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Steady and transient flow behaviour of fresh cement pastes

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Abstract

Fresh cement pastes behave as non-Newtonian viscous fluids. During steady flow, their apparent viscosity depends on the applied strain rate. During transient flow, the apparent viscosity is a function of time. In this work, a thixotropic model is presented. Its four parameters are identified experimentally for a tested cement paste using coaxial viscometer test. Viscometer flow simulations are then carried out. The model proves to be able to predict the trends of the fresh behaviour of cement pastes in various flow situations.

Keywords: Rheology; Cement paste; Thixotropy

1. Introduction

Cement-based suspensions, such as cement pastes and grouts, are colloidal suspensions consisting of fine particles dispersed in a liquid. Interactions among the particles may lead to microstructures formation in the suspension at rest. Depending on how the structure responds to an applied shear stress, one can observe different types of macroscopic flow behaviour, such as yield stress behaviour, thixotropy and visco-elasticity [1–3]. According to the "dictionnaire de Rhéologie" [4], shear thinning bodies are said to be thixotropic if (i) after a long rest when a shear stress or strain rate is applied suddenly and then held constant, the apparent viscosity is a diminishing function of the time of flow; (ii) the body recovers its initial state following a long enough interval after the cessation of the flow. This time-dependant decrease in the viscosity may be explained by a reversible change of the fluid microstructure during shear. In the absence of shear, the damaged structure rebuilds. Thus, yield stress or shear-thinning behaviour might be considered as a particular case of thixotropy where both structural breakdowns under shear and structure rebuilding take place simultaneously. Although it is still often considered as a single physical parameter of the fluid in the sake of simplicity [5,6], the yield stress as a true property of a suspension is one controversial subject. Numerous experimental methods coexist (Couette Viscometer test, Vane test, etc.) for different measurements (dynamic yield stress, static yield stress, equilibrium yield stress, etc.). Barnes [7–9] has gathered most of this literature.

A large number of experimental and theoretical studies of the rheological characteristics of fresh cement pastes have been published. In the case of steady state flow, several non-Newtonian models have been proposed and tested with success. However, in the case of transient flow, the attempts to quantify and predict the behaviour of cement pastes are not as numerous.

This paper is organised as follows: we start by reminding the existing literature about the steady state and transient behaviour of fresh cement pastes. Then, we present the thixotropic model used in this work. Its parameters are identified using experimental Couette viscometer results obtained for one cement paste. Finally, Couette viscometer simulations are carried out. They show the influence of the strain rate history on the shear stress/strain rate curve and are compared to experimental results.

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2. A thixotropic model

2.1. Literature study and proposed model

In this work, the aging phenomenon due to the hydration process will not be studied. Only the reversible part of the transient behaviour of cement pastes will be described using the proposed model.

2.1.1. Steady state

It is now accepted that the viscosity of cement pastes depends on strain rate. Shear thinning or shear thickening behaviours may be observed. Bingham or modified Bingham, Hershel Bulkley, Ellis, Casson or Eyring models are more or less suitable to describe steady state behaviour of fresh cements pastes. Atzeni et al. [10] tested these models on Portland cement pastes and concluded that Hershel Bulkley and Eyring models are as acceptable to describe the nonlinear strain rate/shear stress curve of cement pastes. Yahia and Khayat [11] studied the influence of the choice of one model in this list on the identification of a yield stress.

The viscosity of cement pastes may also depend on both strain rate and its application time. That is why thixotropic behaviour may be observed while studying the transient flow of fresh cement pastes.

2.1.2. Transient flow

For a constant shear rate, Lapasin et al. [12] measured the difference between the maximum shear stress τ_{max} needed to initiate flow and the equilibrium value τ_e at different viscometer rotating speeds. A logarithmic evolution of the shear stress was obtained.

