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Abstract

Polypropylene fibers are accepted in the literature as an efficient preventative measure for concrete spalling due to fire. Use of the high dosage of fibers enhances this effect but drastically reduces the workability of concrete. A lack of the literature on the rheological behavior of fresh cementitious materials with flexible fibers prevents from the identification of an optimal fiber dosage and geometry. This work is aimed at studying the influence of fiber dosage and geometry on the rheological behavior of fresh fluid cementitious materials. Slump flow tests conducted on cement pastes containing fibers allowed to determine the influence of fiber dosage and geometry on the yield stress of fresh cement pastes. It is concluded that the rheology of cement pastes with flexible fibers is more complex in comparison to the rheology of cement pastes with rigid fibers due to their bending.

1 Introduction

It is widely known that self-compacting concrete outperforms other types of concrete for the casting of thin and/or densely reinforced concrete structural elements [1]-[4]; however, due to its high matrix volume fraction, its resistance to fire is considered as weak [5], [6]. Numerous studies conducted by the researchers have indicated a positive effect produced by polypropylene fibers in terms of the concrete spalling risk reduction due to fire [5], [7]-[10]. Higher fiber dosage has been proven to be more efficient in terms of spalling prevention [7-10]; however, it has a negative effect on the flowability of self-compacting concrete.

The information about the influence of flexible fibers on the rheology of fresh cementitious materials is not abundant, the effect of rigid fibers on the rheology is far better studied. The difference between both types of fibers is the ability of flexible fibers to bend. Several studies have been conducted on cementitious materials containing flexible fibers identifying a negative effect on the workability at the high dosage of fibers [11]-[17]. Researchers have stated a decrease in the slump for the dosage of 0.2% vol. of fibers [16], [18]. It is peculiar to note that even with a decrease in the workability with the use of 0.1% vol. of fibers, concrete mix could still meet the flowability criterion for self-compacting concrete [11].

In search of the compromise between fire resistance and fresh concrete requirements, it is essential to identify potential optimal fire dosage and geometry. Therefore, the purpose of this paper is to understand the effect of flexible fibers on the rheology of fresh concrete. First, we study the influence of fiber dosage on the yield stress of cement paste. Then, we conclude on the fact that the curvature of flexible fibers in cementitious material depends on the nature of consecutive paste. Following this, we study the influence of the diameter and the length of fibers on the yield stress. The results show that the rheological behaviour of cementitious materials with flexible fibers is different from cementitious materials with rigid fibers.

2 Rheology of cement-based materials

A common model used to describe the flow of cementitious materials is Bingham model. It allows determining the yield stress of the cementitious material from the following equation:

$$\tau = \tau_0 + \dot{\gamma}\mu_0 \tag{1}$$

where τ is the total stress, τ_0 is the yield stress, $\dot{\gamma}$ is the shear rate and μ_0 is the viscosity of the fluid.

The yield stress is the threshold value of the stress which is necessary to apply on the solid body to initiate a flow of a viscous fluid. In the rheology, the biphasic approach for describing concrete is used. This approach suggests that concrete is composed of a continuous phase of the suspending fluid (a cement paste which we assume to be homogeneous) and a dispersed phase (the inclusions such as sand, gravel and fibers) [19]. Using the extrapolation for Krieger-Dougherty relation for apparent viscosity, the yield stress of concrete is presented as the yield stress of the suspending fluid and the function of the ratio of the volume fraction of its inclusions and the dense packing fraction of the inclusions [20]:

$$\tau_0^{concrete} \approx \tau_0^{paste} f\left(\frac{\phi}{\phi_m}\right) \tag{2}$$

where $\tau_0^{concrete}$ is the yield stress of concrete, τ_0^{paste} is the yield stress of cement paste, ϕ is the volume fraction of the inclusions, ϕ_m is the dense packing fraction of the inclusions. The dense packing fraction is the packing regime which is achieved through an exertion of a large amount of energy. During dense packing regime, direct friction between the aggregates is a dominant force. A comprehensive explanation of spherical inclusions packing regimes is given in [19].

