Impact of Alfa fibers morphology on hydration kinetics and mechanical properties of cement mortars

Soukaina Ajouguim, Jonathan Page, Chafika Djelal, Mohamed Waqif, Latifa Saâdi

Impact of Alfa fibers morphology on hydration kinetics and mechanical properties of cement mortars

Soukaina Ajouguim[1,2(*)], Jonathan Page[1], Chafika Djelal[1], Mohamed Waqif[2], Latifa Saâdi[2]

Corresponding author; **e-mail**: ajouguim@gmail.com

[1] Univ. Artois, Laboratoire de Génie Civil et géo-Environnement (LGCgE), ULR 4515, Béthune, F-62400, France.

[2] Univ. Cadi Ayyad, Matériaux innovants, Énergie et Développement Durable (IMED-Lab), 40000, Marrakech, Morocco.

Abstract

The Alfa plant is indigenous and spans a large zone throughout North Africa. Recently, Alfa plant has been used in building materials, notably as a reinforcement. This study aims to valorize the Alfa plant into fiber-reinforced mortar based on a cement-glass composite mix design. Two Alfa fiber morphologies are considered herein: different cutting lengths (10, 20 and 30 mm), and ground using a knife mill (shorter than 2 mm). These fibers were added to mortars at various volume ratios: 1, 2 and 3%. The workability and density of these distinct formulations were then measured in their fresh state. In comparison with the control mortar (CM), the introduction of Alfa fibers (either cut or ground), with ratios below 2% vol., leads to a slight decrease in mixture workability. However, Alfa fibers do not significantly alter the fresh material density. It was recorded a delay in setting time of the composites as a function of fiber addition rate. In the hardened state, an improvement in flexural strength is noticed for mortars reinforced with 1% vol. of fibers compared to the CM. However, results show that the increase in either type of fiber (cut or ground) generates a decrease in compressive strength compared to the CM. This outcome can be confirmed by both the decrease in heat released during the hydration reaction and water-accessible porosity inside the matrix.

Keywords: Mortar, Alfa fibers, Morphology, Workability, Porosity, Mechanical strength, Hydration kinetics.

I. Introduction

Previous studies [1–6] have highlighted the feasibility of producing, under specified conditions, building materials containing natural fibers that are more environmentally-friendly and of a quality comparable to that of conventional materials.

Alfa fiber, like all plant fibers, is basically composed of cellulose, hemicellulose, lignin, pectin and extractible elements [7,8]. The presence of these components changes from one fiber to the next and depends on several parameters, including age, growth conditions and source [9]. According to Hajj et al. (2019), such elements rich in hydroxyl groups are responsible for the hydrophilic nature of plant fibers [10]. This characteristic directly influences the rheological and mechanical properties of the cementitious material. It has in fact been reported that the incorporation of plant fibers results in a loss of workability, limited crack propagation, improved tensile and flexural strength, and lastly a more resistant hardened concrete [4,11,12].

The stiffness of natural fibers, which is also correlated with their chemical composition, heavily influences the mechanical properties of cementitious composites. According to Li *et al.* (2000), the strength and stiffness of natural fibers depend on both the cellulose content and the microfibril direction within the cell wall [13]. A high cellulose content actually causes potentially significant natural fiber deformations. Furthermore, the high ductility of these fibers is beneficial in reducing the fragility associated with cement-based composites [14,15].

Several parameters will influence the composite's mechanical and rheological properties, led by the poor level of fiber/matrix adhesion due to a fiber contraction effect subsequent to matrix hardening [16], coupled with the morphology and fiber addition rate parameters [4].

A number of works [11,17,18] have actually demonstrated that for lengths ranging from 12 to 30 mm and an Alfa fiber addition rate varying between 0.1 and 2.5%, expressed as a volumetric fraction, an increase in the composite's flexural strength combined with a drop in its compressive strength could be observed. For example, incorporating 1% vol. and 1.5% vol. Alfa fibers cut 20 to 30 cm long into a structural concrete induces a 14% decrease in compressive strength. Nonetheless, a tensile strength on the order of 4.58 MPa has been obtained, which amounts to a 3% gain compared to ordinary concrete [17]. This same behavior has been recorded for self-compacting concretes, with an addition rate of 0.1% vol. Alfa fibers cut to 12-mm lengths [18]. These conclusions differ for 2 to 5-mm long patching mortars reinforced with Alfa fibers with a volumetric fraction of 0.70% [19]. The rise in flexural strength and compressive strength of the microfiber-reinforced mortar has been measured at 15% and 30%, respectively.

The behavior of Alfa fibers in a cementitious matrix could be influenced by both chemical composition, which is correlated with fiber origin, and the type of selected cementitious matrix. As a case in point, Alfa fibers from Morocco contain 39% cellulose [8], compared with cellulose contents of 43% and 46% for fibers sourced in Tunisia and Algeria [7,20]. This difference in Alfa fiber chemical composition could exert an influence on its mechanical properties as well as on its capacity to reinforce the matrix. It would thus be worthwhile to study the effect of adding Alfa fibers from Morocco on the properties of a cementitious material.