$$\tau = \tau_e(\tau_{max} - \tau_e)\exp(-Bt) \quad (1)$$

with B a constant depending on the viscometer rotating speed. The thixotropic behaviour was quantitatively characterised by the authors by the area between the maximum shear stress and the equilibrium shear stress in the shear stress–rotating speed diagram. The authors demonstrated a link between the thixotropic behaviour and the specific surface of the cement powder. Otsubo et al. [13] studied the time dependence of the apparent viscosity of cement pastes submitted to a constant shear rate after a rest period of 1 min. In a first phase, the apparent viscosity decreases with time until it reaches a minimum. Then it starts to increase. The authors using these minimum shear stress values plotted the steady state flow curve. They stated that the behaviour once this minimum is reached is rheopectic but they did not check that the viscosity increase was reversible. Indeed, if the measured phenomenon was due to aging or hydration process, it was not reversible and as such could not be characterised as rheopexy. In fact, other authors [12,14] demonstrated that the first phase is dominated by a destructuration phenomenon under constant shear rate (thixotropic behaviour). Once this phenomenon has reached equilibrium, the behaviour keeps on evolving because of the hydration process. This second phenomenon is not reversible. Geiker et al. [15] studied recently the characteristic time or relaxation period needed to reach steady state in the case of concrete. Concrete, of course, containing thixotropic cement paste, displays also thixotropic behaviour. For the tested concrete, for the apparatus used and for the studied strain rates, they found that this relaxation time was about 10 s.

2.1.3. Hysteresis loop

Flow curves are usually obtained by applying a succession of constant strain rates for short times. Shauhgnessy and Clark [16] or Atzeni et al. [10] pointed out that the shape of the hysteresis loop is directly related to the experimental duration of the measuring cycle. In fact, if the strain rate is applied for a time shorter than the relaxation period, steady state is not reached. If the flocculation in the sample is higher than the equilibrium state of flocculation, the measured shear stress is higher than the equilibrium shear stress. The measured flow curve is then above the equilibrium flow curve. The deflocculation process does not have enough time to bring the structure to its equilibrium state. On the other hand, if the flocculation in the sample is lower than the equilibrium state of flocculation, the structure rebuilding process does not have enough time to bring the structure to its equilibrium state and the measured flow curve is below the equilibrium flow curve as shown on Fig. 1(a). For very long measurement cycles as demonstrated by Banfill and Saunders [14], the hydration process and the long-term increase in viscosity perturb the previous patterns and hysteresis loops similar to the one on Fig. 1(b) may be obtained.

2.1.4. Structuration at rest

Thixotropy is by definition a reversible phenomenon. If a cement paste is left at rest, its flocculation will increase. This flocculation is however reversible by mixing the sample strongly enough. This is not the case with aging phenomena. These phenomena affect in an irreversible way the rheological behaviour.

The thixometer is an apparatus developed by Kalousek [17]. It allows the measurement of both the thixotropic behaviour and the paste aging effects. A first set of test is carried out on vibrated samples. This imposed vibration of the sample prevents the sample from flocculating. A second set is carried out on properly resting samples. The load needed to initiate flow is measured in both sets for several resting times. The load needed to “break” the flocculation is higher than the load needed to initiate flow in the vibrated samples. This relative difference increases with the resting time. This thixometer is an interesting way to quantify the structuration regime and to separate it from the aging phenomenon. However, because of the complex shape of the rotating apparatus generating the flow, it is not possible to link the measured load with any intrinsic properties such

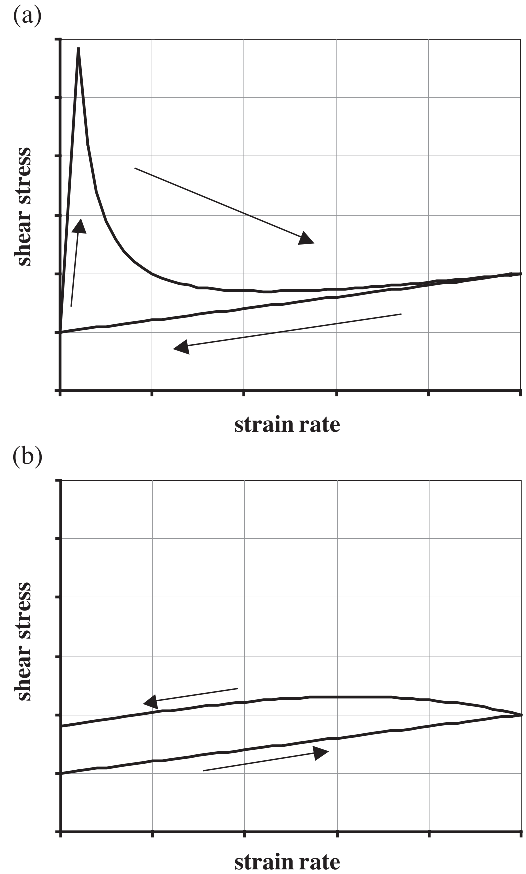

Fig. 1. Cement paste flow curves: (a) Short cycle test; steady state is not reached. (b) Long cycle test; steady state is reached but the fresh behaviour is irreversibly changing because of the hydration process.

as apparent viscosity or with the τ_{max} value measured by Lapasin et al. [12].

