# STRUCTURAL BUILD-UP OF RIGID FIBER REINFORCED CEMENT-BASED MATERIALS

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**Abstract:**

The structural build-up of rigid fiber reinforced cement-based materials is studied. It has recently been shown that the behaviour of fiber reinforced concrete depends on the orientation of the fibers that has to be optimized during casting. As a result, there is a great interest to study the rheology of fiber reinforced concrete. One of the most important characteristic of modern fresh concretes is the structural build-up which is involved in many recent issues of concrete casting. This characteristic depends on the cement pastes chemical activity. This present work shows that structural build-up modelling used for common concretes can be generalized to fiber reinforced concretes. It can be shown that, if the inclusions percolation threshold is not reached, the structural build-up rate $A_{thix}$ is amplified by the addition of fibers and aggregates. Finally, this amplification of the structuration is estimated using modelling initially developed for spherical inclusions and aggregates.

## 1 Introduction

Reinforcing concrete with steel fibers improves the mechanical behaviour of the concrete in different ways. It explains why steel fibers reinforced concrete has been the subject of numerous studies in the past recent years (Altun et al. 2007; Ferrara et al. 2007; di Prisco et al. 2009; Rokugo et al. 2009; Tokgoz 2009; Walraven 2009; Wang et al. 2010; Kovler and Roussel 2011). Steel fibers are known to improve the ductility, the tensile behaviour and the resistance to cracking of concrete (Wille et al. 2012; Ferrara et al. 2007; Pujadas et al. 2012; Colombo et al. 2010; Ferrara et al. 2011). It has also been showed that steel fibers increase the flexural strength and hence that steel fibers can be seen as a partial or total alternative to common steel rebars (Katzer and Domski 2012; Michels et al. 2012).

Many researchers have pointed out that the efficiency of the steel fibers reinforcement depends on their dispersion and orientation (Boulekbache et al. 2010; Kang and Kim 2011; Boulekbache et al. 2012). As example, tensile and shear strengths are largely influenced by the fibers orientation.

Consequently, recent researches have focused on the monitoring of the fibers orientation in order to optimize the aimed mechanical behaviour using two main techniques. The first one consists in using magnetic fields to monitor the fibers orientation (Ferrara et al. 2012a; Ferrara et al. 2012b; Torrents et al. 2012). The second one consists in a flow-induced orientation of the fibers (Boulekbache et al. 2010; Martinie and Roussel 2011; Boulekbache et al. 2012). For the second technique, the material rheological behaviour description is required in order to predict the fibers orientation (Martinie et al. 2010; Martinie and Roussel 2011; Laranjeira et al. 2012; Laranjeira et al. 2011).

Rheology of steel fibers reinforced concrete has already been studied by many researchers (Kaufmann et al. 2006; Kuder et al. 2007; Wallevik 2009; Martinie et al. 2010; Martinie and

Roussel 2011). Martinie et al. (2010) provides a classification of the fiber stiffness according to the concrete yield stress. They also shows that steel fibers can be considered as rigid if the deformation of the fibers due to shearing remains negligible in front of the fiber length. For such rigid fibers, the authors show that the concrete yield stress depends on a relative packing which depends on the aggregate volume fraction, fiber aspect ratio r (ratio of the fiber length $l_f$ over the fiber diameter $d_f$) and fiber volume fraction. Such approach provides a simple and efficient tool that can be very helpful for mix-design.