Based on a literature review, the use of Alfa fiber as a reinforcement fiber has been explored in only a limited number of applications. A comparison between Alfa fibers and three other types of plant fibers (Diss, date palm and hemp) has been drawn in the study conducted by Belkadi (2018) [21]. This author showed that the incorporation of plant fibers led to reducing both the endogenous shrinkage and drying shrinkage of the composite relative to the reference concrete. From a mechanical perspective, the concrete containing Alfa fibers shows a sharp decline in flexural strength compared to the concrete containing the other types of fibers; however, its incorporation did improve the composite's deformation capacity. These results are in close agreement with the work performed by Khelifa *et al.* (2018) [17], which also revealed that integrating Alfa fibers is able to reduce shrinkage during the early age and provides a composite with characteristics basically similar to those of a structural concrete. Krobba *et al.* (2018) assessed the effectiveness of adding Alfa microfibers, manually cut to a length of 3-5 mm, to a patching mortar containing sand with a 0/0.5 mm particle size range. Their results indicated that the incorporation of volume of 0.75 % served to limit drying shrinkage while improving the composite's compressive strength, as compared to a reference mortar devoid of Alfa fiber [19]. On the other hand, Ajouguim *et al.* (2020) included Alfa fibers 20 to 25 mm long crushed using an electric mixer in a mortar containing sand with a 0/4 mm particle size range. The crushed fibers underwent surface treatment by means of an alkaline solution. A set of interesting results were recorded, revealing a 39% gain in flexural strength for the mortar containing 1% vol. of treated Alfa fibers [22]. The choices of cementitious matrix and Alfa fiber condition prove to be critical parameters in the development of an end product featuring good behavioral qualities from either a physical or mechanical standpoint.

The objective of this study is to make efficient use of fibers stemming from the Alfa plant, which for the most part is found in North Africa and Spain. This plant grows spontaneously in arid or semi-arid environments and moreover covers a land area estimated at 4,000,000 ha in Algeria, 3,186,000 ha in Morocco, 600,000 ha in Tunisia, 350,000 ha in Libya and 300,000 ha in Spain [23–25]. The application of these fibers derived from natural resources can serve to both lower production costs and mitigate serious pollution problems. The inclusion of these fibers in a cementitious matrix requires a preliminary study of the fiber properties, especially their hydrophilic and mechanical properties, as well as their interaction with the cementitious matrix.

The originality of this work program consists in developing an Alfa fiber-reinforced mortar based on a cement-glass composite mix design. According to the literature, this type of formulation that makes use of Alfa fibers has never been officially catalogued. The most fundamental characteristics of the composite produced during this study pertain to the use of: a highly-concentrated cement paste, a fine sand particle distribution (0/1 mm), fillers, and admixtures to adjust the mixing water. The benefit herein consists of obtaining a composite comparable to the cement-glass composite, with low porosity and a high level of mechanical strength, especially in tension. The first part of this effort will be devoted to optimizing the mix design by varying the water-to-cement and sand-to-cement ratios. The second part will examine the influence of both morphology and fiber addition rate on the properties of the fiber-reinforced mortar. Two morphologies have been selected for this part of the study: crushed and cut into various lengths (10, 20 and 30 mm). The effect of incorporating Alfa fibers into the cement mortar will be identified. The flexural strength and compressive strength were measured at various time intervals. A final study will compare the different effects of cut and crushed Alfa fibers on the properties of the resulting composite in both the fresh and hardened state.

II. Materials and methods

II.1. Materials

The mortar specimens were manufactured by mixing a Portland cement (CEM III/B 42.5N) from “La Grave de Peille” (France), the Blaine fineness is 5300 cm^2/g, and the density about 3.00 g/cm^3. Limestone filler was used (total carbonates equal to 98.8%) with a Blaine fineness of 4620 cm^2/g, and with a density of 2.7 g/cm^3. A siliceous sand from “ULTIBAT” with a particle size distribution of 0-1 mm (**Fig.1**) and a density of 2.61 g/cm^3 was used as aggregates.

To improve workability, a polycarboxylates-based superplasticizer form “Sika” with a density of 1.070 g/cm^3, was added to the mixture with a ratio of 1 % relative to the cement weight. In addition to avoid segregation, a viscosity-modifying agent (VMA) form “Sika” with a density of 1.025 g/cm^3, was also added with a ratio of 0.5% relative to the cement weight. It has been previously reported in the literature that the use of a superplasticizer and VMA in bio-based cementitious composites helps to reduce workability disturbances [4,26].