2.1.5. Existing models

Cheng and Evans [18] suggested a general mathematical form of the equation of state of a thixotropic material. The following relation links the shear stress to the shear rate:

$$\tau = \eta(\lambda, \dot{\gamma})\dot{\gamma} \tag{2a}$$

An evolution equation is added where λ is a structural parameter related to the flocculation level inside the material.

$$\frac{\mathrm{d}\lambda}{\mathrm{d}t} = f(\lambda, \dot{\gamma}) \tag{2b}$$

Papo [19] derived from these ideas and his own experimental data a rather complete constitutive equation. The steady state model adopted by Papo is the Casson model.

$$\tau = \tau_{00} + \eta_{\infty}\dot{\gamma} + 2(\tau_{00}\eta_{\infty}\dot{\gamma})\frac{1}{2} + \left[(\tau_{01} - \tau_{00}) + 2(\eta_{\infty}\dot{\gamma})\frac{1}{2}\left(\tau_{01}\frac{1}{2} - \tau_{00}\frac{1}{2}\right)\right]\exp(-k_b t) \tag{3}$$

where η_{α} is the viscosity at infinite shear rate, k_b is the constant rate of deflocculation, τ_{00} and τ_{01} are, respectively, the steady state yield stress and the initial yield tress. The deflocculation rate is assumed not to depend on the strain rate. The structural rebuilding process is neglected compared to the deflocculation phenomenon. In the opinion of the present author, this is a valid assumption only if the studied characteristic time is the duration of a cycle during a viscometric test.

This model involves four parameters. It is only one more than a Hershel Bulkley model, for instance, that only predicts steady state flow. However, this model does not predict the structuration at rest when the strain rate is equal to zero. τ_{01} cannot be predicted in term of resting time and has to be fitted.

The interest of the recent approach developed by Wallevik [20] is that it is derived from a rather complete physical description of the flocculation and dispersion of the cement grains. It is demonstrated that using these mechanisms, the steady state and transient behaviour of fresh cement pastes can be mathematically described. Instead of using an evolution equation of a structure parameter, fading memory integrals are used to take into account the flow history. However, the five parameters of this model have to be fitted using numerical simulations. This model does not predict the flocculation at rest either.

The model used in this work is based on the same assumptions as Cheng and Evans [18]. The basic added proposal consists in considering that the rate of change of λ is equal to the sum of a "natural" material restructuration term and a rate of destructuration due to flow, which is proportional to the rate of shear and to the flocculation state. The model of Coussot et al. [21] uses these simple basic ideas to predict the shear stress. In this phenomenological model, the apparent viscosity is an increasing function of the structure parameter λ or "degree of jamming".

$$\tau = \mu_0(1 + \lambda^n)\dot{\gamma} \tag{4a}$$

$$\frac{\partial\lambda}{\partial t} = \frac{1}{T} - \alpha\lambda\dot{\gamma} \tag{4b}$$

where μ_0 is the viscosity at infinite shear rate when λ tends towards zero, n is a constant positive parameter, $1/T$ is the flocculation term and the second term in Eq. (4b) can be associated with the deflocculation rate. This model has been used with success to model bentonite flow in a Couette viscometer with a large gap [22]. The local predictions of the model were then compared with success to RMI measurements. One may note that there is no explicit yield tress in this model. However, when the strain rate tends towards zero, the apparent viscosity increases just as any shear-thinning model as it will be shown in the next section.

This model has several advantages:

It predicts flocculation at rest. This should allow the prediction of τ_{max} in terms of the resting time.

It describes the deflocculation phenomenon under an applied strain rate (constant or variable in time).
It describes steady state as an equilibrium between deflocculation and flocculation phenomena.
The number of parameters is low (only one more parameter than most models only describing steady state behaviour). As it will be shown in Section 2.2., three of the parameters can be easily identified using classical viscometric tests. This makes this model suitable for a practical use.
It is easy to implement in numerical simulations. As no yield stress is involved, no mathematical discontinuity appears in the calculations.

It has however several drawbacks:

As it will be shown in Section 3.2., the model is not able to predict quantitatively the structuration state for resting time longer than 1 min.
The proposed model does not have the ambition of predicting the global behaviour in terms of the local interactions between cement particles or mix fitting. It is a phenomenological model.
As already stated, this model does not either predict any aging phenomenon or the influence of the hydration process. It only deals with the reversible part of the evolution of the viscosity.

