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Rheological and tribological behaviors of polypropylene fiber reinforced concrete

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HIGHLIGHTS

- Rheological and tribological properties of fiber reinforced concrete.
- Fibers shape, length and dosage influence on the fresh concrete properties.
- Superplasticizer effect on fiber reinforced concrete rheology and tribology.
- The combined effect of different fibers shape and length in the same concrete mix.

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ABSTRACT

The historical data showed a positive influence of polypropylene fibers (PPF) on concrete performance in terms of mechanical properties, shrinkage and fire resistance. However, in regards to fresh state properties, the workability is negatively affected by fibers inclusion. Therefore, several studies have been done to evaluate the workability loss of fiber-reinforced concrete (FRC), but there has been little research about the rheological and tribological properties such as the plastic viscosity and the viscous constant. In this context, the present study aims to evaluate the effect of PPF inclusion on both rheological and tribological properties of ordinary concrete through two phases (without and with incorporation of superplasticizer), using fibrillated twist and wave fibers shapes at different dosages (0.12, 0.24, 0.36%) and with various lengths (19, 30 and 54 mm). The obtained results of the first part showed that the plastic viscosity of FRC without superplasticizer is not affected by fibers length while it augments with increasing PPF percentage. Regarding the tribological behavior, segregation phenomenon was observed for mixtures with high fiber dosage (0.24 and 0.36%) during the test. In the second part, the use of superplasticizer has improved the concrete workability in addition to the rheological and tribological behaviors. Finally, a special attention was devoted to the effect of using two different shapes and lengths of PPF on the same fresh concrete, indicating that this combination of fibers leads to decrease both the plastic viscosity and the constant viscous for all mixtures comparing to that of concrete mixtures with one fiber type.

1. Introduction

According to ACI Committee report about the fibrous concrete worldwide application, fibers have been widely used in concrete all over the world. Indeed, large and interesting projects were established with the use of fiber-reinforced concrete (FRC), such as demountable panels for parking garages, runway slabs and nuclear waste container [1,2].

Massive quantities of several types of FRC are fabricated annually by dint of its low environmental impact and its enhancement properties in the hardened state, compared to conventional concrete [3]. In fact, FRC has various technical advantages, including a low permeability [4], high flexural strength [5], good failure impact resistance [6], ductility and cracks control [3] besides the reduction of shrinkage and expansion rate of concrete [4]. Nevertheless, it has been reported that the workability of fresh concrete was negatively affected by the introduction of fibers [7–9]. As a matter of fact, the influence of fibers on fresh concrete properties depends on their nature, length, shape and volume fraction [10]. For instance, adding steel fibers reduces the concrete workability and requires more mixing time than ordinary concrete because of its high specific gravity [3]. On the other hand, PPF reinforced concrete requires less mixing time than steel fiber reinforced one [11]. It is worth noting that,

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polypropylene fibers have a lot of advantages over other commercially available synthetic fibers because of their light weight, cost efficiency, low thermal conductivity and being resistant to attack by acids and alkalis. Besides, polypropylene fibers have hydrophobic levels, which protect them against wetting with cement paste and have no effect on the water dosage needed. Hence, the use of PP fibers in field concrete is gaining popularity nowadays. In addition, it has been reported that adding polypropylene fibers have a low impact on air content and fresh density because of the low density of PPF unlike other types of fibers as steel fibers. Akça et al. [12] found that adding 1.5% of PPF (by volume) in concrete increases the air voids from 1 to 1.3%. In the same time Hassanpour et al. [3] used PPF on lightweight aggregate concrete indicating that PPF have no effect on concrete fresh density.

In terms of PPF length effect on the workability, Hassanpour et al. [3] reported that the workability of PPF reinforced lightweight concrete decreases with the increase of fibers length, and among the two previous fibers types, the lowest effect on the slump was attributed to PPF [3]. This result was confirmed by Li et al. [10] whose studied the combined effect of the water film thickness and PPF length reporting that increasing PPF length in mortar decreased significantly the slump flow. The workability loss of PPF reinforced concrete and mortars depends greatly on the friction between fibers and cement pastes as well as the use of admixtures. As the inclusion of PPF, causes an increase of the granular structure and a drop of the maximum compactness which increases the friction between fibers and cement particles and hinders the granulate movement during the test. This phenomenon results in a decrease of the slump value and an augmentation of the viscosity of mixture. Zhang et al. [8] have investigated the flowability and rheology of polypropylene fiber reinforced cement paste, indicating that increasing PPF length and dosage increased evenly the apparent viscosity and the shear stress of the cement paste. In the same study, it has been proved that adding a superplasticizer in the cement paste showed three times higher flowability. Actually, the incorporation of a superplasticizer in FRC has also been suggested by other researchers as a technic to maintain concrete workability besides other solutions such as the augmentation of the paste amount in the mix or using pozzolanic additions [3,13].

It is worth noting that slump test value is an important indicator of fresh properties, yet still not sufficient to characterize the fundamental rheological properties of concrete, namely plastic viscosity and yield stress [14,15], especially with the growing development of construction technics and complicated shapes of buildings which required a better understanding of the concrete fresh state. Despite this fact, only few investigations have been devoted to studying the rheological behavior of fiber reinforced ordinary concrete. Moreover, the tribological behavior of FRC has been ignored in the previous studies, even though concrete implementation by the traditional or pumping technics depends on the tribological properties of concrete such as the shear stress and the viscous constant [16].

Therefore, the rheological and tribological behaviors of FRC were investigated in the present study. First of all, the control concrete (CC) formulation was selected with respect to the best rheological and tribological behaviors via the optimization of the paste volume. Thereafter, PPF was added with different lengths, shapes, and dosages in the first step. Afterward, a polycarboxylate superplasticizer (Sp) was introduced in the mixes with numerous percentages to maintain the concrete flowability, while the plastic viscosities and the viscous constants were determined and compared with those of the previous step. Finally, based on the practical use of fibers in construction sites, two fiber lengths were used in the same mix with different weight combinations and both rheological and tribological parameters were analyzed.

2. Experimental program

2.1. Materials

The cement used to formulate all concrete mixes is an ordinary Portland cement (CEM I 52.5N) manufactured by EQIOM cement plant in France. It is characterized by a density of 3.1 g/cm^3 and a specific surface area of 4300 cm^2/g. Its chemical and mineral compositions are given in Table 1.

In addition, Table 2 gives all characteristics of the coarse and the fine aggregates while Fig. 1 shows their grading curves.

Moreover, in the present investigation, PPF produced by SikaFibre® were added to concrete mixes with 3 different lengths (19, 30 and 54 mm) as shown in Fig. 2.

The 19 and 54 mm fibrillated twist PPF are intended to be used for reinforcement and precast concrete due to their high tensile strength (689 MPa). However, 30 mm PPF have a wavy shape and lower tensile strength (486 MPa). At the same time, this type of fibers is more flexible than the others, thanks to its high elastic modulus (6.9 GPa), unlike 19 and 54 mm fibers (5.75 GPa). The properties of these fibers are depicted in Table 3. Using scanning electron microscope (SEM) analysis, the difference between fibers shape can be clearly seen in Figs. 3 and 4.

Lastly, the superplasticizer (Sp) used was polycarboxylate based type, with a solid mass content of $33.0^{\pm 1.5}$% and a specific gravity of $1.07^{\pm 0.02}$.