However those studies do not focus on the time-dependent behaviour of the concrete (Lapasin et al. 1979; Roussel 2005, 2006; Wallevik 2009). Lapasin et al. have shown that the cement-based pastes are thixotropic (Lapasin et al. 1979). Roussel and co-workers have shown that rheological behaviour of the cement paste at rest exhibits a structural build-up that leads to a linear increase of the yield stress (Roussel 2005, 2006). This behaviour is due to reversible grains nucleation by CSH formation at the grains contact points (Roussel et al. 2012). The structural build-up rate denoted $A_{thix}$ and expressed in $Pa.min^{-1}$ is the rate of the yield stress increase of a cement-based material left at rest. It can be easily computed as the slope of the yield stress vs. resting time curve at very early age (few dozens of minutes). This coefficient has been showed to be sufficient to describe casting process issues such as formwork pressure (Ovarlez and Roussel 2006; Tchamba et al. 2008; Perrot et al. 2009) or distinct layer casting (Roussel 2007; Roussel and Cussigh 2008).

This study aims to describe the structural build-up behaviour of rigid fiber reinforced cement-based materials. This will help to predict the time of casting and transportation available for fiber reinforced concrete. This present work shows that structural build-up modelling used for common concretes can be generalized to fiber reinforced concretes. Indeed, it is highlighted that the evolution of the yield stress of fiber reinforced concrete at rest is linear and that the structuration rate $A_{thix}$ can be used. For this study, an experimental campaign has been performed. The yield stress of six different mortars has been measured at five different resting times (from 0 to 40 minutes of rest). For each mortar, different fiber volume fractions are added. It can be shown that, if the inclusions percolation threshold is not reached, the structural build-up rate $A_{thix}$ is amplified by the addition of fibers and aggregates. Especially, the influence of relative packing as described by Martinie et al. (Martinie et al. 2010) on the structural build-up coefficient is analysed. A biphasic approach is considered with no physicochemical interactions between the particles ad the paste. It is assumed that inclusions do not absorb water, in spite of the fiber high surface exchange. Finally it is shown that the modelling initially developed for spherical inclusions and aggregates (Mahaut et al. 2008b) in order to predict the structural build-up rate are also valid with fibers.

## 2 Materials and methods

### 2.1 Materials

A CEM I type cement of specific gravity 3.15 is used in this study. Its specific surface measured using a Blaine apparatus is 3390 cm²/g.

The sand is a usual Loire river-sand. It has minimum /maximum sizes of 20 µm to 3.15 mm and an absorption capacity of 0.9%.

High range water reducing admixture (HRWRA) is also used. It is a polycarboxylate type polymer conditioned in liquid form containing 20 % of dry material. Its recommended dosage ranges from 0.3 to 3% per weight of cement. In this study, two dosages of 1.5% or 2.5% in mass of cement were chosen depending of the studied mortar. The HRWRA is added to the mixing water before water/cement contact.

Tested fibers are short steel fibers. Their specific gravity is 7.85 and their young modulus E is 210 GPa. They have a length of 6 mm and a diameter of 160 μm leading to an aspect ratio r of 37.5.

According to the criterion defined by Martinie et al., the ratio of the deflexion f over the fiber length $l_f$ when the fiber is sunk into a cement-based paste exhibiting a yield stress denoted $t_0$ is:

$$\frac{f}{l_f} = \frac{\tau_0 r^3}{E} \tag{1}$$

For the present fibers, this ratio ranges from 0.012% to 0.12% for a paste yield stress between 100 Pa, and 1 kPa. This clearly shows that this type of fiber can be considered as rigid even with firm ordinary concrete (exhibiting a yield stress of the order of 1 kPa).

The different mix designs are presented in table 1. Tested fiber volume fraction ranges from 0 to 6%, and the sand volume fraction ranges from 0 to 36%. Reference cement pastes, with no aggregate are also tested. Two W/C ratios were tested, with different HRWRA dosage to evaluate the influence of the initial yielding behaviour of the samples on their setting at rest. A total of 29 mixes are tested.