2.2. Steady state flow

In steady state,

$$\frac{\partial \lambda}{\partial t} = 0 \tag{5}$$

Eq. (4b) gives:

$$\lambda = \frac{1}{\alpha T \dot{\gamma}} \tag{6}$$

Eq. (4a) becomes

$$\tau = \mu_0 \dot{\gamma}(1 + a^n \dot{\gamma}^{-n}) \tag{7}$$

with

$$a = \frac{1}{\alpha T} \tag{8}$$

The apparent viscosity becomes:

$$\mu = \frac{\tau}{\dot{\gamma}} = \mu_0(1 + a^n \dot{\gamma}^{-n}) \tag{9}$$

As the parameter n is positive, the apparent viscosity tends towards μ_0 when the strain rate becomes infinite and it tends to infinity when the strain rate tends towards zero. As a consequence, if the strain rate/shear stress curve is measured in steady state for a given cement paste and for high strain rates, the parameter μ_0 may then be identified for the tested material. A derivation of Eq. (9) according to the strain rate writes:

$$\frac{\partial \mu}{\partial \dot{\gamma}} = -\mathrm{na}^n \mu_0 \dot{\gamma}^{-n-1} \tag{10}$$

The viscosity derivative follows a power law in terms of the strain rate. This viscosity derivative may be calculated from the experimental flow curve measurements using a centred finite differences approximation. A power law function can then be fitted. Knowing μ_0 from the previous step, a and n can be identified.

2.3. Transient flow and characteristic time

As noticed by Saak et al. [6], the time scale of the measurement is much longer at low rotational speeds. Using Eqs. (4a) and (4b), it can be demonstrated that the evolution of λ in time for a constant applied strain rate and for an initial lambda value equal to λ_0 follows:

$$\lambda(t) = \frac{a}{\dot{\gamma}} + \left(\lambda_0 - \frac{a}{\dot{\gamma}}\right)\exp\left(-\frac{\dot{\gamma}t}{aT}\right) \tag{11}$$

The characteristic time t_c of this evolution decreases with the strain rate and may reach very high values for low strain rates. In these cases, steady state may become very difficult to reach.

$$t_c = \frac{aT}{\dot{\gamma}} = \frac{1}{\alpha \dot{\gamma}} \tag{12}$$

The three parameters identified in Section 2.2. were sufficient to describe steady state flow. It can be seen in Eq. (11) that the last of the four model parameters (either α or T) is needed to describe transient flow.

2.4. Structuration at rest

The evolution of the structuration state at rest is given by Eq. (4b) when the strain rate is equal to zero.

$$\frac{\partial \lambda}{\partial t} = \frac{1}{T} \tag{13}$$

After integration:

$$\lambda = \frac{t}{T} + \lambda_0 \tag{14}$$

where λ_0 is the initial lambda value.

3. Experimental material and tests

3.1. The tested cement paste and the viscometer

Its mix fitting is given in Table 1 with E/(C+SF)=0.27. The behaviour is studied using a coaxial viscometer (HAAKE ViscoTester® VT550). Shaughnessy and Clark [16] made an extensive review of the problems and methods

Table 1
Tested cement paste composition

Component	kg/m^3
Cement H.T.S. (class A)	1500
Silica fume S.E.P.R.	150
Superplasticizer Glenium B201 F	3
Viscosity agent Collaxim L4	1.5
Water	445

involved in the study of rheological properties of fresh cement pastes using this type of viscometer. Lapasin et al. [23] focused on several measuring procedures and their influences on the measured flow curves.

The torque C and the rotational speed Ω are measured through the test. The inner radius R_i is 18.9 mm and the outer radius R_e is 20.5 mm. The associated gap is $e=R_e-R_i=1.6$ mm. Fine sand paper is glued on both cylinders to prevent any slipping from occurring.

Before each steady state test and before any resting phase, a 100 s^{-1} strain rate is applied for 200 s.

3.2. Parameters identification in steady state

It is assumed in this study that the entire gap is sheared and that the sample stays homogeneous. Moreover, it is assumed that no slipping occurs at the interface between the rough cylinders and the sample.

It should be noted first that, for our tested cement paste, it is difficult to reach steady state for low strain rate (<5 s^{-1}) with a standard measurement time of 10 or 20 s. The measured torque keeps on decreasing if the tested cement paste was at rest before the test or increasing if the tested cement was submitted to a preshearing phase. This is in agreement with the proposed model. If the cement paste was at rest before the test, the value of the structure parameter λ is rather high. For a given applied strain, the corresponding steady state λ value is then smaller than the initial λ value. λ has to decrease to reach the steady state value given by Eq. (6) and the apparent viscosity decreases through the test. On the other hand, if the cement paste was submitted to a preshearing phase, the initial λ value is smaller than the steady state λ value. Therefore, λ and the apparent viscosity increase with time.