2.2. Concrete mix design

First of all, knowing that the rheological and the tribological behaviors of concrete depend on mixture compositions and its workability, four concrete mixes (without fibers) namely CC1, CC2, CC3 and CC4 were produced in order to obtain the control formulation. All concrete mixes were formulated with the same optimal G/S ratio (1.44), determined by Dreux-Gorisse method [17] using the grading curves of aggregates (Fig. 1). In addition, W/C ratio has been fixed at 0.5 unlike the cement paste volume which was different for each mixture, to obtain four various concrete mixes with several workabilities. The best formulation is chosen with respect to the best workability, rheology and tribology properties.

Once the optimum formulation was determined, PPF were added in mixes to study their effect on concrete rheological and tribological properties. Nine mixes were produced with three different fiber lengths (19, 30 and 54 mm) and three PPF percentages (0.12, 0.24, 0.36% by volume of concrete) namely FRC19, FRC30 and FRC54.

Noted that using fibers in concrete decreases its workability [8], researchers proposed adding superplasticizer in FRC to improve its workability and fluidity. Therefore, the formulations made in the previous phase were reproduced by adding a different percentage of superplasticizer (0.2–0.4%) to obtain the optimum concrete workability without segregation.

In order to control micro and macrocracks in construction sites, FRC are often made with 2 different lengths in the same mix. Considering this fact, the last part aims to investigate this combined effect by studying three concrete mixes with different 19 mm/30 mm fibers ratios equal to 0/100, 30/70, 70/30 and 100/0 respectively which leads to obtain the best combination percentage. It is worth noting that the target strength class of all concrete formulations is C35/45. The detailed mix proportions of all phases are shown in Table 4.

2.3. Test protocol and measurements

The concrete mixes were prepared basing on the technical sheet of fibers and according to NF EN 14845-1 standard, using a concrete mixer. Starting with mixing fine and coarse aggregates for 1 min, cement and fibers were then added and mixed for 2 min, and finally the water containing the superplasticizer was added.

Table 1
Chemical and mineral compositions of Portland cement (CEM I 52.5 N).

Chemical composition		Mineral composition	
Element	(%)	Element	(%)
PAF	1.4	C_3A	8.5
INS	0.4	C_3S	61.8
SiO_2	20	C_4AF	10.7
Al_2O_3	5.1	C_2S	19
Fe_2O_3	3.2	–	–
CaO	64.5	–	–
MgO	0.8	–	–
SO_3	3.2	–	–
K_20	0.82	–	–
Na_2O	0.23	–	–
S^{2-}	0.01	–	–
Cl^-	0.06	–	–
CO_2	1	–	–
CaO	2	–	–
Na_2Oeq	0.77	–	–

Table 2
Aggregates properties.

Aggregates type	Size (mm)	Specific gravity (g/cm^3)	Compactness	Water absorption (%)	Finesse modulus
Gravel (G)	6.3–20	2.42	0.61	2.3	–
Sand (S)	0–4	2.79	0.64	0.9	2.32

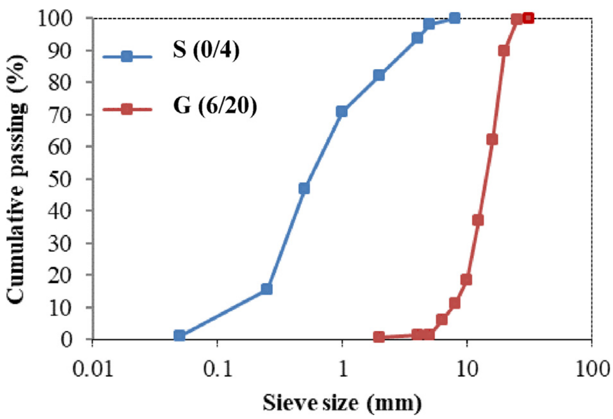

Fig. 1. Grading curves of fine and coarse aggregates.

Fig. 2. Polypropylene fibers (PPF).

2.4. Testing program

After mixing, the fresh concrete was instantly subjected to the following measurements:

- Workability

In this study concrete workability was measured according to the standard NF-EN 12350-2 [18] using Abrams cone, in which fresh concrete was poured in three layers, each layer is tamped 25 times, and the cone is carefully lifted which makes concrete flowed. The slump was then measured as the drop-in height of the concrete mix.

- Rheological measurement

It has been reported by Wallevik et al. [19] that two different concrete formulations with the same slump value may have different rheological properties (yield stress and plastic viscosity). In addition, previous studies proved that concrete flow depends on its rheological behavior during the implementation. As the slump test is related to the yield stress only which represents the flow initiating, however as soon as the flow begins it is the viscosity that influences the concrete flow. Therefore, several studies proved that the slump test is not efficient to characterize the fundamental rheological properties of concrete [20].

A new concrete rheometer, developed by Soualhi et al. [21], was used to determine the rheological properties (Fig. 5). The apparatus is composed of an agitator with speed electronic control, a steel vane with a double U shape of 15 cm and 10.5 cm in height and diameter respectively and a cylindrical container (h = 25 cm and d = 30 cm) with 18 square steel rods 9x9 mm^2 and 22 mm of length welded in the inner wall in order to optimize the adhesion of concrete to the container inner wall [22].

The rheological test consists to fill the metallic container with fresh concrete in two layers; each layer is tamped 25 times with a metal rod. Then the vane is placed in the center and plunged into the concrete mix. Thereafter, corresponding to the imposed rotation profile shown in Fig. 6, and for each speed level, the total torque is measured and recorded. The rotating vane creates two concrete layers during the rotation process. The first one is beyond the vane and moves with it while the second one still stagnant in the recipient borders. This phenomenon creates friction between the two concrete layers which allows to determine the concrete viscosity (Fig. 7).

The plastic viscosity μ was then determined by assimilating concrete rheological behavior to a Bingham fluid to fit the shear stress and shear rate according to the following equation:

$$\tau = \tau_0 + \mu\dot{\gamma} \quad (1)$$

It has been admitted by many authors in the literature that the concrete rheological behavior presents a laminar flow therefore the Bingham model is used for various types of concrete [19,24–32]. It is worth noting that, the test protocol and the calculation method used are based on the Bingham model. Besides, the degree of accuracy is 5% and rage of confidence is 5.8% for the viscosity and 3.1% for the yield stress [21].

Furthermore, the Bingham model relates linearly the shear stress and the shear rate between adjacent layers of concrete and explains the load distribution of the shear stress which is divided in two parts:

- The yield stress τ_0 that represents the minimal stress provided to overcome the aggregates frictions.
- When the yield stress excessed the shear stress the flow starts and the evolution of the shar stress is described by a linear equation, thereafter the plastic viscosity represents the delay effect induced by the friction between the underlying layer during the flow as follows:

The determination of the Bingham model parameters is based on Reiner-Riwlin equation. (Eq. (2))

$$\Omega = \frac{M}{4\pi h\mu}\left(\frac{1}{R_1^2} - \frac{2\pi h\tau_0}{M}\right) - \frac{\tau_0}{2\mu}\ln\frac{M}{2\pi h\tau_0 R_1^2} \quad (2)$$

WhereΩ, M, h, R_1, μ, and $\tau_0$present respectively the rotational speed (rad/s), torque (N.m), vane height (m); vane radius (m); plastic viscosity (Pa·s) and the yield stress (Pa).