Water and HRWRA are mixed with dry powder and fibers in a planetary Hobart mixer. The mixing phase consists in two steps: 2 minutes at 140 rpm and then 3 minutes at 280 rpm.

| N° | Name | W/C | Pl/C | S/C | $\phi_f$ (%) | $\phi_s$ (%) |
|---|---|---|---|---|---|---|
| 1 | CP 1 | 0.34 | 0.015 | 0 | 0 | 0 |
| 2 | | | | | 0.05 | 0 |
| 3 | | | | | 1 | 0 |
| 4 | | | | | 2 | 0 |
| 5 | CP 1 + 0.14S | | | 0.3 | 0 | 14 |
| 6 | | | | | 0.5 | 14 |
| 7 | | | | | 1 | 14 |
| 8 | | | | | 2 | 14 |
| 9 | | | | | 5 | 14 |
| 10 | | | | | 6 | 14 |
| 11 | CP 1 + 0.35S | | | 1 | 0 | 36 |
| 12 | | | | | 0.5 | 36 |
| 13 | | | | | 1 | 36 |
| 14 | | | | | 1.5 | 35 |
| 15 | | | | | 2 | 35 |
| 16 | | | | | 3 | 35 |
| 17 | CP 1 + 0.28S | | | 0.7 | 0 | 28 |
| 18 | | | | | 0.5 | 28 |
| 19 | | | | | 1 | 28 |
| 20 | | | | | 1.5 | 28 |
| 21 | | | | | 2 | 27 |
| 22 | | | | | 4 | 27 |
| 23 | CP 2 | 0.29 | 0.025 | 0 | 0 | 0 |
| 24 | | | | | 1 | 0 |
| 25 | | | | | 2 | 0 |
| 26 | CP 2 + 0.14S | | | 0.3 | 0 | 14 |
| 27 | | | | | 1 | 14 |
| 28 | | | | | 2 | 14 |
| 29 | | | | | 3 | 14 |
| 30 | CP 2 + 0.42S | | | 1.2 | 0 | 42 |
| 31 | | | | | 1 | 42 |
| 32 | | | | | 2 | 42 |

Table 1: Summary of tested mixtures (W/C: water over cement mass ratio, HRWRA/C: HRWRA over cement mass ratio, S/C: sand over cement mass ratio)

## 2.2 Structural build-up measurements

Different techniques can be used to measure the structural build-up coefficient $A_{thix}$ (Roussel 2006; Amziane et al. 2008; Mahaut et al. 2008b; Sleiman et al. 2010; Khayat et al. 2012; Lecompte et al. 2012). Field oriented test methods such as portable vane test, plate test or undisturbed slump flow allow accurate measurements of the structural build up of resting cement-based pastes. In this study, vane test on undisturbed samples is used. This method is accurate and relatively easy to carry out (Mahaut et al. 2008b; Lecompte et al. 2012).

An Anton Paar Rheolab QC rheometer equipped with a vane geometry well adapted for cement paste and mortar is used. The vane geometry used in this study consisted of four blades around a cylindrical shaft. The vane height and diameter are respectively 60 mm and 40 mm. These dimensions allow for an accurate measurement of the yield stress from 10 to 700 Pa. The ratio between fiber length and tool diameter is close to seven and ensures that the measurement provides a value representative of the paste behaviour.

Yield stress is the more relevant parameter to study the impact of rheology on common casting process. However its measurement is especially difficult to achieve as the yield stress largely depends on the structuration state of the nucleating cement suspension (Roussel et al. 2012). As a result, yield stress of cement based materials increases at rest as the material structurates. Roussel predicts a linear increase of the yield stress $\tau_0$ with resting time (Roussel 2005, 2006):

$$\tau_0 = \tau_0^{\,i} + A_{thix}.t_{rest} \qquad (2)$$

where $t_{rest}$ is the resting time in minutes, $\tau_0^{\,i}$ is the yield stress just after mixing, in Pa, and $A_{thix}$ is the structural build up rate, in Pa/minute. As a result, the resting time of the material must always be considered when measuring its yield stress.