A reduction of the inclusions' contribution to the development of the yield stress of cementitious material cannot simply turn regular concrete into fluid one [19]. In order to design fluid concrete, it is necessary to ensure first that cement paste is fluid. Therefore, we start by designing fluid cement paste. Our experimental protocol is based on a simple and fast characterization method developed by Roussel et al.[21] which allows calculating the yield stress of cement paste from the slump flow tests. This test is suitable for cement pastes with flexible fibers as the material flow is too short to impose a preferential orientation of fibers. The equation which calculates the yield stress of cement paste from a material spread radius is a follows:

$$\tau_0 = \frac{225\rho g V^2}{128\pi^2 R^5} \tag{3}$$

where τ_0 is the yield stress of cement paste, ρ is the density of cement paste, V is the volume of cement paste tested, g is the gravity and R is the radius of cement paste spread.

3 Distinction between rigid and flexible fibers

As it mentioned earlier, the influence of flexible fibers on the rheology of cementitious materials is less understood compared to the influence of the rigid fibers. Both types of fibers, rigid and flexible, behave in a different manner when mixed in concrete. Rigid fibers can move the aggregates that are relatively large if compared with fiber length thus increasing the void space. Flexible fibers tend to bend and to occupy the empty spaces between the aggregates [22].

The rigidity criterion for fibers in cementious materials was developed by Martinie et al. [20]. She has identified a set of parameters that influence the deflection of fibers in fresh cementitious materials. The order of magnitude of the deflection of fibers is then presented as:

$$f \cong \frac{\tau_0 D L^4}{EI} \tag{4}$$

where f is the order of the deflection, τ_0 is the yield stress of the fresh cementitious material, D is the diameter of fiber, L is the length of fiber, E is Young's modulus of fiber and I is the second moment of area.

Depending on mechanical and geometrical properties of fiber and the nature of the suspending fluid, different flexure responses can be obtained. For example, in case of steel fibers with an aspect ratio (a ratio between the length and the diameter of fiber) of 50, the Young's modulus of 210 GPa in SCC mix (the yield stress of approximately 50 Pa) this value is around 0.03%, whereas for carbon fibers of the aspect ratio of 500 and the Young's modulus of 190 GPa in regular concrete mix (the yield stress of 1000 Pa), the magnitude of deflection is around 66% [20].

4 Prediction of the yield stress

Martinie et al. [19] has found that the yield stress of fiber reinforced cementitious material is a function of two parameters: the ratio of fiber dosage and dense packing fraction (ϕ/ϕ_m) and the aspect ratio of fibers R (ratio of the length and the diameter). Dense packing fraction of rigid fibers is obtained experimentally. In her work, Martinie [19] used Philipse's approach for slender bodies (with an aspect ratio higher than 1) that allowed representing maximum packing fraction of rigid fibers as inversely proportional to the aspect ratio of fibers. She has found the coefficient of proportionality to be equal to 4 ($\phi_m = 4/R$).

Unfortunately, it is impossible to measure experimentally the dense packing fraction for flexible fibers due to the fact that their flexure depends on the suspending fluid. As we have concluded that two parameters are sufficient for the yield stress prediction in case of the paste with rigid fibers (fiber volume fraction ϕ and aspect ratio R), we shall apply this predictive framework for the yield stress in order to verify if flexible fibers behave as rigid fibers in fresh cementitious mix.

5 Materials and experimental protocol

5.1 Materials

In the first part of the experimental program we have two objectives: to study the influence of the dosage of fibers on the rheology of cement pastes and identify that the flexure of fibers changes depending on the nature of cement paste.

Cement pastes with two different water-to-cement ratios (w/c= 0.47 and w/c=0.5) are tested with a single geometry of fibers at various dosages (0 %, 0.25 %, 0.5 %, 1 %, 2 % and 3 % vol. of cement paste). All cement pastes for experiments were prepared using Portland cement CEM I 52.5 N Brest. The dimensions of the polypropylene fibers are: the length is 12 mm, the diameter is 34 µm and aspect ratio is 353.

In the second part of the experiment, our aim is to study the influence of fiber geometry on the yield stress. In order to accomplish this, cement paste with w/c=0.5 is chosen as our reference paste and then tested with nine different geometries of fibers at several dosages (0 %, 0.25 %, 0.5 %, 1 %, 2 % and 3 % vol. of cement paste). Fiber geometry is presented in Table 1.

Table 1 Polypropylene fiber geometries tested.