Based on (Eq. (2)), and using the assumed values of μ andτ_0, the mean squared error is calculated as the difference between the calculated and the measured rational speed for each measured torque point (Eq. (3)).

$$mse = \frac{\sqrt{(\Omega_{calculated} - \Omega_{measured})^2}}{n} \quad (3)$$

Lastly, the plastic viscosity was obtained by minimizing the *mse* values [22].

Table 3
PPF properties.

Length (mm)	Diameter (mm)	Shape	Specific gravity	Elastic modulus (GPa)	Tensile strength (Mpa)
19	0.34	Fibrillated twist	0.92	5.75	689
30	0.48	wave	0.91	6.90	486
54	0.34	Fibrillated twist	0.92	5.75	689

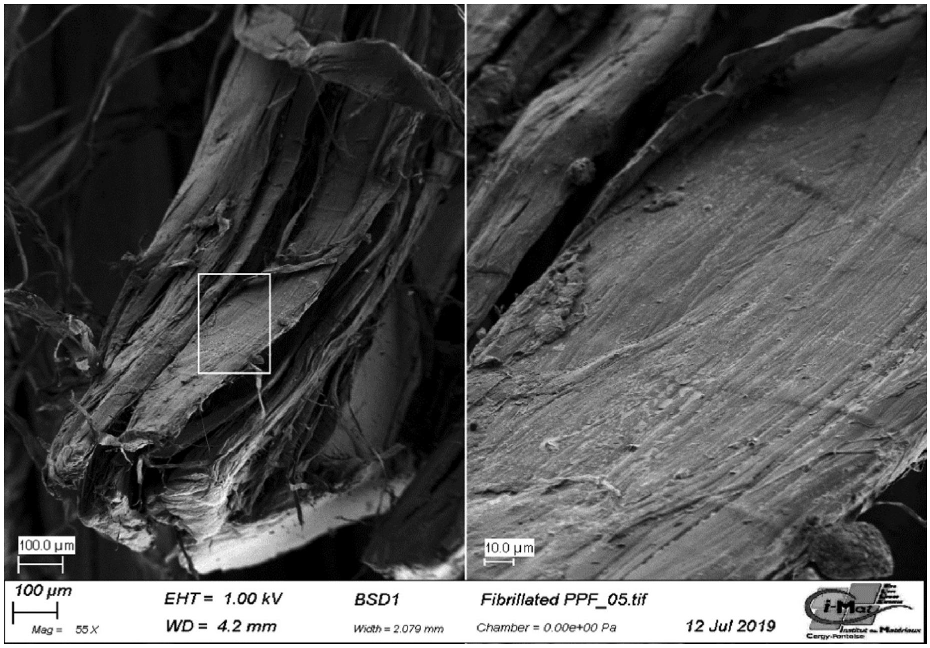

Fig. 3. SEM images of fibrillated twist PPF.

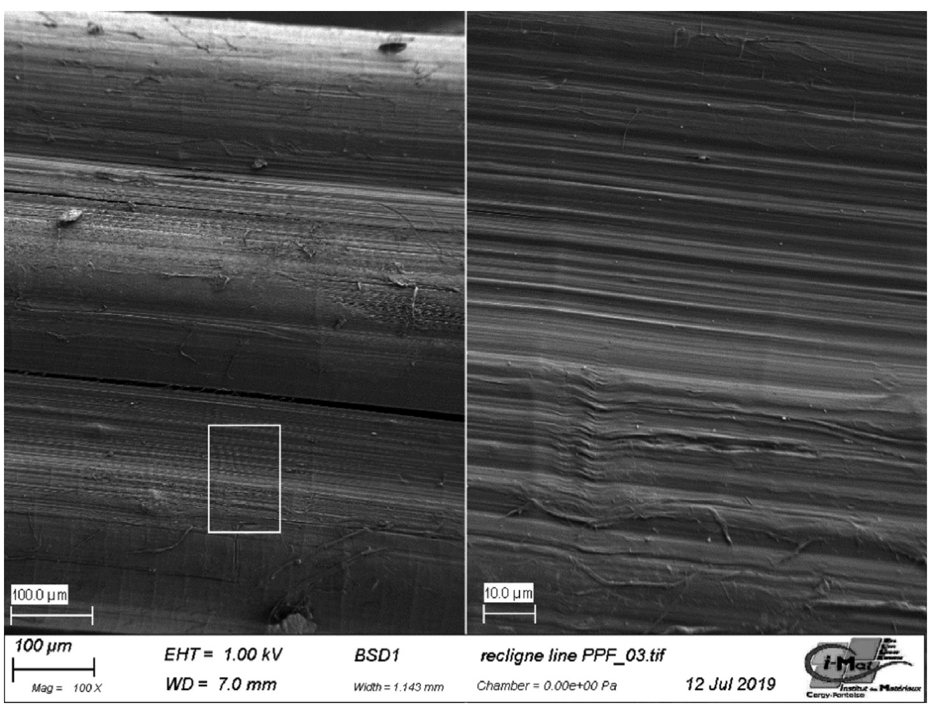

Fig. 4. SEM images of wave PPF.

- Tribological measurement

Given that pumpability of concrete depends on the steel–concrete friction occurred during the concrete flow through the pumping pipe, the purpose of this part is the determination of the viscous constant. Therefore, a new tribometer developed by Ngo et al. [34] was used (Fig. 8). The latter is composed of an agitator with electronic speed regulator and torque recorder, which is placed on the top of a smooth steel cylinder (h = 10 cm, d = 10.7 cm). The test consists in measuring the friction between the metal cylinder and concrete which allows to obtain the interfacial properties as the shear stress and the viscous constant of the boundary layer formed during the test as shown in Fig. 8.

The measurement of the friction couple was performed with an imposed speed profile (Fig. 9), according to the following steps:

- As it is shown in Fig. 8(b), the first layer of fresh concrete was filled up to the half of the container and received 25 stocks by a metal rod. Then the steel cylinder was fixed to the agitator and centered in the middle of the container.
- After saving the data from the previous phase, the second layer of concrete was filled up to the top of the container Fig. 8(c). The same process of the previous step was followed and measurements were recorded [16].

It is worth noting that, the first step consists on determining the friction between the bottom of the cylinder and concrete, while the second one permits to measure frictions between concrete and the cylinder (bottom plus lateral surface). As only the lateral frictions are required, the final results are obtained by subtracting the first step data from the second step ones.

Table 4
Mix proportions.