After mixing, the fiber dispersion and isotropic orientation was checked. Then, the material was slowly poured in five different cylindrical containers of 10 cm in diameter and 15 cm in height. The slow pouring velocity is required in order to avoid the fiber orientation. The containers walls were covered with sandpaper to avoid material slippage during tests. The first vane test is then performed, few seconds after the end of the pouring step and close to one minute after the end of the mixing step. We consider that the first vane test starts the resting period. Also, it can be noted here that a pre-shear phase before each test could not be performed for this specific study as it would have strongly modified the orientation of the fibers in the bowl and the structuration state of the cement paste.

A measurement stage was performed during 180 s on the Anton Paar rheometer to obtain the yield stress at five given resting times, following the procedure described by Mahaut et al. (Mahaut et al. 2008b). Stress growth is used to determine the yield stress with an apparent shear rate of 0.001 $s^{-1}$. At such shear rate, viscosity effects are negligible. As a consequence, the yield stress is computed from the maximum torque value which is required for the onset of the flow, i.e. when the apparent yield stress (static yield stress) is reached on the cylindrical shearing surface:

$$\tau_0 = \frac{C}{\frac{\pi . D^2}{2} . \left( H + \frac{D}{3} \right)} \qquad (3)$$

where C is the torque peak value, H and D are respectively the tool height and diameter.

This value depends on the structuration state of the cement-based materials and is different than the dynamic yield stress (intrinsic yield stress) (Roussel 2005). If the material is unstructured (i.e. with no resting time), the torque vs. time curve does not exhibit a peak but a plateau and the dynamic yield stress is measured.

Then as shown on figure 1, the torque vs. time curve may present different trends depending on the resting time and the fiber content. With no resting time and no fiber, the curve presents a torque plateau (this is also the case with low amount of fibers). After a resting period or for high fiber content, a peak curve is obtained. This is due to the cement paste destructuration after a resting period and to the energy required for the fiber orientation for mix with high amount of fibers (Martinie et al. 2010).

Every ten minutes, an undisturbed sample was measured.

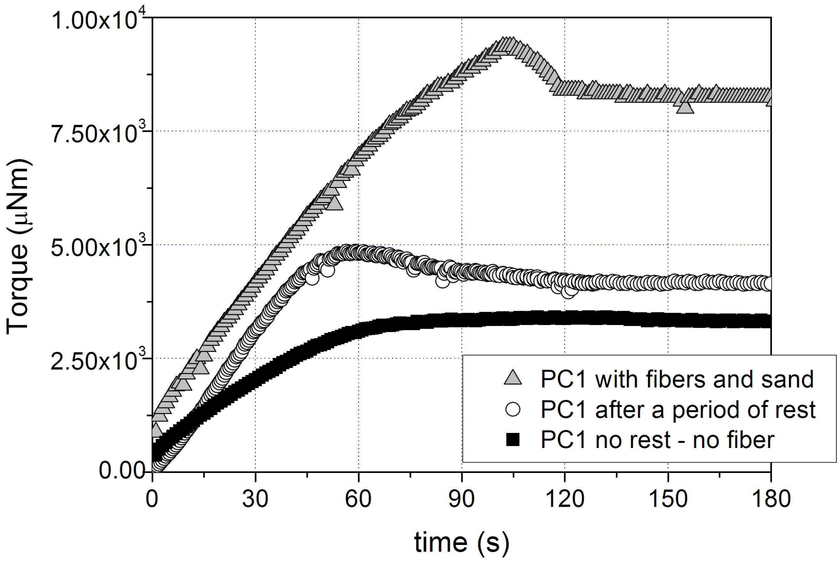


Figure 1: Typical torque vs. time curves for different scenarios

## 3 Results

Figure 2 shows the evolution of the yield stress vs. time for the mix CP2-0.28S with different amount of fibers. It highlights that the Roussel prediction on the linear evolution of yield stress over resting time accurately describes the material behaviour during the first 40 minutes. It means that the $A_{thix}$ coefficient is sufficient to model the structural build-up behaviour of the studied materials. The linear increase of yield stress during the first 40 minutes is common to all tested mixes. The measured values of $A_{thix}$ range between 0.37 and 7 Pa.min$^{-1}$.