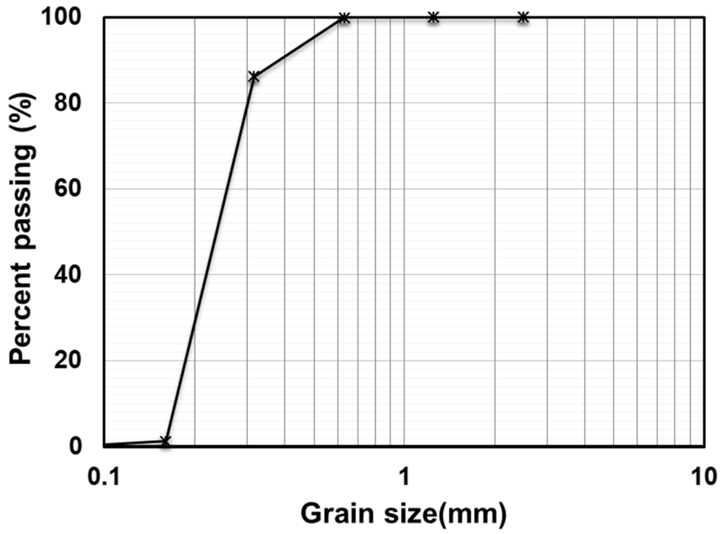


Fig. 1: Grain size distribution of sand aggregates

II.2. Alfa fibers characterization

The Alfa stem (*Stipa tenacissima L*) was harvested in the northeastern region of Morocco. The bulk density of Alfa fibers was determined using a helium pycnometer [4] to be 1.40 g/cm^3. The Alfa fiber chemical composition was specified in a previous work, with the main fiber components being as follows: 39.53% cellulose, 27.63% hemicellulose, 19.53% lignin, and 13.28% extractible elements [8]. The Alfa fibers were cleaned in order to remove any dust and impurities deposited on the surface. In the present study, two Alfa fiber morphologies have been considered: cutting at different lengths (10, 20 and 30 mm), and ground with a knife mill (length shorter than 2 mm). **Fig. 2** shows the external surface of Alfa fibers observed by means of scanning electronic microscopy (SEM). The micrograph indicates that Alfa stems has a rough appearance, with defects and many impurities (fat, wax, etc.) named as stomata distributed on the surface [8]. **Fig. 3** presents both Alfa morphologies studied in this paper.

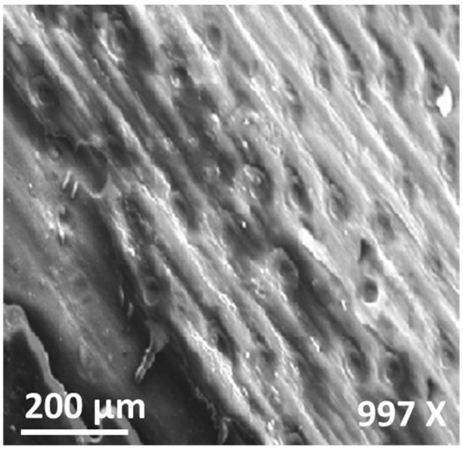


Fig. 2: SEM micrograph of the external surface of Alfa fiber **[8]**

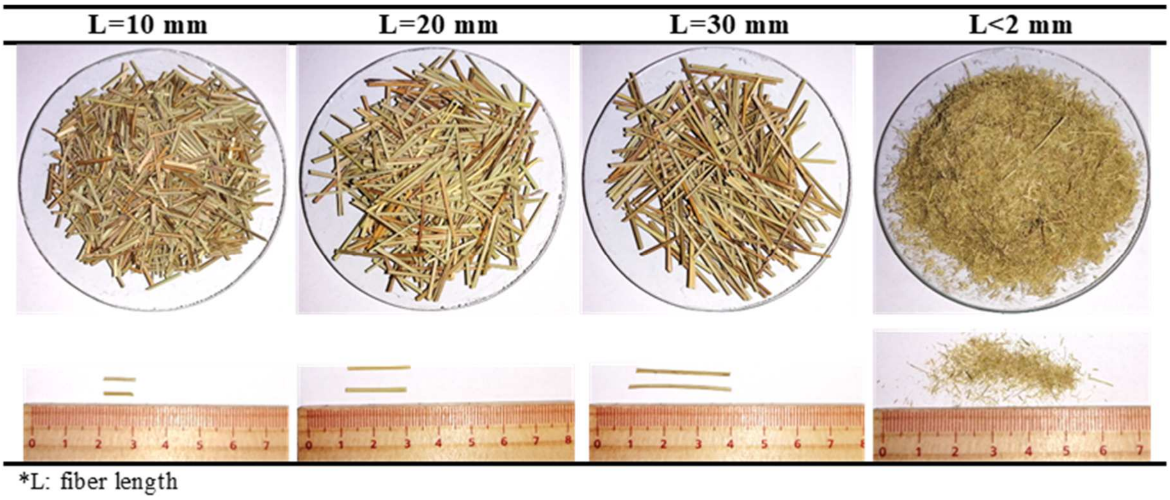


Fig. 3 : Cut and grinded Alfa fiber

Because of their chemical composition (mainly cellulose and hemicelluloses), Alfa fibers are very sensitive to water [8]. The water absorption kinetics of Alfa fibers were measured according to the procedure described in a previous work [12]. The applicable test protocol is as follows: (1) Alfa fibers were oven-dried at 60°C for 24 hours; and (2) 3.00 g of Alfa fibers were placed in a micro-perforated plastic bag, then immersed in water for various lengths of time (1 min to 48 h). The water absorption ratio was calculated using the following equation (1), with m_t denoting the mass of fibers at time (t) and m_0 the initial dry mass of fibers:

$$WA_t(\%) = \left(\frac{m_t - m_0}{m_0}\right) \times 100 \quad (1)$$

The water absorption kinetics of cut and ground Alfa fibers are presented in **Fig.4**. It should be noted that extending the immersion time leads to higher water absorption of both fiber morphologies. The water absorption kinetics of cut and ground Alfa fibers can be distinguished in two areas, separated by an intersection point at approximately 8 hours. The first area shows that ground Alfa fibers absorb more water than cut fibers during the first few minutes of absorption. After 8 hours, a different water absorption behavior was observed; therefore, the cut fibers display a higher water absorption than ground fibers after 8 hours of immersion. More specifically, the water absorption of ground fibers was approx. 55% after 8 hours of immersion, with a slow evolution reaching 62% at 48 hours. Cut Alfa fibers thus seem to possess greater water retention capacity but slower absorption kinetics in comparison with ground Alfa fibers. Nevertheless, the cut fibers follow a logarithmic evolution law that depends on immersion time, with the water absorption of fibers reaching about 86%, making it obvious that the water absorption of fibers increases with immersion time. This increase is typically correlated with fiber hydrophilicity, which depends on the fibers' chemical composition and nature. These results are in accordance with the literature [4,27], with a similar behavior observed for different types of fibers: the water absorption of fibers increases the longer the water immersion time.