Phase	Concrete	$C_{P.V}$ (m^3)	W/C	G/S	L_{Fiber} (mm)	Fiber (%)	Cement (kg)	Water (kg)	Aggregate (kg)	Sand (kg)	Sp (%)	Fresh density (kg/m^3)	Air content (%)
1	CC1	0.280	0.5	1.44	–	–	340	170	1071	744	–	2335	2.2
	CC2	0.316					384	192	1032	717		2339	2.1
	CC3	0.380					462	231	963	669		2358	2.2
	CC4	0.395					480	240	947	658		2361	2.3
2	FRC19	0.380	0.5	1.44	19	0.120	462	231	963	669	–	2308	2.0
						0.240						2305	2.2
						0.360						2301	2.1
	FRC30				30	0.120						2310	2.1
						0.240						2309	2.0
						0.360						2306	2.1
	FRC54				54	0.120						2316	2.1
						0.240						2314	2.2
3	FRC19$_{Sp}$	0.380	0.5	1.44	19	0.120	462	231	963	669	0.2	2329	2.1
						0.240					0.4	2350	2.3
						0.360					0.4	2347	2.3
	FRC30$_{Sp}$				30	0.120					0.2	2333	2.2
						0.240					0.2	2330	2.3
						0.360					0.4	2353	2.2
	FRC54$_{Sp}$				54	0.120					0.2	2357	2.2
						0.240					0.2	2355	2.3
4	FRC19/30$_{Sp}$	0.380	0.5	1.44	19(50%)	0.060	462	231	963	669	0.2	2329	2.3
					30(50%)	0.060							
					19(70%)	0.084	0.036	30(30%)				2330	2.2
					30(30%)	0.036							
					19(30%)	0.036	0.084	30(70%)				2328	2.2
					30(70%)	0.084							

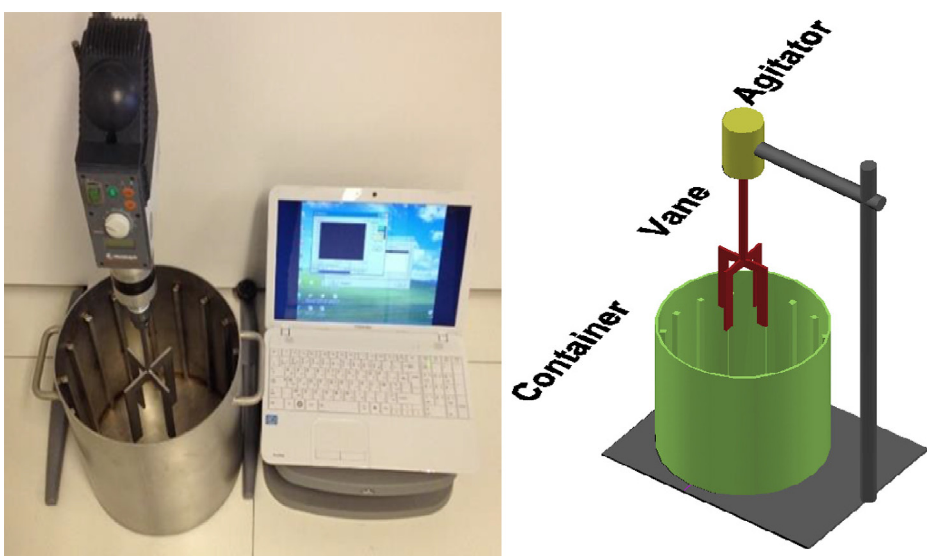

Fig. 5. Equipment used for the determination of the rheological parameters [23].

The viscous constant (η) was determined from the obtained measured torques using the empirical correlation (Eq. (4)) and the interface law equation (Eq. (5)) to fit the test results as follows:

$$T = T_0 + kV \tag{4}$$

$$\tau_t = \tau_{0t} + \eta v \tag{5}$$

Where T (N m) and T_0 (N m) are the torque imposed and the initial torque respectively, V (cycles/s) is the cylinder rotating speed and k (N ms) is the linear coefficient. Besides, the interface parameters are the shear stress τ_t (Pa), the viscous constant η (Pa s/m), the interface yield stress τ_{0t} (Pa) and the angular speed v (m/s).

In addition, taking into account the cylinder shape and dimensions, the interfacial parameters were calculated using the following equations:

$$\tau_{0t} = \frac{T_0}{2\pi R_t^2 h_t} \tag{6}$$

$$\eta = \frac{k}{(2\pi)^2 R_t^3 h_t} \tag{7}$$

While R_t (m) and h_t (m) represent respectively the radius and the cylinder height.

3. Results and discussion

3.1. Validation of the control formulation (without fibers)

In this phase, the rheological and tribological behaviors of control concrete were evaluated in order to choose the optimal formulation with the best workability, rheological and tribological parameters. Thus 4 mixes namely CC1, CC2, CC3 and CC4 were performed with W/C and G/S of 0.5 and 1.44 respectively, while the

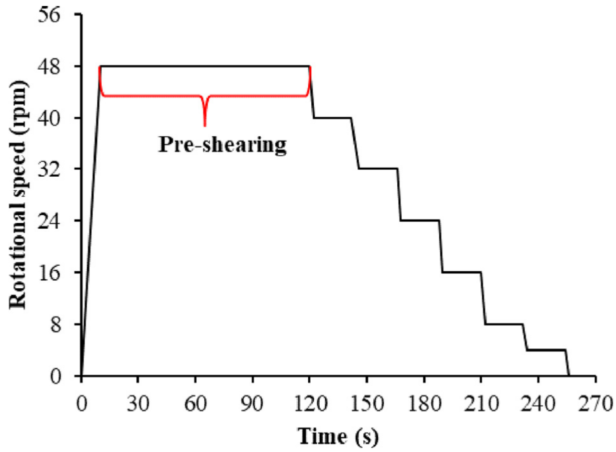

Fig. 6. Imposed vane rotation speed profile [22].

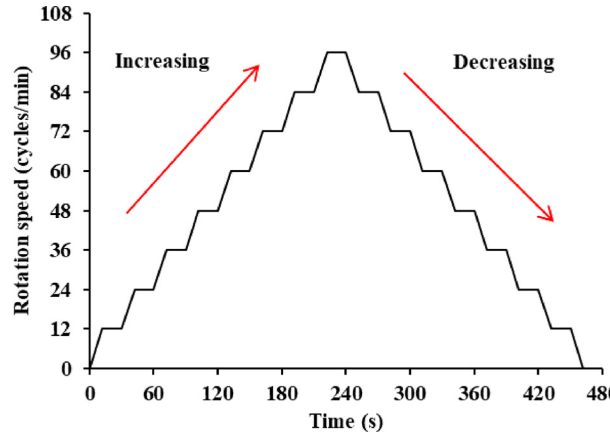

Fig. 9. Imposed cylinder rotation speed profile [34].

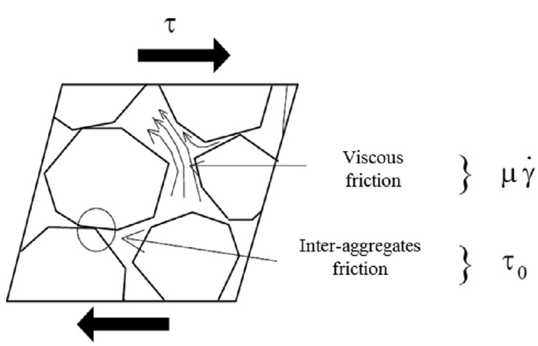

Fig 7. Contribution of solid phase and liquid phase to the shear strength of concrete [33].

cement paste volume was changed. Results of slump against cement paste volume are presented in Fig. 10. On one hand, it can be observed that the slump value increased by increasing the cement paste volume for the first three mixes. However, it decreased beyond 0.380 m^3 of paste volume, and the mix obtained was segregated this is may be explained by the fact that the tested formulations have a W/C equal to 0.5 which results in a fluid matrix, and we found that the optimum paste volume is 0.380 m^3 beyond that the aggregates are much distant that there is no relation between them. That's why the cement paste flows out of the granular skeleton and induced concrete segregation. Consequently, this mix was eliminated from both rheological and tribological tests.