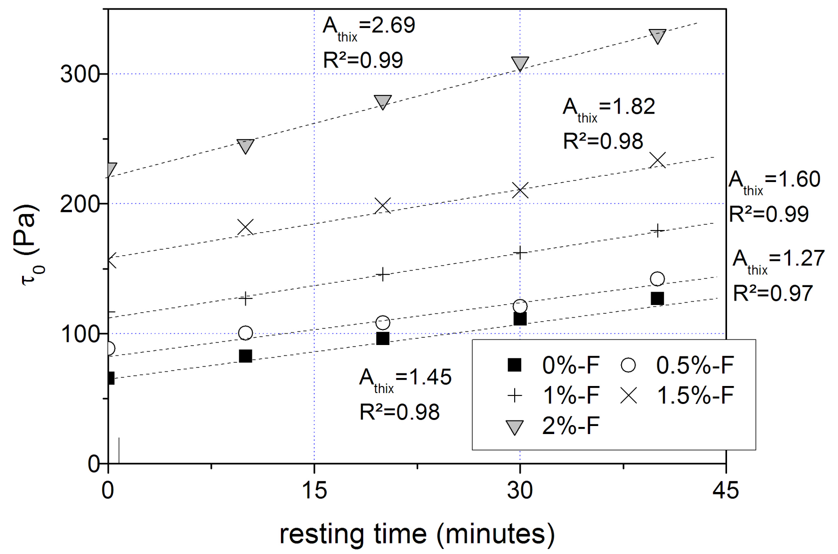


Figure 2: Yield stress vs. Resting time for different fiber content (CP1-0.28S)

According to Martinie et al. (2010), the initial yield stress of rigid fiber reinforced concrete depends on the inclusions relative volume fraction which is defined as the sum of the relative volume fraction of fibers and the relative volume fraction of the granular skeleton:

$$P_f = \phi_f \cdot \frac{r}{4} + \frac{\phi_s}{\phi_m} \qquad (4)$$

where $\phi_s$ is the volume fraction of sand and $\phi_m$ is the dense packing fraction of the sand (Martinie et al. 2010). The ratio 4/r represents the dense packing of fibers. According to the authors, the real global relative volume fraction of the inclusion mixture is probably underestimated due to wall effects: the decrease of packing fraction of each individual species close to wall is neglected. Also, we assume that each type of inclusions does not modify the packing fraction of the other type of inclusion which is probably wrong. For the used rounded sand, the estimated dense packing fraction is about 0.63.

For each mortar, the ratio of its structural build-up rate over the one of the cement paste is plotted on figure 3, versus the relative volume fraction. All experimental values seem to be on a same curve. It appears that the structural build-up rate follows the same tendency as the yield stress according to Martinie et al. (Martinie et al. 2010) as it only depends on the inclusions relative volume fraction. As mentioned by those authors, it is possible to combine linearly the effects of both fibers and sand in order to identify the rapid increase in the yield stress of fiber-reinforced cement-based materials around the critical volume fraction at which all these inclusions combine in order to generate a strong direct contact network in the material. Below this critical value, the yield stress of the material is close to the suspending cement paste whereas, above this value, the material yield stress dramatically increases. Finally, the structural build-up rate of a given mortar can be written as a function of the relative volume fraction $P_f$ and the cement paste structural build-up $A_{thix}^{CP}$:

$$A_{thix}(\phi_s, \phi_f) = A_{thix}^{CP}.g(P_f) \qquad (5)$$

Where $g(P_f)$ is a function depending on $P_f$. This relationship is similar to the one obtained by Mahaut et al. for mortars (Mahaut et al. 2008b).

