}x} = -\frac{\tau_0}{\rho g}\left(\frac{1}{h} + \frac{2}{l_0}\right) \qquad (11)$$

As already stated, in the case of $L=L_0$, the thickness variation between the two ends of the box is almost linear with $x$; therefore,

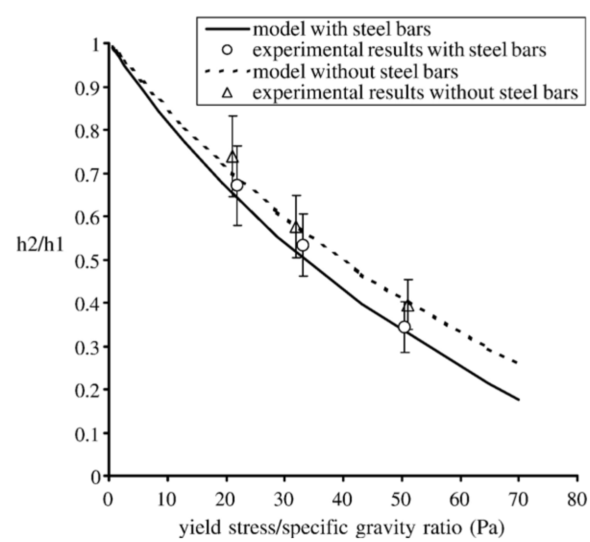


Fig. 9. Ratio $h_2/h_1$ as a function of the yield stress/specific gravity ratio in the case of the standard L-box with and without 3 steel bars when the gate is slowly lifted and when no segregation is induced by the flow.

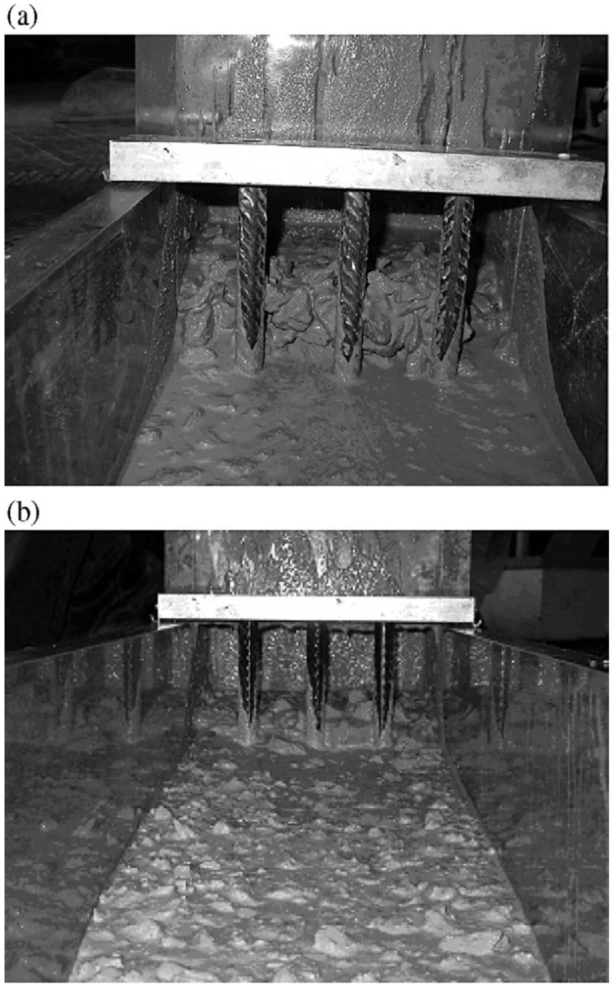


Fig. 10. L-box tests carried out on an unstable SCC (a) and on a stable SCC (b). If compared with tests performed without bars, the unstable SCC presented a 50% loss in the $h_2/h_1$ ratio, whereas the stable SCC presented no measurable differences.

$h$ in Eq. (11) may be approximated by its average value $h_{avg} = (h_1 + h_2)/2 = V/(l_0 L_0)$. The solution of Eq. (11) becomes

$$h_1 - h_2 = \frac{\tau_0 L_0}{\rho g}\left(\frac{l_0 L_0}{V} + \frac{2}{l_0}\right) \cong 15\frac{\tau_0}{\rho g} \text{ in the case without bars} \tag{12}$$

$$h_1 - h_2 = \frac{\tau_0 L_0}{\rho g}\left(\frac{l_0 L_0}{V} + \frac{2}{l_0}\right) + B\frac{\tau_0}{\rho g} \cong 18\frac{\tau_0}{\rho g} \text{ in the case with bars} \tag{13}$$

The direct application of the results presented here is the correlation between the standard $h_2/h_1$ ratio with the yield stress/density ratio, provided that the material stays homogeneous and the gate is slowly lifted. This ratio is equal to

$$\frac{h_2}{h_1} = \frac{2h_{avg} - (h_1 - h_2)}{2h_{avg} + (h_1 - h_2)} \cong \frac{\rho g - 84\tau_0}{\rho g + 84\tau_0} \text{ in the case without bars} \tag{14}$$

$$\frac{h_1}{h_2} = \frac{2h_{avg} - (h_1 - h_2)}{2h_{avg} + (h_1 - h_2)} \cong \frac{\rho g - 100\tau_0}{\rho g + 100\tau_0} \text{ in the case with bars} \tag{15}$$

These relations are plotted in Fig. 9. As already stated, these correlations cannot be validated in the case of concrete as there does not exist any concrete rheometer that gives an absolute value of the yield stress. However, as shown in Fig. 9, this correlation works well for fine particle suspensions.

In the range of yield stresses we are interested in (20–150 Pa), the difference between the cases with or without steel bars when the tested material stays homogeneous is very small, at least compared to the uncertainty of the measurements (see Fig. 9). This property could be used to quantify the segregation of a given concrete. By carrying out successively two L-box tests (one with steel bars and the other one without steel bars) on the same concrete, the difference, if any, between the two measured L-box values is linked to the segregation induced by the steel bars as shown by Fig. 10(a) and (b) and therefore to the ability of the tested concrete to stay homogeneous.

## 6. Conclusions

First of all, it has been emphasized that the L-box gate should be opened slowly instead of promptly. Otherwise the test result depends on a combination of intrinsic properties of the sample (yield stress, plastic viscosity, density) and external parameters (gate lifting rate for example). If the gate is lifted slowly, then the test result in the case of an homogeneous yield stress fluid only depends on its yield stress, which is the most important parameter when controlling whether or not a given concrete will fill a given formwork.

In the present work, all the physical phenomena that have an influence on the test result when the material stays homogeneous have been dissociated and studied (free surface flow of a yield stress fluid in a bounded domain with obstacles). A theoretical analysis of the flow and its stoppage has been proposed in the case of L-box without steel bars and an experimental quantification of the influence of the steel bars has been considered.

The final result is a relation linking the L-box value $h_2/h_1$ with the yield stress/specific gravity ratio when the material stays homogeneous and when the gate is slowly lifted. Knowing that the difference between the case with or without bars is small compared to the uncertainty of the test, carrying the two versions of the test (with and without steel bars) might allow the quantification of the ability of a tested SCC to stay homogeneous when cast.

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