On the other hand, as it can be seen in Fig. 11(a), plastic viscosity decreased progressively with increasing the cement paste volume. This is due to the lubricating effect of cement paste on the distance inter-aggregates, which creates more distances between aggregates and minimizes the friction. As a matter of fact, during the formulation of 1 m^3 of concrete, the aggregates volume decreases in increasing the paste volume. Thus, for a high paste volume, the aggregate volume is low and the aggregates are more discarded and surrounded by the paste. This phenomenon enhances the aggregates movement in concrete during the flow and decreases the concrete rheological parameters. Indeed other studies proved that using a high volume of paste improves the rheological behavior of concrete [22].

Likewise, Fig. 11(b) shows a loss of viscous constant corresponding to the increase of cement paste volume. In fact, the paste cement in the mix reacts as a transporter of small particles (cement

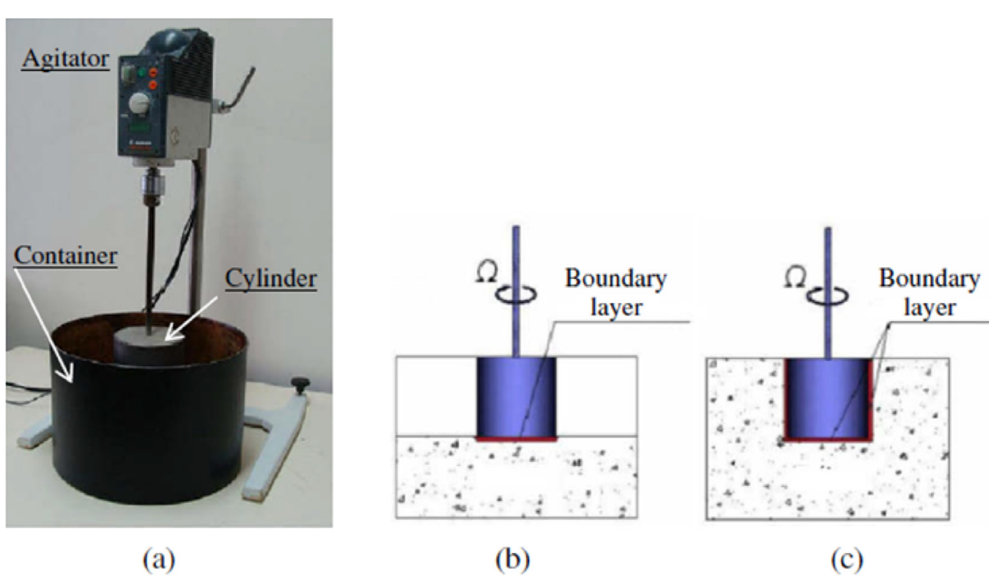

Fig. 8. Equipment used for the determination of the tribological parameters [34].

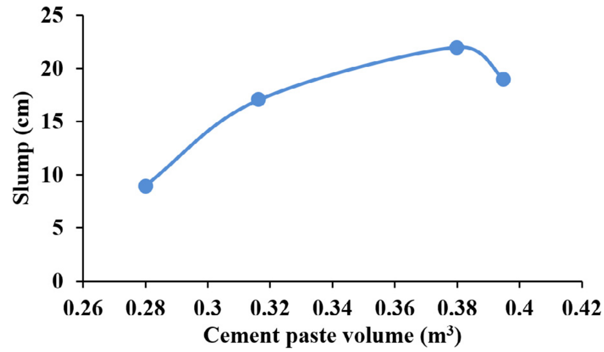

Fig. 10. Slump test results of control concrete.

and sand) to produce the boundary layer in the mix. Consequently, using an important volume of paste reduced the interfacial friction, which facilitates the aggregates movement and enhances the tribological behavior of concrete. This result is consistent with the literature [35,36].

It is commonly known that the implementation of fresh concrete by traditional technique or by pumping technic depends on rheological or/and tribological parameters. Furthermore, as much as the rheological and tribological parameters are low as much the implementation is easier. According to this fact, and taking into account the segregation phenomenon, the optimal formulation was attributed to the third mix (CC3) which has the lowest plastic viscosity and viscous constant comparing to other mixtures (Table 5).

3.2. Effect of PPF dosage, length and shape on concrete

This part aims to evaluate fibers length and percentage effects on the rheological and the tribological concrete behavior. Hence, nine formulations have been tested using three different fiber lengths (19, 30 and 54 mm) with various percentages (0.12, 0.24 and 0.36% from the total weight of concrete). Table 6 illustrates the obtained slump results as well as the rheological and the tribological parameters.

3.2.1. Workability results

According to Table 6, it appears that the slump value decreased for all mixes with the increase of the fibers length and dosage which explain that the concrete workability is negatively affected by the inclusion of PPF. For all cases, the mixture composed of 0.12% of PPF was classified as fluid concrete (slump class S4). However, increasing fibers percentage to 0.36% leads to obtain a plastic concrete (slump class S2), therefore the concrete behavior completely changed. These results are consistent with previous studies [8,9,37].

3.2.2. Rheological and tribological results

Fig. 12 outlines the variation of the viscosity and the viscous constant as function of the percentage of fibers for different lengths. Results show that, for each given length, the tribological and rheological parameters increased with increasing PPF percentage.

Furthermore, the plastic viscosity results, presented in Fig. 12 (a), indicates that the rheological behavior of mixes with 19 and 54 mm PPF was approximately the same, while the results values are overlapped around the same trend line, concluding that fibers length has no effect on the rheological behavior of concrete. Moreover, FRC30 rheological behavior was different from the others (FRC19 and FRC 54) where the plastic viscosity trend is presented in two parts. In fact, from 0 to 0.12% of PPF the plastic viscosity remains constant. However, beyond this percentage, it increased significantly to 12 Pa·s and remains constant again. This difference of behavior between the fibrillated twist and wave fibers based concrete may be explained by the fact that PPF 30 (wave shape) are more flexible and they are characterized by a high capacity to adapt with granulates movement in the mix. Hence, they can easily fill into the voids between the fine aggregates particles and pass through them making a different distribution of that of 19 and 54 mm PPF [10]. Furthermore, adding 0.36% for PPF30 have shown a slow increase of the plastic viscosity which is resulted by the fibers important dosage used in the mixtures. Results showed

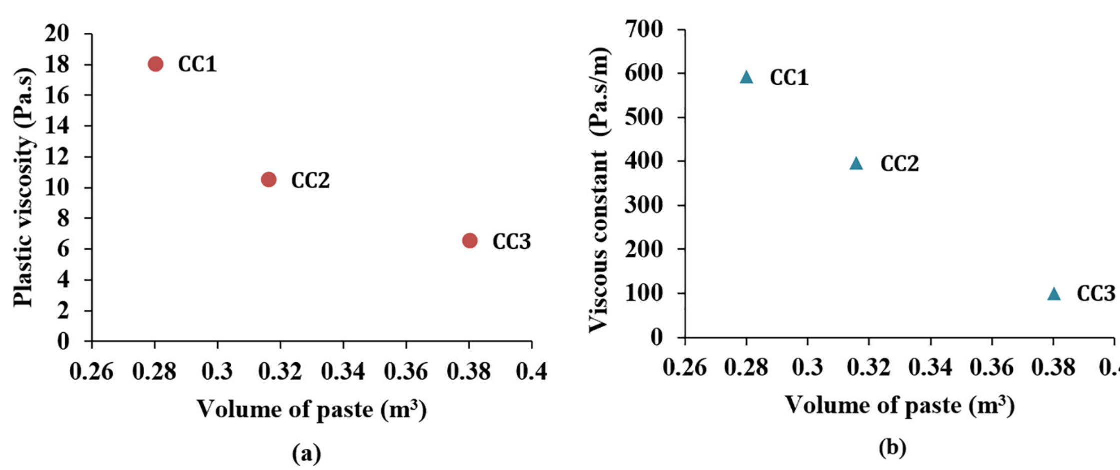

Fig. 11. Plastic viscosity of control concrete (a), viscous constant of control concrete (b).