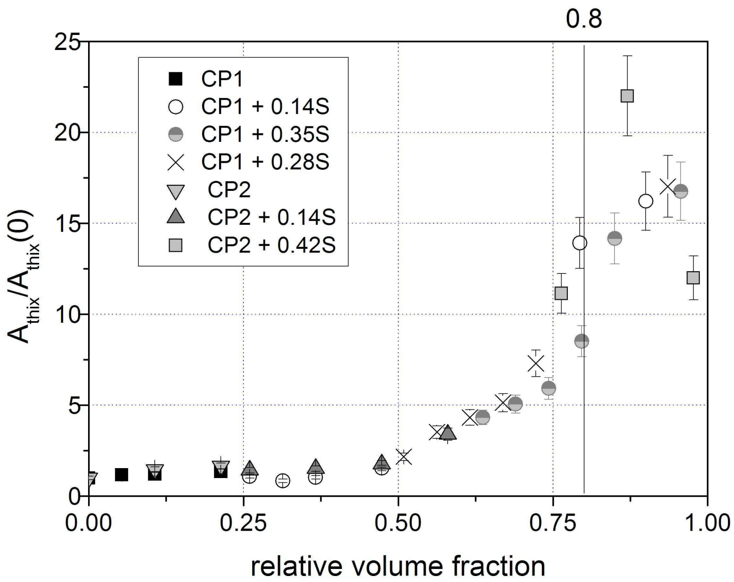


Figure 3: Non-dimensional structural build-up vs. Relative packing

Mahaut et al., based on homogenisation work of Chateau et al. (Chateau et al. 2008; Mahaut et al. 2008a; Mahaut et al. 2008b), provide an expression to characterise the evolution of the yield stress of a model concrete (with spherical inclusions of the same diameter) as a function of the yield stress of its cement paste $\tau_0^{CP}$ and the volume fraction of it aggregates $\phi_s$:

$$\tau_0(\phi_s) = \tau_0^{CP} . \sqrt{\frac{1-\phi_s}{(1-\phi_s/\phi_{RLP})^{2.5\phi_{RLP}}}} \quad (6)$$

Where $\phi_{RLP}$ is the random loose packing fraction of the aggregates.

Combining eq. (2) and (6), it is possible to compute $A_{thix}(\phi_s)$ for any aggregate fraction from the structural build-up rate of the cement paste $A_{thix}^{CP}$. As a result, $A_{thix}$ can be written as follows:

$$A_{thix}(\phi_s) = A_{thix}^{CP} . \sqrt{\frac{1-\phi_s}{(1-\phi_s/\phi_{RLP})^{2.5\phi_{RLP}}}} \quad (7)$$

This has been experimentally verified by Lecompte et al. (Lecompte et al. 2012) on mortars for aggregate volume fraction ranging from 0 to random loose packing fraction (the range of application of this modelling).

It can be interesting to make an analogy between fibers and aggregates for the prediction of the structural build-up and yield stress based on the work of Martinie et al. (Martinie et al. 2010). In the work of Mahaut et al., the relative random loose packing fraction writes $\phi_s/\phi_{RLP}$. According to previous works on granular packing in concrete pastes (Roussel et al. 2010; Yammine et al. 2008), it is possible to write relative random loose packing fraction versus dense packing fraction as $\phi_{RLP}$=0.8$\phi_m$. Then, the relative loose packing fraction for a concrete or mortar without fibers writes:

$$\frac{\phi_s}{\phi_{RLP}} = \frac{\phi_s}{0.8\phi_m} \quad (8)$$

Martinie et al. define an equivalent solid volume fraction $\phi_{s,eq}$ for reinforced concretes and mortars by using equation (4) and multiplying it by the dense packing of sand.