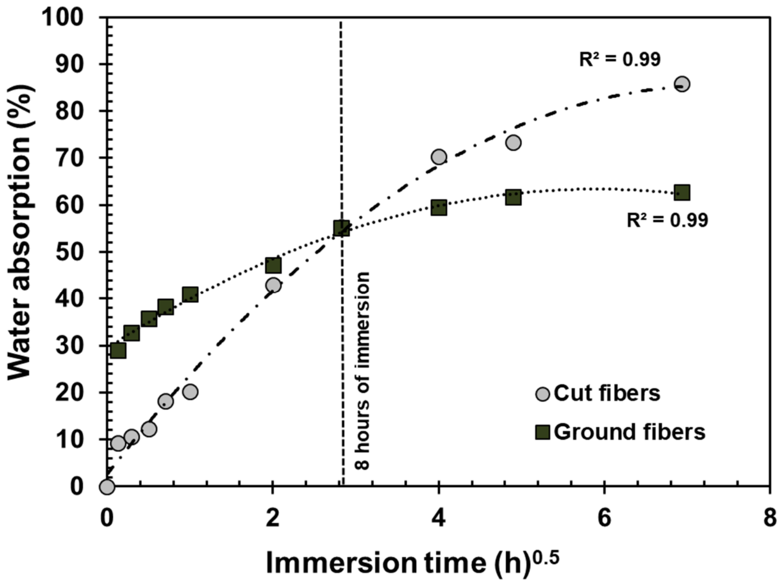


Fig. 4: Water absorption kinetics of Alfa fibers

II.3. Preparation of specimens

The sand and Alfa fibers were oven-dried at 60 °C to remove all traces of moisture. First, a dry mixing of the various constituents (cement, filler and sand) at slow speed (140 ± 5 min^{-1}) for 30 seconds. The 2/3 of the mixing water is introduced by mixing for 1 min 30 seconds. The superplasticizer is introduced (mixing for 30 sec), followed by 1/3 of the remaining mixing water (mixing for 60 sec), then, the VMA is added (mixing for 30 sec). Switch the mixer to the high speed (285 ± 10 min^{-1}) and continue the mixing for an additional 60 sec. Finally, the Alfa fibers were added progressively with slow mixing for 180 sec. The addition of Alfa fibers in the mixtures was based on volume. Specimens sized 40 x 40 x 160 mm were generated and then cured in a humid room (RH > 90%, T = ±20°C) until testing.

II.4. Methods

II.4.1. Fresh properties

- **Workability test**

The workability of the various mixes was measured by the flow table test, in accordance with the EN 1015-3 standard. In this procedure, a fresh mortar sample is placed on the flow table tamper, by means of a truncated conical mold, and struck with 15 vertical hits by raising the flow table and allowing it to fall freely from a height of 10 mm. The flow value of the mixture is estimated by averaging the slump diameters measured in two orthogonal directions.

- **Calorimetry**

The cement hydration kinetics were thus measured by a two-channel (I-Cal 2000 HPC) isothermal conduction calorimeter (**Fig. 5**). An isothermal calorimeter consists of a heat sink with a thermostat, two heat flow sensors and a specimen vial holder attached to each sensor. The heat of hydration released by the reacting cementitious specimen is transferred and passes across a heat flow sensor. The calorimeter output is calculated from the difference between outputs from the test specimen heat flow sensor and the inert specimen heat flow sensor. Since the heat is allowed to flow away from the specimen, this measurement will essentially take place at constant temperature (i.e. isothermal conditions). In order to ensure a representative test, the mixture sample here was introduced into the calorimeter immediately after mixing. Next, the heat evolution of the various formulations was monitored for the first 48 hours of hydration process.

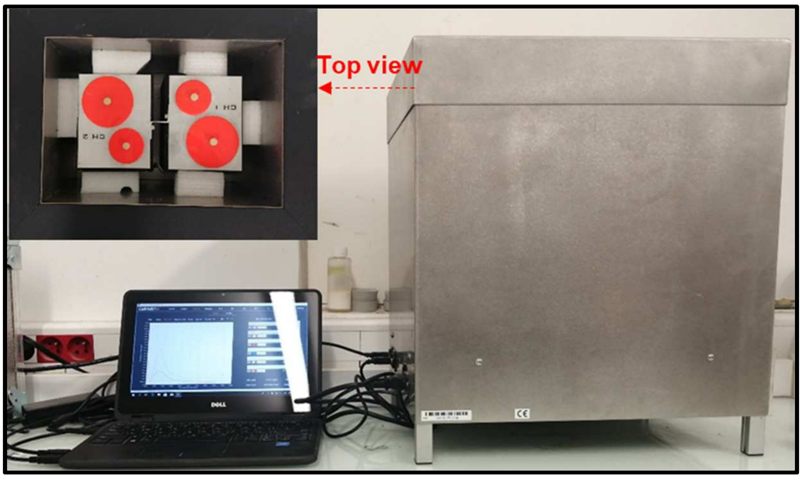


Fig. 5: Isothermal calorimeter I-Cal 2000-HCP

II.4.2. Hardened properties

- **Mechanical properties**

The flexural and compressive strengths of the various specimens were measured after curing, according to the EN 1015-11 standard. For flexural strength, three specimens from each mix were prepared and tested with a three-point bending. Six portions of the mortar prisms previously tested in bending were used for the measurement of the compressive strength.