Table 5
Formulation of the control mix.

Nomination	$C_{P.V}$ (m^3)	W/C	G/S	Cement (kg)	Water (kg)	Gravel (kg)	Sand (kg)	Slump (cm)	μ (Pa·s)	η (Pa·s/m)
CC3	0.380	0.5	1.44	462	231	963	669	22	17.3	92.7

Table 6
Rheological and tribological results of FRC.

Phase	Concrete mixes	$C_{P.V}$ (m^3)	W/C	G/S	L_{Fiber} (mm)	Fiber (%)	Slump (cm)	μ (Pa·s)	τ_0 (Pa)	η (Pa·s/m)	τ_{0t} (Pa)
2	FRC19	0.380	0.5	1.44	19	0.12	19	9.9	153.0	214.7	40.9
						0.24	17	10.5	214.2	270.5	27.6
						0.36	11	14.8	182.5	315.7	32.4
	FRC30				30	0.12	20	7.1	114.0	122.9	70.4
						0.24	16	12.6	140.2	250.3	77.9
						0.36	10	11.7	159.4	141.8	71.2
	FRC54				54	0.12	16	9.3	250.0	256.5	75.5
						0.24	13	10.8	282.9	225.5	32.7

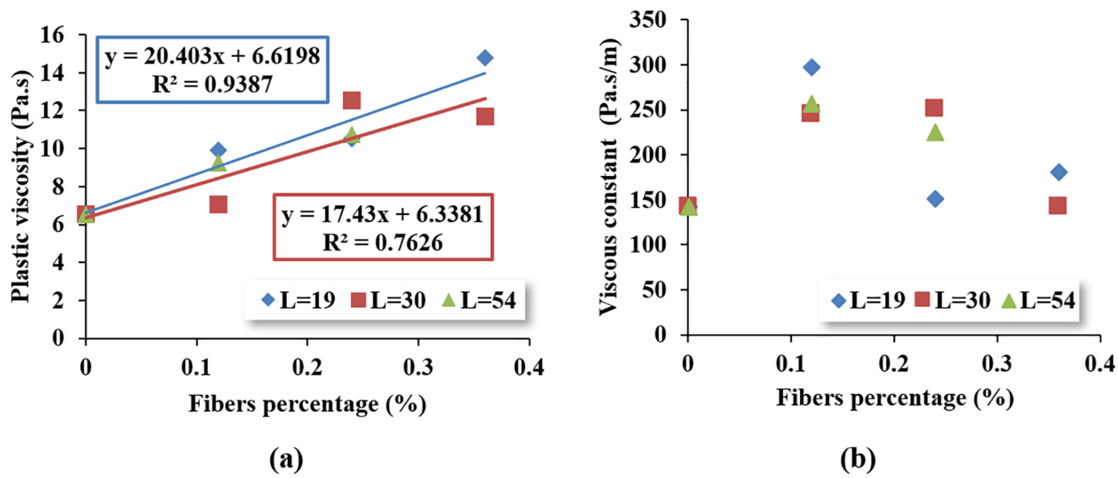

Fig. 12. Evolution of plastic viscosity (a) and viscous constant (b) as function of fibers percentage.

that as the fiber dosage is important as the friction inter-granulate increased. These frictions are caused by the granulates rearrangement and the voids filling in mixtures. Besides, the 0.24% represents the optimum dosage of fiber in concrete.

For each given length, the plastic viscosity is more important when the fibers amount is high. This is explained by the fact that the plastic viscosity depends on the solid concentration in the mix [10,11] which is modified by the PPF inclusion, causing an increase of the granular structure and a drop of the maximum compactness. In addition, the inclusion of fibers hinders the granulate movement during the rheological test (the shearing). This phenomenon results in a decrease of the slump value and an augmentation of the viscosity.

Fig. 12(b) represents the evolution of the viscous constant against PPF percentage. It can be established that for mixtures with only 0.12% of fibers the viscous constant increases when PPF were added. This is partly explained by the increase of both the concrete viscosity and the interfacial frictions between granulates and fibers. Furthermore, the viscous constant depends on the boundary layer formation which is hindered by the interfacial frictions rustling in an increase of the viscous constant.

Otherwise, FRC54 behavior is more disturbed than that of FRC19 and FRC30 and shows a blockage phenomenon with 0.36% of PPF. For this reason, FRC54 has been eliminated and both rheological and tribological tests have not been carried out for this mix. In fact, during the tests, a high risk of segregation was observed which has been confirmed in the obtained data.

Even though 54 and 30 mm PPF have not the same shape, both FRC54 and FRC30 have approximatively the same viscous constant trend. This finding indicates that the fibers shape has no effect on the tribological behavior. At the same time, the viscous constant was not well defined by the test equipment because of the high dosage of fibers in mixtures which caused an inhomogeneous PPF distribution as it can be seen in Fig. 13.

3.3. Superplasticizer effect

Basing on the previous phase outcomes, it has been concluded that the concrete workability and both rheological and tribological properties shows a significant degradation with the augmentation of the PPF concentration. In order to fix this problem, many researchers in the literature proposed the addition of a superplasticizer in the mix [6,8,38].

Through this part, the superplasticizer effect on rheological and tribological properties of concrete has been investigated. 8 mixes

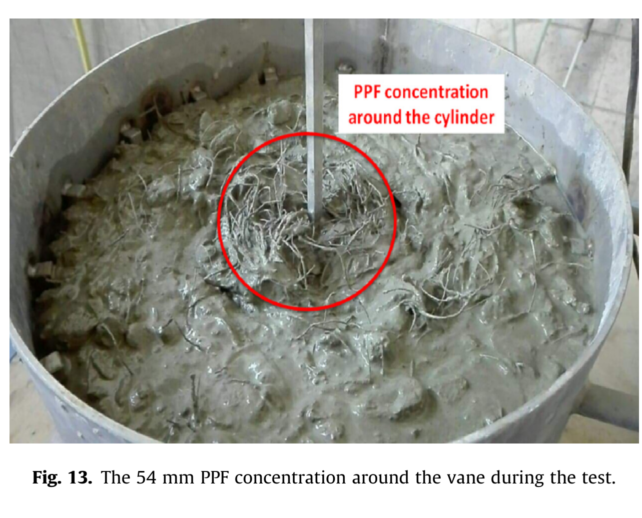

Fig. 13. The 54 mm PPF concentration around the vane during the test.

from the previous phase have been reformulated with the superplasticizer addition to highlight its effect on both rheological and tribological FRC behaviors. The Sp ratio was determined in order to maintain a constant slump (20 ± 2 cm) with a maximum ratio of 0.4% by the weight of cement. It should be noted that, beyond this limit, concrete segregation was observed. The Rheological and tribological results of FRC_{Sp} are resumed in Table 7.