In order to reduce the impact of the pretest flow history on the measurements, several experimental procedures were tested. Finally, a strain rate equal to 100 s^{-1} is first applied for 200 s; then, the strain rate is increased logarithmically from 0.15 to 100 s^{-1} with 14 measurement points. The conditions to increase the strain rate to the next level are the following: either the measured torque is stabilised, either the maximum duration of a step (50 s) is reached. The obtained results are plotted on Fig. 2. The apparent viscosity is plotted in terms of the strain rate on Fig. 3. The parameter μ_0 may then be identified keeping in mind that the apparent

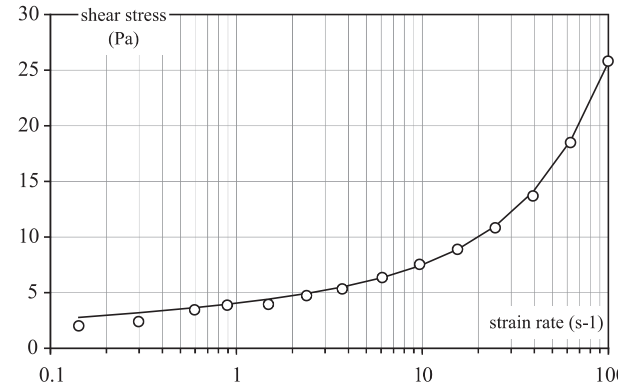

Fig. 2. The tested cement pastes flow curve in steady state obtained with the coaxial cylinders test. Comparison between experimental results and the fitted model.

viscosity tends towards μ_0 when the strain rate tends to infinity. $\mu_0=0.17$ Pa s is obtained. The derivative of the apparent viscosity in term of the strain rate is calculated from the experimental results and is plotted on Fig. 4. The two lowest strain rate values are not plotted as steady state seems not to be reached for these low rotation speeds. We will come back on this point in Section 4. The n and a parameter values may then be identified using Eq. (10) and a power law regression of the experimental curve.

$n=0.82$
$a=44$

The model prediction and the experimental results for steady state can be compared on Fig. 2. Three parameters are fitted in steady state. $\mu_0=0.17$ Pa s, $n=0.82$ and $a=44$. One last parameter, either α or T, has to be identified in a nonsteady state.

3.3. Transient flow

The studied transient flow is obtained by applying a strain rate equal to 0.5 s^{-1} to the sample. The obtained results are similar to the ones obtained with a Vane test. They can be divided into several phases [24]. The first phase

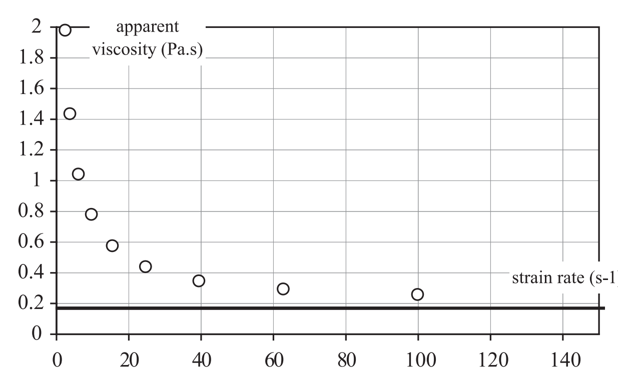

Fig. 3. The apparent viscosity tends towards 0.17 Pa s when the strain rate tends to infinity.

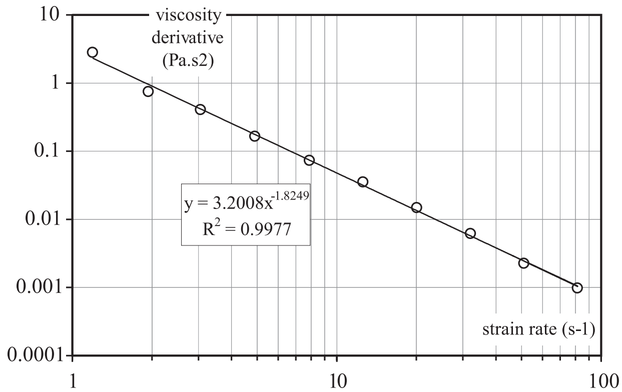

Fig. 4. Derivative of the apparent viscosity in terms of the strain rate. Identification of the values of the n and a parameters by a power law regression.

is a linear increase in stress. It is followed by a break from linearity after reaching a peak. An equilibrium stress is reached at the end of the test. This final equilibrium stress corresponds to a steady state regime.