- **Water accessible porosity**

The measurement of water-accessible porosity was carried out according to Standard NF P18-459. After 90 days of curing, the various specimens were dried in an oven at 105°C for 24 hours, until attaining constant mass. After cooling in a desiccator, the specimens were immersed in water under vacuum for 48 hours in order to reach saturation. The specimens were then weighed using a hydrostatic balance (m_{water}) as well as being weighed in air (m_{air}). Lastly, the specimens were dried in an oven at 105°C and weighed once again (m_{dry}). The porosity (ε) and specific gravity (ρ_d) were both calculated using Equations (2) and (3), respectively:

$$\varepsilon(\%) = \left(\frac{m_{air} - m_{dry}}{m_{air} - m_{water}}\right) \times 100 \quad (2)$$

$$\rho_d = \frac{m_{dry}}{m_{air} - m_{water}} \times \rho_{water} \quad (3)$$

III. Parametric study of the mortar composite

Both the water-to-cement (W/C) ratio and sand-to-cement (S/C) ratio are crucial parameters in defining the final properties of a cementitious material. Singh *et al.* (2015) exhibited that the mechanical properties of cement mortar decreased with an increase in S/C ratio [28]. Those authors also reported that a W/C ratio determination is required to make the mortar workable; otherwise, the addition of natural fibers is widely known to greatly influence composite workability and composite mechanical properties [29]. In this regard, when choosing an adequate mix design, incorporating Alfa fibers has been essential to studying the combination of the fiber effect with the variation in dosage of the set of constituents.

III.1. Cement composite mix design

To study the effect of incorporating Alfa fibers on the cement mortar properties, a major preliminary step focused on optimizing the cement paste parameters. The rheological, mechanical and physical properties of cementitious materials usually depend on the nature and amount of its various constituents. Likewise, the addition of cellulosic fibers into a cement matrix influences the behavior of these materials, which means that the amount of each constituent must be studied beforehand. By varying the water-to-cement ratio (W/C = 0.3, 0.4 and 0.5) as well as the sand-to-cement ratio (S/C = 1, 2, and 3), a set of nine formulations were mixed, containing Alfa fibers at 2% volume and 20 mm in length. The length and content of Alfa fibers correspond to the median values tested in the next part of this study.

Table 1: Composition of fiber-reinforced mortar with variation of the W/C and S/C ratios

Constituents (g)	Cement	Sand 0/1	Limestone (filler)	Superplasticizer	VMA	Water	Alfa fibers
FRM(0.3)$_1$	900	900	225	9	4.5	259.7	28.6
FRM(0.4)$_1$						349.7	31.1
FRM(0.5)$_1$						439.7	33.7
FRM(0.3)$_2$	600	1200	150	6	3	173.1	25.6
FRM(0.4)$_2$						233.1	27.3
FRM(0.5)$_2$						293.1	29.1
FRM(0.3)$_3$	450	1350	112.5	4,5	2.3	129.8	24.1
FRM(0.4)$_3$						174.8	25.4
FRM(0.5)$_3$						219.9	26.7

III.2. Fresh properties

The flow diameters measured on fresh mortars are presented in **Fig. 6**. **Fig. 7** shows the appearance of slump flows across the various mixtures. It is observed that the workability of reinforced mortar decreases as the S/C ratio rises; therefore, an increase in W/C ratio leads to higher composite workability. For S/C = 1, workability increases according to the W/C ratio. $FRM(0.3)_1$ and $FRM(0.4)_1$ display a respective workability of 19.5 and 20.9 cm and moreover present a homogeneous appearance, which is indicative of good fiber distribution in the cement matrix. However, $FRM(0.5)_1$ has a workability of 24 cm along with a fluid appearance, thus suggesting a heterogeneous distribution of Alfa fibers in the cement matrix. For this mixture, segregation has been observed, with a conglomeration of fibers in the middle of the fresh mixture sample (**Fig. 7**).

The increase in S/C ratio leads to a decrease in workability, i.e. slump values of 10.0 cm for $FRM(0.3)_2$ and 10.3 cm for $FRM(0.4)_3$, with a firm appearance, and a slump of 12.6 cm for $FRM(0.5)_3$. Based on these values, mixtures with a high S/C ratio and low W/C ratio should be avoided. In addition, the consistency of the $FRM(0.3)_3$ mixture was unmeasurable; nevertheless, the increase in W/C ratio for mixtures containing a high S/C ratio could improve the workability of a plant-based mortar. This finding has been confirmed by $FRM(0.5)_2$, which has a slump diameter of 20.2 cm while exhibiting a homogeneous appearance.

The correlation between fiber addition and composite workability has been confirmed by several studies. Singh *et al.* (2015) reported that insufficient water content leads to poor workability; therefore, a method for determining the optimal water content and W/C ratio influence on cement mortar should obviously be pursued [28]. Also, Haach *et al.* (2011) confirmed that mortar workability increases with an increase in W/C ratio [30]. Bouhamou *et al.* (2009) observed that increasing the water dosage serves to increase concrete fluidity and causes a decrease in solid concentration inside the matrix. An excessive injection of water actually causes segregation phenomena to appear in the fresh state [31].