Aspect ratio (R)	Length (L), mm	Diameter (D), µm
176	6	34
188	6	32
300	6	20
333	6	18
353	12	34
400	6	15
529	18	34
588	20	34
706	24	34

5.2 Experimental protocol

Water is added to cement and mixed by the machine for 2 minutes. Then, cement paste is left for the rest during 20 minutes and remixed for 2 minutes by the machine. Then, polypropylene fibers are added into the formed cement paste and mixed by hand for 2 minutes. Paste with fibers is poured on the plate and spread diameter and volume of paste tested are recorded. An isotropic flow of material is assumed as a flow of the material is too short to impose any direction. Protocol was kept the same for all the mixes and for each dosage of fibers a new sample was prepared. Samples which showed signs of instability were discarded from consideration.

6 Results and discussions

6.1 Influence of the dosage of fibers

In this part, we study the influence of the dosage of fibers on the yield stress of the cement paste. We present the results in the form of the relative yield stress (a ratio of the yield stress of cement paste with fibers and without fibers) in order to account for the effect of fibers as inclusions. The results were obtained from the slump flow test on cement pastes of two different w/c ratios that contained single fiber type. Fig.1 presents the relative yield stress of the fresh cement paste with fibers as a function of the dosage of fibers. The error of 11% was found through the repetition of the experiment five times on 1% vol. fibers. This value is assumed as an error bar for all the experimental results presented in this paper. It can be seen from the results that the yield stress of the cement paste with fibers increases with an increase of fiber dosage. This result corresponds to the literature [20, 22].

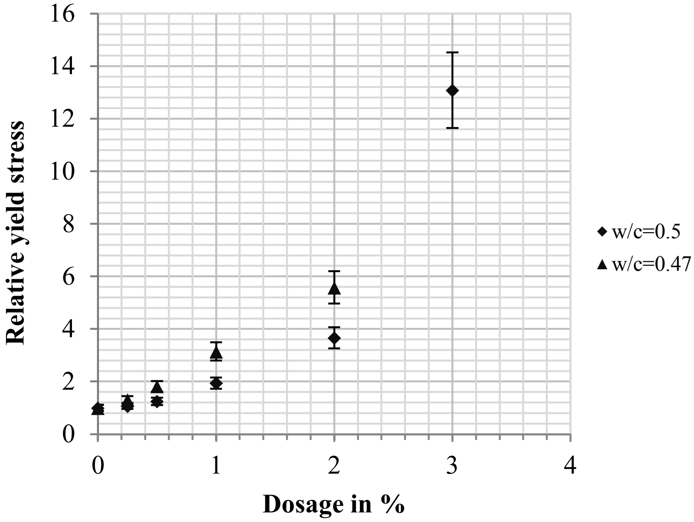

Fig. 1 Relative yield stress (a ratio of the yield stress with fibers and the yield stress without fibers) as a function of the dosage of fibers.

6.2 Influence of the rheology of paste

We plot our data from Fig. 1 on the log scale in the Fig 2. We use our data from Fig.2 in order to examine whether the flexible fiber flexure depends on the nature of the cement paste.

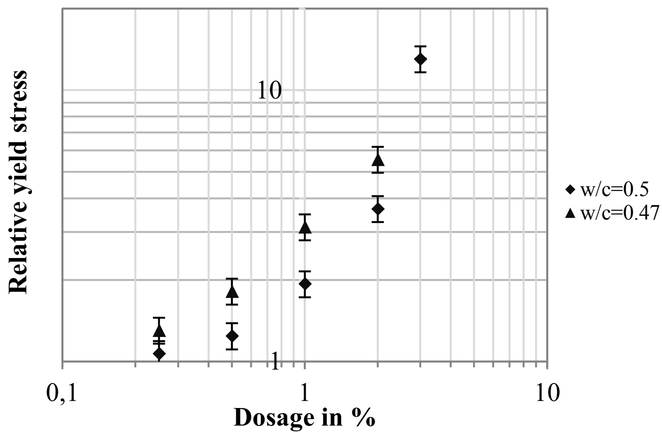

Fig. 2 Relative yield stress plotted on the log scale as a function of the dosage of fibers and the yield stress of reference paste.

We therefore introduce the yield stress of the reference paste, i.e. paste without fibers, in x-axis as shown in the Fig. 3. The results confirm the idea that the rheology of the cement paste influences the flexure of fibers. This means that under highly viscous cement paste fibers tend to flex more and vice versa. To compare with rigid fibers, regardless of the cement paste their flexural response is negligible (less than 1%).