Four tests are carried on the prepared cement paste with varying resting time between mixing and testing (0, 300, 600 and 1800 s). All the tests tend towards the same steady state no matter what the resting time before the test is. However, for the 30-min (1800-s) resting time, there seems to be an aging effect and the steady state stress is higher (Fig. 5). The effect of the hydration process described by Shaughnessy and Clark [16], Otsubo et al. [13] and Banfill and Saunders [14] explains this increase in viscosity. The behaviour after 30 min is irreversibly changing. The proposed model is not able to predict this phenomenon. The time needed to reach the steady state increases with the rest time. This is in accordance with the model as the value of the structure parameter λ at the beginning of the test

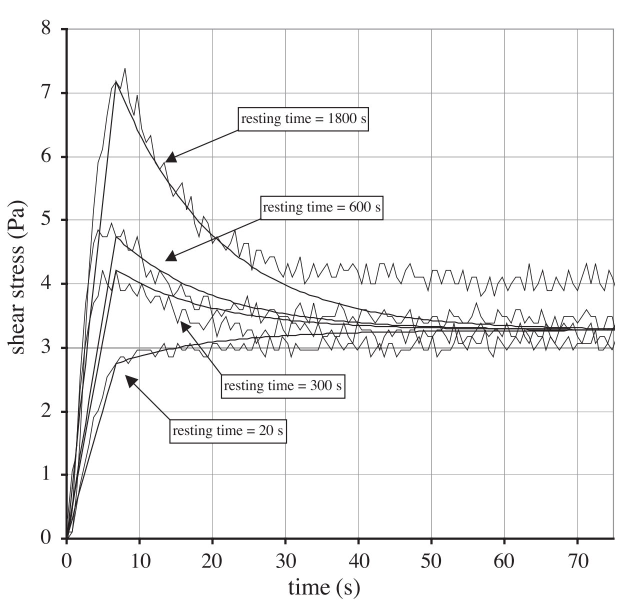

Fig. 5. Measured and predicted shear stress as a function of time for different resting times. α=0.15.

increases with the rest time whereas the steady state λ value to be reached stays the same. Therefore, the time needed for λ to decrease from its initial value to the steady state value increases.

The model predicts the measured stress in steady state. The initial λ value for each test is calculated at the end of the linear phase, which coincides more or less with the beginning of the destructuration. This peak appears at $t \cong 7$ s. As the rotation speed is the same for the four tests, it seems that this peak could be associated with a maximum deformation before destructuration starts. The parameter α is fitted on the 300-s resting time curve so that the predicted and experimental curve reach the steady state in the same amount of time (about 20 s). All the model parameters are then known.

μ_0=0.17 Pa · s
n=0.82
α=0.15
T=0.154 s

The characteristic time t_c for this strain rate can be calculated using Eq. (10). It is equal to 13 s. Results for the other resting times are calculated and plotted on Fig. 5. The model is able to predict the measured stress through the test as a function of time with a good agreement on a qualitative and quantitative point of view.

3.4. Structuration at rest

On Fig. 6, the measured apparent viscosity is compared to the predicted apparent viscosity calculated using Eq. (14). The comparison stands for short resting times but quickly, a major discrepancy can be observed. The model is able to predict the structuration trend but not to quantify it for resting times longer than 1 min. This limit was already observed when applying the model to bentonite flows [22].

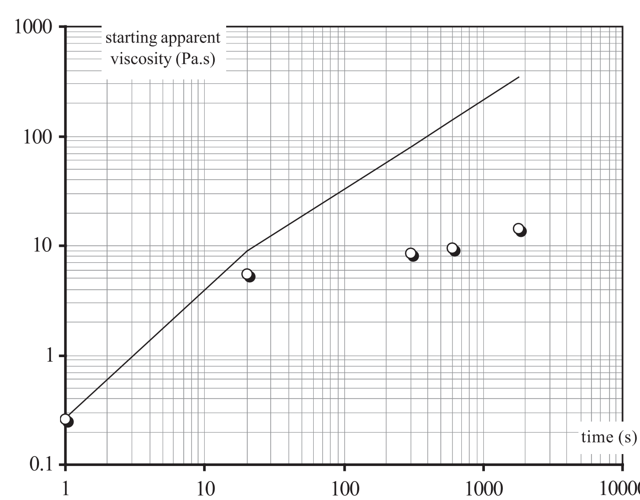

Fig. 6. Starting apparent viscosity in terms of the resting time. Comparison between experimental measurements and model predictions. A major discrepancy appears for resting times longer than 1 min.