$$\phi_{s,eq} = Pf \times \phi_m = \phi_s + \phi_m . \phi_f . r/4 \quad (9)$$

Then by analogy, the relative loose packing fraction could become:

$$\frac{\phi_{s,eq}}{\phi_{RLP}} = \frac{P_f}{0.8} \tag{10}$$

With eq. (9) and (10), it is possible to rewrite the Mahaut et al. relationships (6) and (7) for rigid fiber reinforced cement-based mixes:

$$\frac{\tau_0(\phi_s,\phi_f)}{\tau_0^{CP}} = \frac{A_{thix}(\phi_s,\phi_f)}{A_{thix}^{CP}} = \sqrt{\frac{1-\phi_m P_f}{(1-P_f/0.8)^{2.5.P_f/0.8}}} \tag{11}$$

Comparison between experimental relative yield stress, relative structural build-up rate and predictive modelling for rigid fiber reinforced mortar is shown on figure 4. As predicted by Mahaut et al., the relative yield stress and structural build-up rate follow the same evolution in function of the relative volume fraction $P_f$ ranging from 0 to 0.8. One can remark that for $P_f$ = 0.8, the relative volume fraction is equal to the random loose packing fraction, (see equation 10). Then, Mahaut et al. modelling is able to describe the evolution of the studied non-dimensional ratios in the same range of relative volume fraction than for cement-based mixes without fibers. Between $P_f$ =0.5 and $P_f$ =0.75, the modelling slightly underestimates the experimental results, showing the same trend obtained by Lecompte et al. for mortars (Lecompte et al. 2012). An explanation can be that the modelling has been written and validated for monodisperse spheres suspensions. Then, the polydispersity and complex forms of rough sand grains probably induce more energy dissipation that increases the measured shear stress of the tested materials.

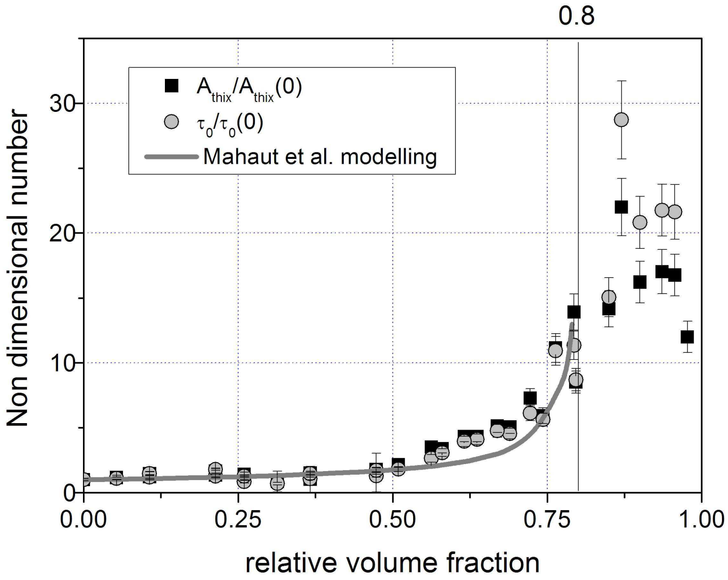


Figure 4: Non dimensional structural build-up and yield stress vs. Relative packing. Comparison with Mahaut et al. predictive modelling (Mahaut et al. 2008a). The plotted relative yield stresses corresponds to measurements with no resting period (dynamic yield stress). The non dimensionnel yield stress for the mix CP2-042S with 2% fibers is not plotted in this figure ($P_f = 0.98$ ; $\tau_0/\tau_0(0)= 62.3$).

Another interesting result is the discrepancy between relative yield stress and relative structural build-up rate observed for relative volume fraction higher than 0.8 where the relative yield stress presents higher values. This results seems similar to the one obtained by Lecompte et al. for mortar (Lecompte et al. 2012). The authors show that high content of inclusions (such as sand and fibers) creates a solid contact network that limits structural build-up effects.