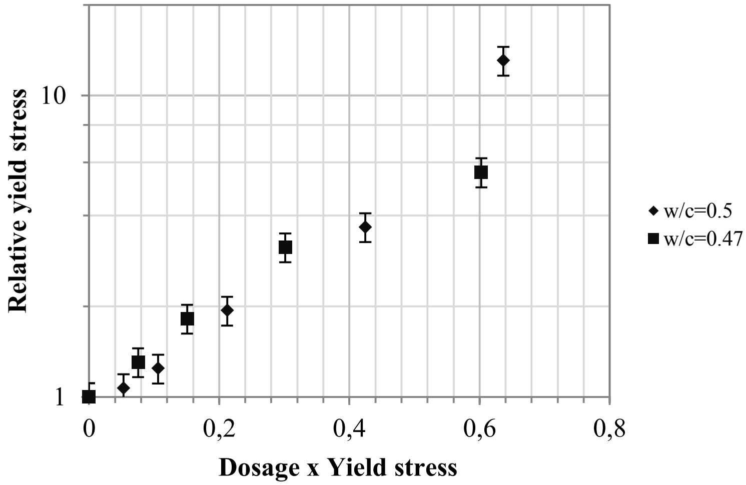

Fig. 3 Relative yield stress plotted on the log scale as a function of the dosage of fibers and the yield stress of reference paste.

6.3 Influence of the geometry of fibers

Various fiber geometries listed in Table 1 were tested with a cement paste of w/c=0.5 using the same protocol. The results for different aspect ratios are presented in the Fig.4. It can be seen that the yield stress does not increase with the increase of aspect ratio of fibers as it is generally accepted in the literature. Fig. 5 and Fig.6 present the effect of the diameter and the length of fibers on the relative yield stress respectively. It is hard to conclude on the influence of the increase of the diameter on the yield stress. It appears that in general, the diameter increase promotes a decrease in the yield stress. The increase of the length of fibers, on the contrary leads to the increase of the yield stress.

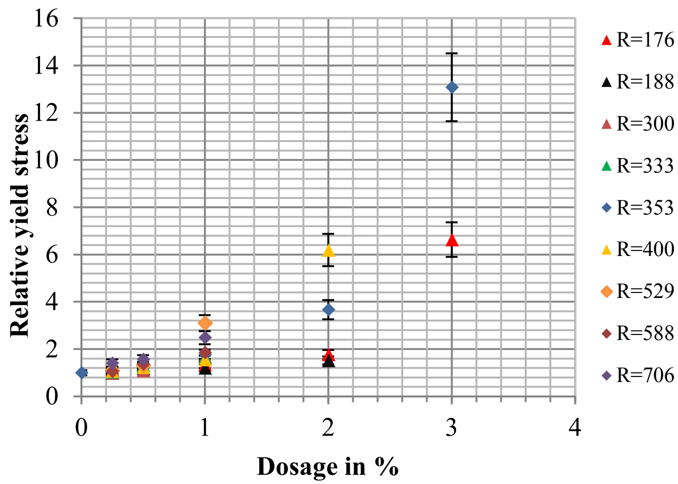

Fig. 4 Relative yield stress plotted as a function of the dosage of fibers of various aspect ratios.

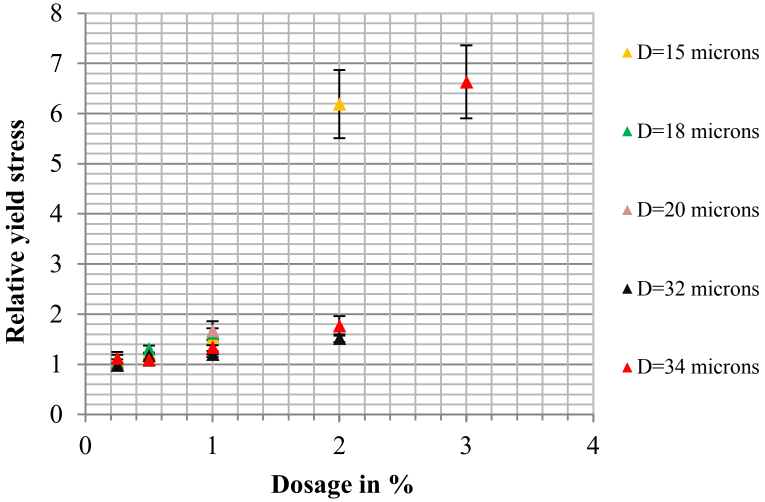

Fig. 5 Relative yield stress plotted as a function of the dosage of fibers. Diameter of fibers is 34 microns and lengths are 6, 12, 18, 20 and 24 mm accordingly.