In fact, the rate of structuration at rest seems to decrease with the state of structuration itself. To take this into account, Eqs. (4a) and (4b) may be modified by introducing a fifth parameter m:

$$\tau = \mu_0(1 + \lambda^n)\dot{\gamma} \tag{15a}$$

$$\frac{\partial \lambda}{\partial t} = \frac{1}{T\lambda^m} - \alpha\lambda\dot{\gamma} \tag{15b}$$

However, for short-term observations or flowing materials (low values of the structure parameter λ), the value of 1/ T obtained in the previous sections is a correct approximation of a more complex behaviour.

4. Consequences on coaxial viscometer tests

Steady state must be reached in order to measure a behaviour that does not depend on the initial state of flocculation of the tested cement paste but measurement time scale appears to be much longer at low rotational speeds. The evolution characteristic time t_c given by Eq. (12) decreases with the strain rate. It may reach several hundreds of seconds for cement pastes submitted to low strain rates. In those cases, the measured torque/rotational speed before steady state is not a meaningful information as it depends mainly on the flow history.

In this section, simulations are carried out to predict the response of the studied cement paste to the step-by-step procedure shown on Fig. 7. Every 4 s, the strain rate is logarithmically increased from an initial value of 0.1 s^{-1} to a final value of 100 s^{-1}. On an experimental point of view, the torque measurement occurs at the end of each 4-s step. Using Eq. (11) with the parameters identified in Section 3.2 and 3.3, the evolution of the shear stress in term of time is simulated. The obtained results are given in Fig. 8. These simulations are very similar to the ones obtained by Wallevik [20]. The predicted shear stress at the end of each strain rate steps is plotted on Fig. 9(b). The corresponding experimental values are plotted on Fig. 9(a). On a quantitative point of view, the comparison is poor in the low strain rates range but the present thixotropy model qualitatively describes the main phenomenon. Moreover, steady state is reached in less than 4 s if the strain rate is

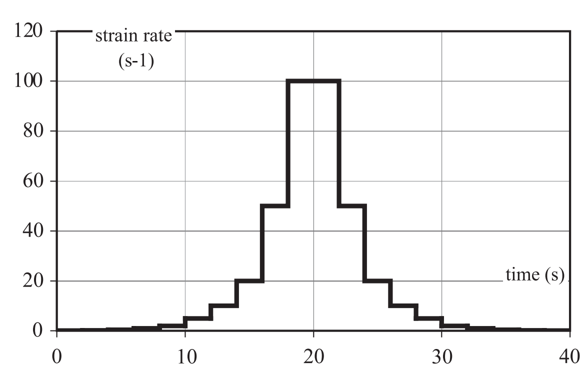

Fig. 7. Studied strain rate history in the coaxial viscometer. Every 4 s, the strain rate is increased from an initial value of 0.1 s^{-1} to a final value of 100 s^{-1}.

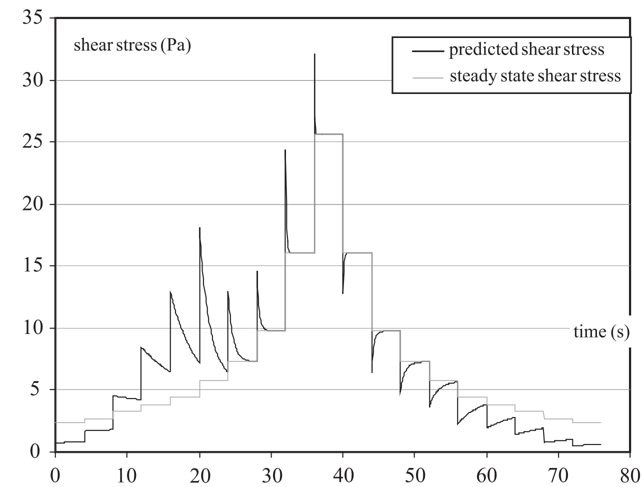

Fig. 8. Evolution of the shear stress in terms of time. dλ/dt is small for small strain rates and a long time is needed to reach steady state. On the other hand, for higher strain rates, the steady state is immediately reached.