This can be verified by computing a characteristic time $t_c$ which corresponds to the time required to double the yield stress value ($2.\tau_0^i = \tau_0^i + A_{thix}.t_c$ leads to $t_c = \tau_0^i/A_{thix}$). Mahaut et al. write that this ratio does not depend on any solid volume fraction but only on the cement paste behaviour. This can be easily verified by dividing eq.(6) by eq.(7). Consequently, for all tested mixtures, we should obtain two different values which only depend on the used cement paste (CP1 or CP2). Figure 5 shows the evolution of the characteristic time $t_c$ versus relative volume fraction. Average values and standard deviations of $t_c$ are plotted. Those values are computed separately for each family of mixtures in function of the used cement paste. We note that average value and standard deviation are computed on mixes with a relative volume fraction lesser than 0.8.

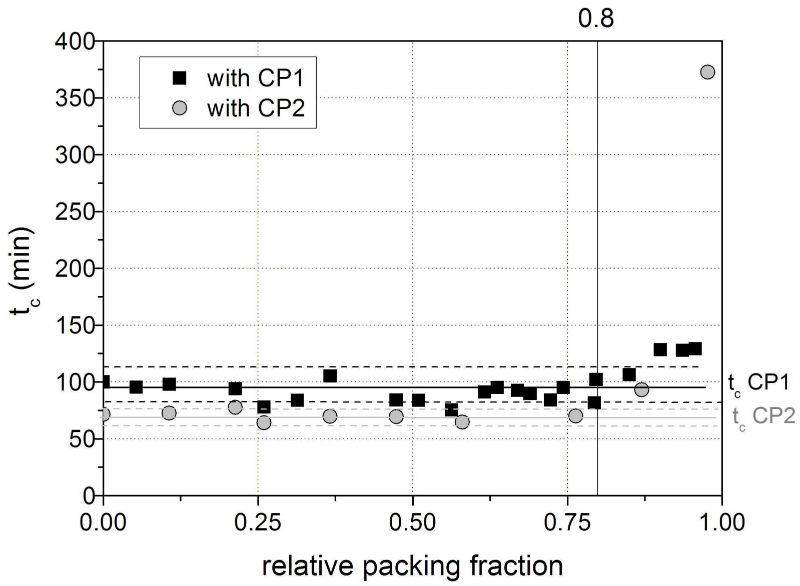


Figure 5: Characteristic structuration time vs. relative packing. Mixes based on cement paste 1 and 2 (CP1 and CP2). Average values (lines) and standard deviations (dot lines) are plotted in the figure.

The figure highlights than the characteristic time $t_c$ does not depend on the relative volume fraction when $P_f < 0.8$. For higher value of $P_f$, the characteristic time value is higher than the one of the cement paste showing that a strong inclusion network slows down structural build-up effect as shown by Lecompte et al. for mortars (Lecompte et al. 2012).

## 4. Conclusions

The evolution of the structural build-up rate of rigid fiber reinforced concrete has been described in function of mix design parameters such as fibers and aggregate volume fraction. Based on the study of Martinie et al. (Martinie et al. 2010) about yield stress of rigid fiber reinforced concrete, it has been shown that the structural build-up rate evolution only depends on the total relative volume fraction, $P_f$.

Then, it has been highlighted that the behaviour of structural build-up depend on the value of $P_f$ :

- Beyond 0.8 (i.e. the random loose packing fraction): the relative structural build-up rate (structural build-up rate of the fiber-reinforced mortar over structural build-up rate of its cement paste) follows the same evolution than the relative yield stress described by Martinie et al. (Martinie et al. 2010). In this case, the structural build-up rate can be predicted by an extension of Mahaut et al. modelling adapted to fibers inclusion (Mahaut et al. 2008a; Mahaut et al. 2008b). The characteristic structuration time $t_c(P_f)$ which defines the time required to double the initial yield stress of the mix does not depend on the relative volume fraction and is equal to the cement paste characteristic time $t_c^{CP}$.
- Over 0.8, relative yield stress increases faster than the relative structural build-up showing that a strong inclusion network is able to reduce the apparent effect of cement paste structuration.

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