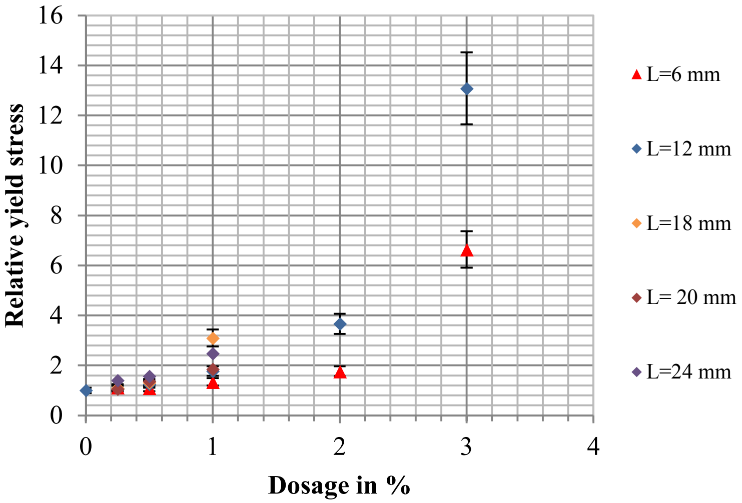

Fig. 6 Relative yield stress plotted as a function of the dosage of fibers. Length of fibers is 6 mm and diameters are 15, 18, 20, 32 and 34 microns accordingly.

6.4 Comparison with rigid fibers

As we can predict the rheology of materials with rigid fibers using the dosage and the aspect ratio of fibers, we have plotted in Fig.7 the results using the predictive scheme for rigid fibers. It can be seen that the scheme is not appropriate for flexible fibers. It works well at low dosages of fibers when the yield stress of the material with fibers is dictated by the yield stress of the cement paste. With an increase of the fiber dosage, after formation of a connected network, direct frictional contacts start to be dominant in the system. Therefore, it is logical after connection of fibers the data on the graph is far more scattered. From the analysis using predictive scheme for the yield stress of rigid fiber reinforced materials we can conclude that the influence of the flexible fibers is far more complex due to their bending.

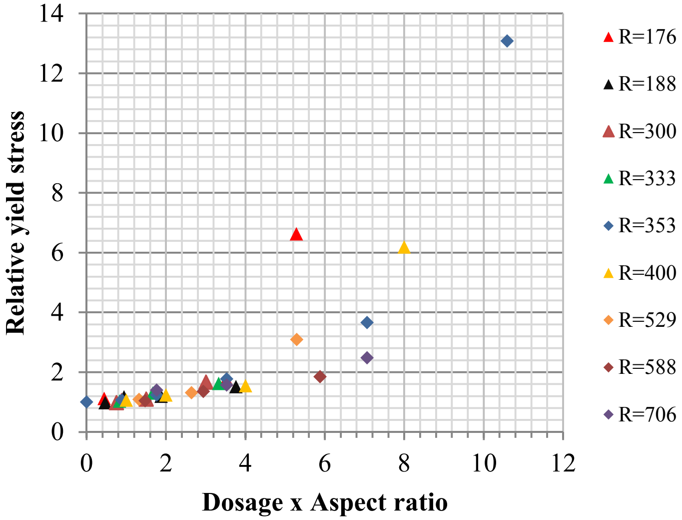

Fig. 7 Relative yield stress plotted as a function of the scaling for rigid fibers.

7 Conclusion

This work is aimed at understanding the influence of flexible polypropylene fibers on the rheology of the fiber reinforced cementitious materials. Simple slump flow tests were realized on cement paste in order to study the effect of the dosage and geometry of fibers on the yield stress of cement paste. It was possible to conclude from the tests that:

- Rheology of fiber reinforced cement based materials is influenced by the nature of the suspending fluid.
- Rheology of the polypropylene fibers cannot be characterized the same way as one of the rigid fibers due to flexure of fibers.

Acknowledgements

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