3.3.1. Rheological and tribological behaviors of FRC_{Sp}

The evolution of the plastic viscosity and the viscous constant of FRC19 with and without superplasticizer are presented in Fig. 14. The results show a decrease of the two parameters when the superplasticizer is used. In fact, they are lower than those of the control concrete (CC).

Fig. 14(a) indicates that the plastic viscosity of concrete without superplasticizer increased with increasing fibers dosage. However, the addition of the superplasticizer in the mix permits the regain of the concrete workability as well as its rheological and tribological properties despite the augmentation of fibers dosage. In addition, a stable behavior was observed revealing a good fibers distribution.

In regards to the viscous constant, presented in Fig. 14(b), it remains approximatively constant and equal to that of the control concrete (CC). This result confirms that the superplasticizer enhances the tribological behavior of FRC.

3.3.2. Rheological and tribological behaviors of $FRC54_{Sp}$

The rheological and tribological behaviors of $FRC54_{Sp}$ are given in Fig. 15. It can be established that the plastic viscosity of $FRC54_{Sp}$ is nearly similar to that of CC3 and it remains constant by adding 0.2% of Sp. This explains that using the superplasticizer with PPF of 54 mm unheeded the negative effect of fibers in fresh concrete. However, adding a high percentage (0.24%) of 54 mm PPF increased significantly the plastic viscosity due to the important length and dosage.

At the same time, adding superplasticizer reduces slightly the viscous constant. As it can be seen in Fig. 15(b), $FRC54_{Sp}$ with 0.12 and 0.24 PPF percentages have almost the same viscous constant, similarly to that of $FRC19_{Sp}$ with 0.12 and 0.24 PPF percentages. It is worth remembering that19 and 54 mm PPF have the same shape which explains the similarity of $FRC19_{Sp}$ and $FRC54_{Sp}$ behaviors.

3.3.3. Rheological and tribological behaviors of $FRC30_{Sp}$

Fig. 16 represents the rheological and tribological results of $FRC30_{Sp}$. The rheological behavior shows a decrease of the plastic viscosity by adding 0.2% of Sp (Fig. 16(a)). Yet, increasing the quantity of PPF to 0.24%, while the Sp ratio remains constant, has always a bad effect on the plastic viscosity. This result permits to conclude that adding superplasticizer in $FRC30_{Sp}$, with a high percentage of PPF, has no significant effect on its rheology.

From Fig. 16(b), it can be seen that the viscous constant of $FRC30_{Sp}$ decreased significantly with 0.2% of superplasticizer and 0.12% of PPF. Nevertheless, adding more quantity of PPF with the same ratio of Sp increased the viscous constant. It is worth noting that, adding more percentage of Sp with this high ratio of PPF (0.24%) induced a segregation phenomenon and that is why it was limited at 0.4%. Despite the fact that adding a Sp in concrete enhances the tribological parameters, an increase of the viscous constant was recorded with 0.36% of PPF due to the high percentage of both Sp and PPF which caused a concrete segregation problem.

In fact, it has been reported that Sp can be absorbed by PPF using the total organic carbon analyses (TOC) manufactured by Shimadzu, TOC-LCPH which measures the amount of PCE absorbed by the cement particles in terms of TOC. In this study the TOC was measured for cement past without fibers and have been compared with TOC results of fibers cement pasts with different dosages and lengths of PPF, the results show that increasing fibers dosage and

Table 7
Rheological and tribological results of FRC_{Sp}.

Phase	Concrete mixes	$C_{P.V}$ (m^3)	W/C	G/S	L_{Fiber} (mm)	Fiber %	Sp %	Slump (cm)	μ (Pa·s)	τ_0 (Pa)	η (Pa·s/m)	τ_{0t} (Pa)
3	$FRC19_{Sp}$	0.380	0.5	1.44	19	0.12	0.2	22	3.9	80.1	127.1	39.2
						0.24	0.4	22	4.1	39.8	151.3	27.6
						0.36	0.4	20	5.5	77.8	121.0	19.6
	$FRC30_{Sp}$				30	0.12	0.2	22	2.6	69.5	64.9	29.6
						0.24	0.2	18	13.7	26.5	106.8	34.8
						0.36	0.4	20	13.1	45.2	228.7	25.0
	$FRC54_{Sp}$				54	0.12	0.2	22	7.1	86.5	186.8	32.4
						0.24	0.4	19	12.1	169.2	177.8	45.8

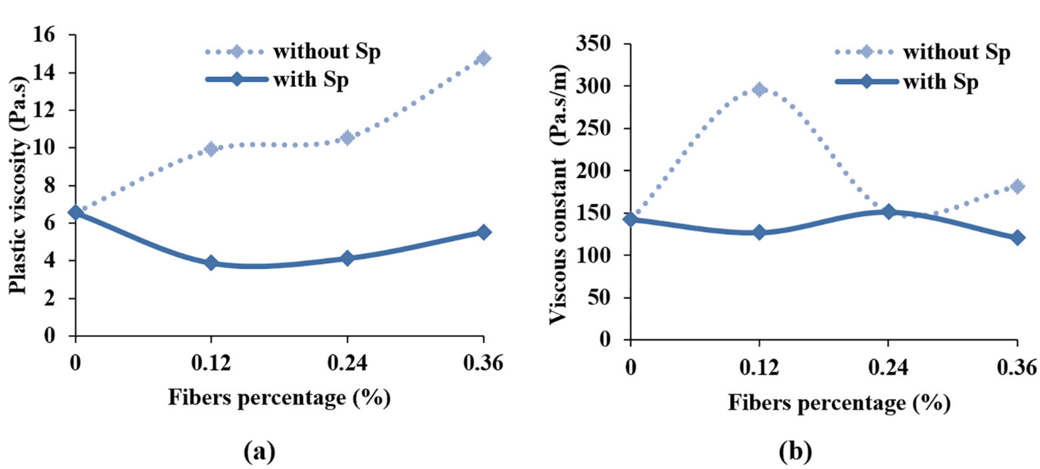

Fig. 14. Evolution of plastic viscosity (a) and viscous constant (b) of FRC19Sp as function of fibers percentage.

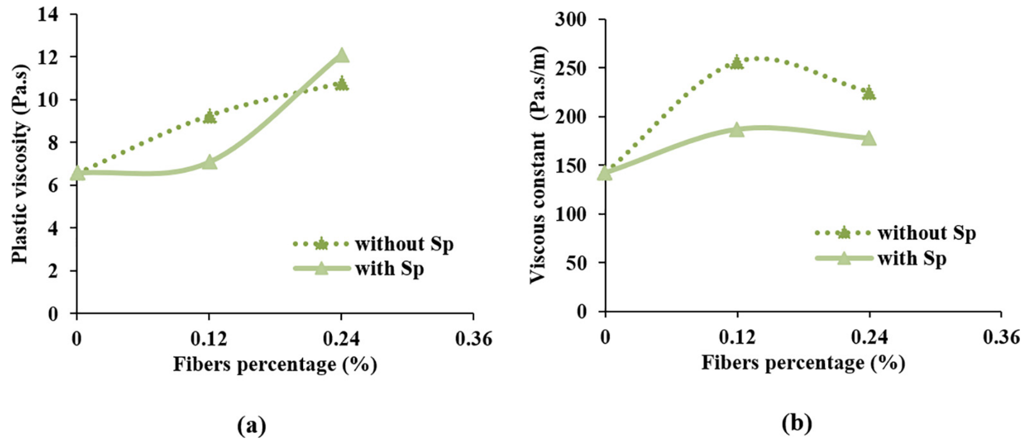

Fig. 15. Evolution of plastic viscosity (a) and viscous constant (b) of FRC54Sp as function of fibers percentage.