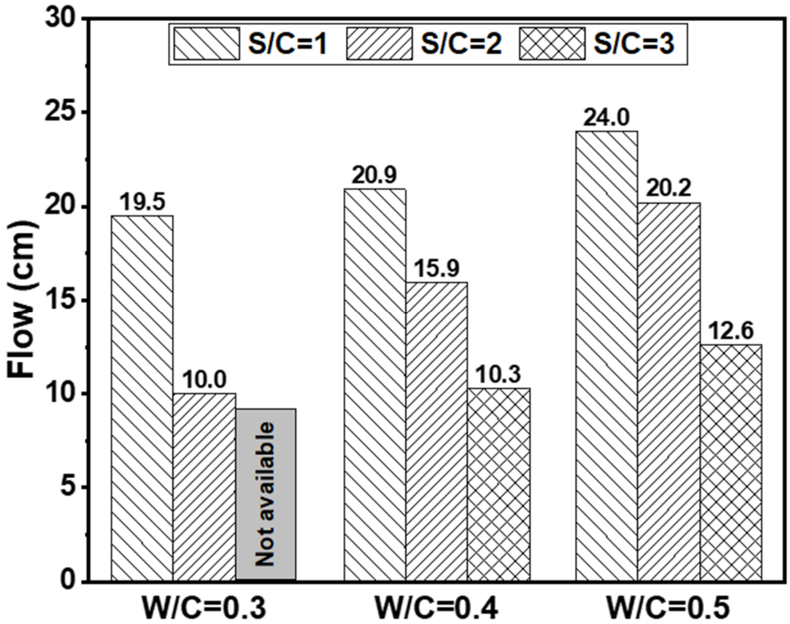


Fig. 6: Slump flow diameter of mortars

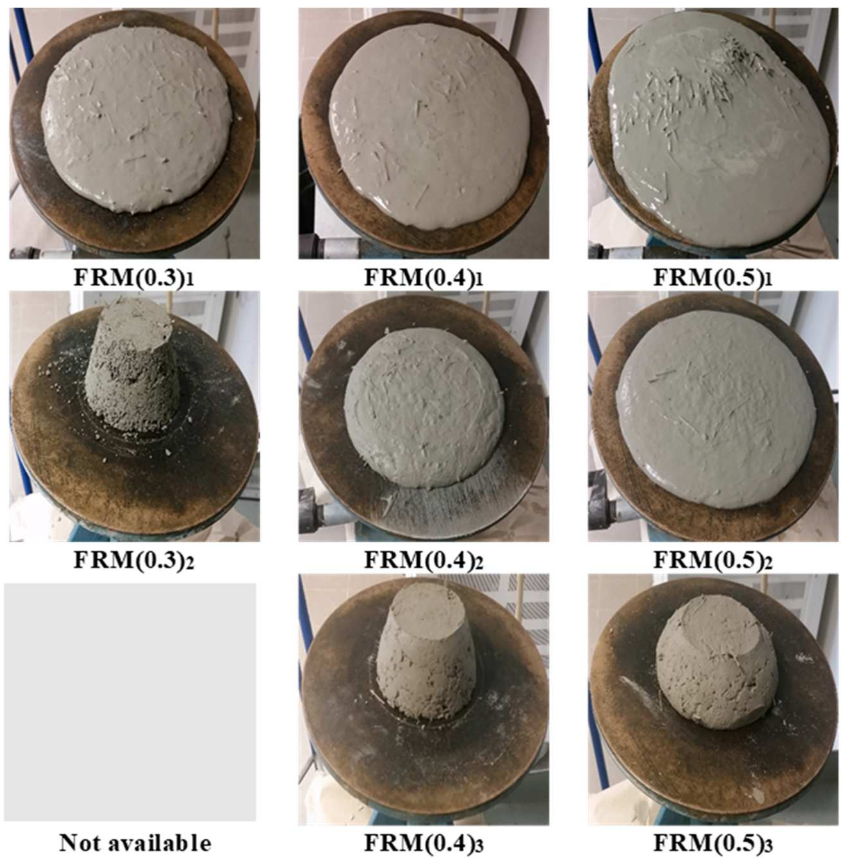


Fig. 7: Pictures of the table test for different mortars

III.3. Mechanical properties

To select the adequate formulation, mechanical tests were also performed in order to complement the conclusions drawn from the workability test. The flexural and compressive strengths of the various specimens were measured after curing of 7 days, according to the EN 1015-11 standard.

Table 2: Mechanical strength of different paste mortar

Specimens	FRM(0.3)$_1$	FRM(0.4)$_1$	FRM(0.5)$_1$	FRM(0.4)$_2$	FRM(0.5)$_2$	FRM(0.5)$_3$
Flexural strength (MPa)	6.3±0.8	4.4±0.5	3.2±0.3	4.6±0.3	3.3±0.3	3.5±0.4
Compressive strength (MPa)	39.3±3.4	25.9±3.6	14.8±1.4	24.5±2.4	13.7±1.7	14.8±4.2

FRM(X)y : Fiber-Reinforced Mortar prepared with X corresponding to W/C and with Y corresponding to S/C.

Based on results obtained from the workability test, mixtures with very low slump diameters (< 12 cm) were not tested in the hardened state. **Table 2** shows the compressive and flexural strengths of fiber-reinforced mortars with different S/C and W/C ratios. The increase in the W/C and S/C ratios lead to a decrease in the compressive strength of fiber-reinforced mortars. For an S/C = 1, the compressive strength of FRM(0.3)$_1$ is capped at 39.3 MPa, which reflects the highest compressive strength, in comparison with the other mixtures. Increasing the W/C ratio from 0.3 to 0.5 leads to a 64% reduction in compressive strength, while the compressive strengths of FRM(0.4)$_1$ and FRM(0.4)$_2$ are nearly identical. The flexural strength result reveals the same trend observed for compressive strength, when increasing the W/C ratio (**Fig. 8**). However, the increase in the S/C ratio leads to a slight increase of the flexural strength of the reinforced mortar. For instance, for the composite with W/C=0.5, increasing the S/C ratio from 1 to 3 leads to an increase of 9.3%. FRM(0.3)$_1$ has the highest flexural strength, i.e. 6.3 MPa, compared to the other formulations.