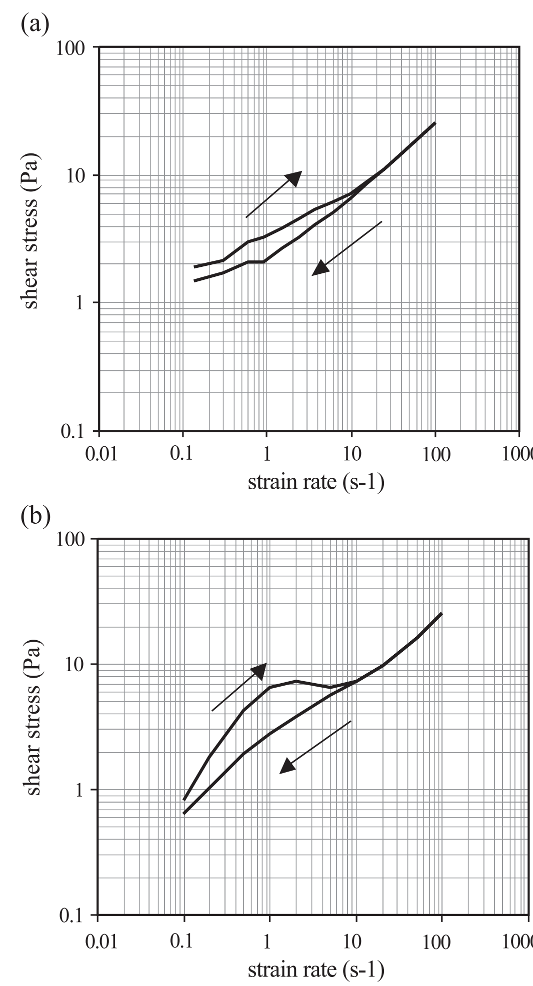

Fig. 9. Measured shear stress at the end of each strain rate step. (a) Experimental values; (b) Simulated values.

higher than 10 s^{-1} for both measured and predicted curves. As a consequence, predicted shear stress and steady state shear stress cannot be dissociated on Fig. 8. Both increasing and decreasing strain rate curve do depend on flow history for low strain rates. As a consequence, using one or the other to study the cement paste behaviour does not seem licit. However, the decreasing strain rate flow curve, at least, does not depend on the pretest history since this one was erased by the high strain rates reached at the peak of the rotating speed. For these high strain rates, the structure state λ reached a value that did not depend on the previous flow history and an eventual resting time before testing. This value only depended on the fresh rheological behaviour of the tested material.

5. Summary and conclusions

The time- and strain-rate-dependant apparent viscosity of a cement paste was experimentally and theoretically analysed. The reversible change of the cement paste microstructure during shear was studied using a thixotropy model describing the evolution of a structure parameter λ.

First of all, as already known, in the absence of shear, the cement paste structure rebuilds. The measured peak shear stress increases with the rest time.

When flowing, the model proposed here allows, as does, for instance, a Hershel Bulkley model, the prediction of the steady state with three steady state parameters that can easily be identified but the present model proved its additional interest in simulating flow properties in different flow conditions and flow history (coaxial viscometer with different cycle duration with or without rest). Although the quantitative results are not yet always accurate in nonsteady state, this model gives valuable qualitative predictions on cement pastes' flow start and stop. The interest of this work is also to show that using a four-parameter (μ_0, α, T and n) model instead of a three-parameter Hershel Bulkley model allows the prediction of both steady state and transient flows.

This is a first attempt to quantify the effect of the thixotropy of cement pastes in several flow conditions. The number of parameters of the proposed model was kept minimum in order to test a model of practical use in the industry. However, there appears limitation due to this low number of parameters, such as the quantitative prediction of the structuration state at rest. This could be improved by using the more complex model proposed in Section 3.4.

In future work, simulations will be performed for more complex flow and flow histories and the model parameters dependence on mix fitting will be studied.

Notations

- C Measured torque during a viscometer test.
- Ω Imposed rotation speed during a viscometer test.
- μ_0 Thixotropy model parameter. Viscosity at infinite strain rate.
- α Thixotropy model parameter relative to the rate of deflocculation.
- T Thixotropy model parameter relative to the rate of flocculation.
- n Thixotropy model parameter relative to the steady state behaviour.
- m Thixotropy model parameter.
- a Thixotropy model intermediate parameter.
- λ Structure parameter or flocculation state or "degree of jamming".
- t_c Characteristic evolution time of flocculation state λ for a constant applied strain rate.

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