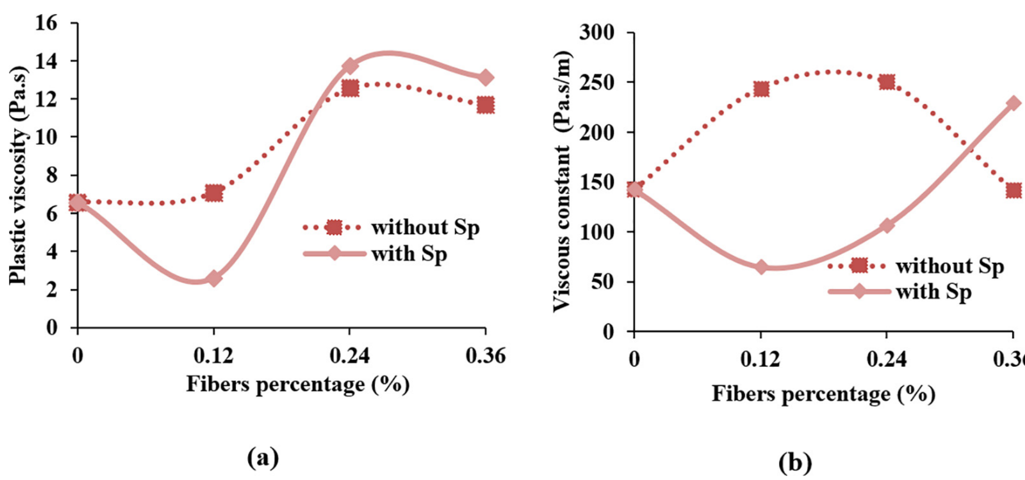

Fig. 16. Evolution of plastic viscosity (a) and viscous constant (b) of $FRC30_{Sp}$ as function of fibers percentage.

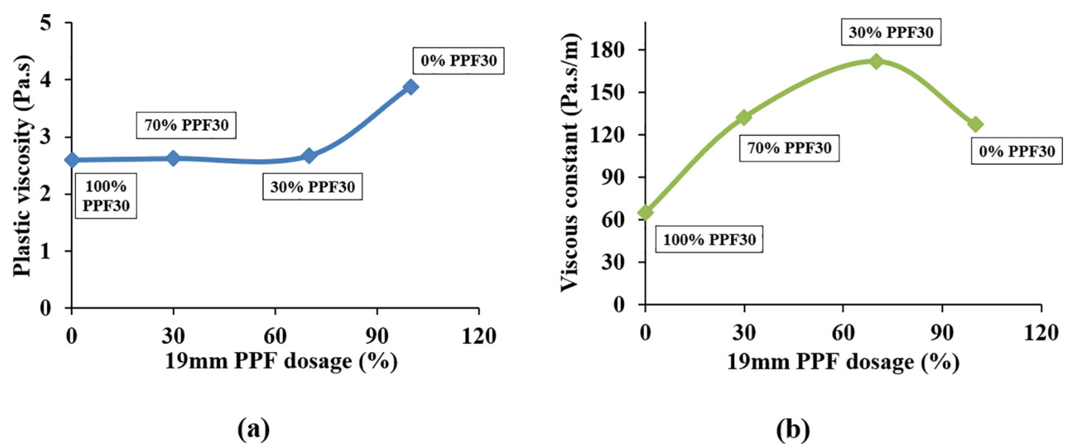

Fig. 17. Evolution of plastic viscosity (a) and viscous constant (b) of FRC19/30Sp as function of fibers percentage.

length increases the amount of TOC which prove the absorption of Sp [8].

As the superplasticizer was absorbed by each fiber and cement particle, the rheological and tribological behaviors improvement is due to the electrostatic repulsion and steric hindrance effects of the superplasticizer in the mixes as they destroy the flocculation state of the cement particles and fibers. This process leads to decrease the interaction between fibers and cement particles. Consequently, the slump values increased and the rheological and tribological properties improved. These results are in accordance with Zhang et al. [8] findings about the rheological behavior of fiber cement paste.

3.4. Effect of PPF mixed length

In terms of rheology, Fig. 17(a) shows the evolution of the plastic viscosity as a function of PPF19 dosages, from 0 to 100%. Up to 70% of PPF19 dosage, it appears that the plastic viscosity remains constant with the increase of PPF19 percentage at the expense of PPF30. In contrast, from 70 to 100% of PPF19, a significant increase was observed. It can be said that the combination of both shapes and lengths till 70/30 of 19 and 30 mm PPF respectively has eliminated the negative effect of PPF on the rheological behavior of concrete. This is due to the different shapes of the fibers used and the good fibers distribution in the mix thanks to the superplasticizer introduction.

At the same time, the viscous constant slightly increased (Fig. 17(b)) with increasing PPF19 percentage up to 70%, and decreased thereafter to become equal to the viscous constant of FRC19/30$_{Sp}$ with 30% of PPF19.

According to the data obtained, it can be concluded that the combination of two different lengths and shapes has a less significant effect on the rheological and tribological concrete behaviors than that of using only one length and shape. It is worth noting that the lowest viscosity was obtained by using 30/70% of 19 and 30 mm PPF respectively.

4. Concluding remarks

This study investigates the PPF effect on both rheological and tribological behaviors of fresh concrete. Therefore 4 series of formulation have been done, where the concrete rheological and tribological behavior was evaluated without and with the addition of different lengths (19, 30, 54 mm) and dosages (0.12; 0.24; 0.36%) of PPF. The inclusion of fibers in mixtures induced a workability loss besides a higher viscosity and viscous constant. Thus, a superplasticizer was added in order to enhance the fresh state concrete parameters.

Based on the obtained results, the main conclusions can be summarized as follows:

- Increasing the cement paste volume effectively enhances the rheological and tribological parameters of ordinary concrete.
- For the same PPF type, the slump decreases with increasing fibers length. However, this later does not affect the plastic viscosity.
- The augmentation of fibers percentage leads to increase the plastic viscosity of FRC. Furthermore, the use of fibrillated twist fibers permits to reduce the plastic viscosity more than wave fibers.
- In regards to the tribological test, the use of a superplasticizer is required in order to insure the smooth functioning of the tribometer.
- The addition of the superplasticizer have not affect the viscous constant. In contrast, adding 0.4% of Sp results in 3 times lower plastic viscosity comparing with FRC without superplasticizer.
- The use of different lengths and shapes of PPF in the same mixture improves the rheological and the tribological behaviors and enhances the fibers homogenization in the FRC.
- Among the various fibers investigated, 19 mm PPF with fibrillated shape seems to have the best effect in terms of rheological and tribological concrete behaviors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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