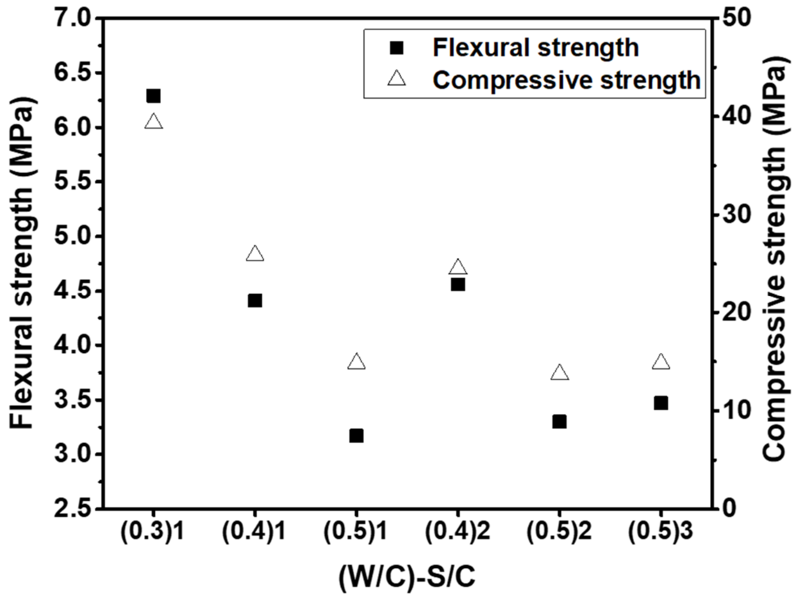


Fig. 8: Flexural and compressive strength evolution of mortar after 7 days of curing
W/C : water to cement ratio and S/C : sand to cement ratio

The workability measurements and mechanical testing were complementary in the effort to choose a basic formulation. Based on analysis of the various results, FRM$(0.3)_1$ shows the best mechanical properties. However, the slump diameter and apparent fiber distribution in fresh mixtures were high enough to confirm the relevance of this mix design in satisfying the objective behind this work, namely manufacturing an Alfa-based composite with good workability and high mechanical strength. Although FRM$(0.4)_1$ presents a relevant mix design candidate with slightly better workability than FRM$(0.3)_1$. However, its mechanical performance is lower than that of FRM$(0.3)_1$. As such, to limit cement content and preserve good workability and mechanical performance, it is preferable to select a W/C ratio ranging between 0.3 and 0.4. The basic formulation used in this work was therefore set at: W/C = 0.35, and S/C = 1.

IV. Influence of adding cut Alfa fibers on mortar properties

Generally speaking, the addition of natural fibers leads to distinct changes in the cementitious materials, in either their fresh or cured state. The length and addition rates require study in order to determine the optimal values of these parameters. The second step of this study aims to assess the effect of Alfa fiber length and addition rate on mortar properties. The Alfa fibers were cut by varying the resulting length (10, 20, and 30 mm) in applying three addition rates (1, 2 and 3% vol.) to the mortar composition. The various mixes are denoted as follows:

RM(CFX)y stands for Reinforced Mortar with cut fibers, where X = length (mm) and Y = addition rate (%). **Table 3** summarizes the previously chosen mortar mix design.

Table 3: Composition of the control mortar

Components	CEM III	Sand 0/1	Limestone (filler)	Superplasticizer	VMA	Water
Quantity (g)	900	900	225	9	4.5	304.7

IV.1. Properties of fresh mixes

The measured flow diameters of mortars reinforced with cut Alfa fibers are given in **Table 4**. The introduction of Alfa fibers does not significantly affect the workability of fresh mixtures, although Alfa fibers 10 and 20 mm in length do cause a slight reduction in the workability of mortars with 1% and 2% vol. of fibers compared to the control mortar (CM), which has a slump flow of 22.7 cm. Mixtures with 3% vol. of Alfa fibers exhibit a relative reduction of 6% in workability for fiber lengths of 10 and 20 mm, and of 15% for fibers 30 mm long. The increase in fiber length with a high volume content leads to the formation of clusters (i.e. RM(CF30)$_3$), which strongly influences the fluidity of fiber mortars (**Fig. 9**). This same behavior has been reported in the literature; it was highlighted that the plant fiber content and length significantly influence cementitious material workability: a major reduction in the slump of flax-reinforced concrete was observed for a fiber length ranging from 12 to 36 mm [4].

Table 4: Slump flow of cut Alfa fiber-reinforced mortar

Specimens	Addition ratio (%vol.)	Slump flow (cm)
CM	0	22.7±0.1
RM(CF10)	1	22.0±0.1
	2	21.8±0.1
	3	21.4±0.1
RM(CF20)	1	22.7±0.3
	2	22.2±0.1
	3	21.6±0.1
RM(CF30)	1	23.9±0.1
	2	22.4±0.2
	3	19.3±0.1

RM(CFX)y : Reinforced Mortar with cut fibers, where X = length (mm) and Y = addition rate (%).

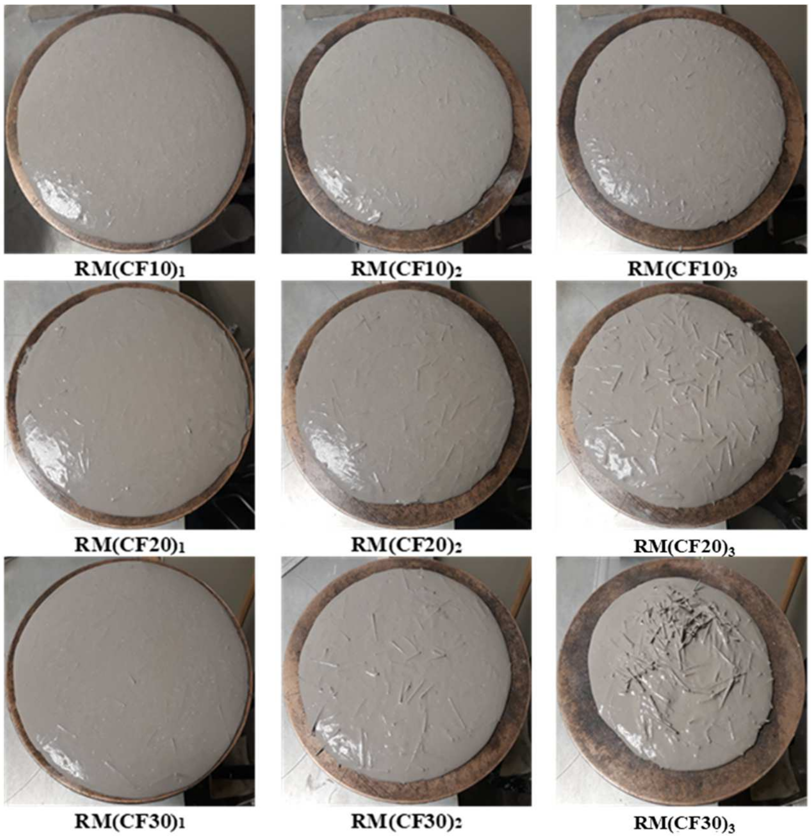


Fig. 9: Flow table test of cut Alfa fiber-reinforced mortar

IV.2. Mechanical properties

Fig. 10 presents the flexural strength of Alfa fiber-reinforced mortar with different lengths and addition rates. The cementitious materials are identified by low flexural strength, typically less than 10 MPa [1]. The control mortar (CM) has a 28-day flexural strength of 7.3 ± 0.3 MPa and 7.4 ± 0.3 MPa after 90 days of curing. The introduction of Alfa fibers into cement mortar leads to an increase in the flexural strength of cementitious materials. At 28 days of curing, a 39~40% gain in flexural strength was observed for RM(CF10)$_1$ and RM(CF20)$_1$, in comparison with CM. However, the increase in the level of Alfa fiber addition leads to a 25% and 27% decrease in flexural strength relative to RM(CF10)$_1$ and RM(CF20)$_1$, respectively. Moreover, it was noted that mortar containing cut fibers 30 mm long (denoted RM(CF30)) has a lower flexural strength, regardless of fiber content. This finding confirms that increasing either the addition rate or fiber length strongly influences the flexural strength. The effect of fibers length or addition ratio were studied in certain research work. However, an opposite fiber behavior was recorded compared to the present work. Page *et al.* (2017) [4] studied the effect of varying flax fiber length on the properties of a structural concrete. Both fiber length and addition rate were found to significantly influence the flexural strength of flax-reinforced concrete. It was noted that for each fiber length, the higher the flax fiber content, the greater the flexural strength. Moreover, these authors confirmed that the flexural strength of the composite increased when decreasing fiber length. Similarly, Çomak *et al.* (2018) [32] corroborated this same correlation between hemp fibers and the mechanical properties of cement-based mortars. It was reported that an increase in fiber content leads to an increase in flexural strength of between 1% and 17%. The difference observed by these two authors could be related to the actual fiber length studied. Page *et al.* used flax fibers cut to 12, 24 and 36 mm, which presents a rather high average length. In contrast, the highest length studied by Çomak *et al.* (2018) was 18 mm, a value closer to the optimal length given the higher flexural strength reported in Page *et al.* (2017)'s research. This discordance compared to the present work could be explained by the difference in fiber morphology. Flax fibers are known for their flexibility, which could ensure a great deformation inside the matrix. Unlike Alfa fibers, it was used in its raw state, which exposes diverse parameters including its rigidity that could influence the flexural strength of the composite.

After 90 days of curing, the flexural strength of the cut Alfa fiber-reinforced mortar decreased relative to its 28-day strength. For instance, the flexural strength significantly decreased, by 27% and 24% respectively, for $RM(CF10)_1$ and $RM(CF20)_1$; moreover, slight to medium decreases were found in $RM(CF10)_2$, $RM(CF10)_3$, $RM(CF20)_2$ and $RM(CF30)_1$. Nevertheless, mortars with fibers cut to a 30-mm length showed maximum flexural strength gains of about 33% and 30% as observed in $RM(CF30)_2$ and $RM(CF30)_3$ respectively.

This behavior could be explained by the degradation of plant fibers in contact with the cement matrix. According to Wei *et al.*, the degradation of natural fibers in a cement matrix could occur in four steps: (i) lignin and hemicellulose degradation, which serves to expose the holocellulose; (ii) reduction in cell wall stability due to hemicellulose degradation; (iii) dispersion of some cellulosic fiber components in the pore solution of the matrix, thereby promoting cellulose degradation; and (iv) a complete degradation of the natural fibers due to alkaline hydrolysis of their amorphous part [33]. Based on this hypothesis, the decrease in flexural strength ascribed to the addition of Alfa fibers could be correlated with fiber hydrolysis taking place inside the matrix over time.

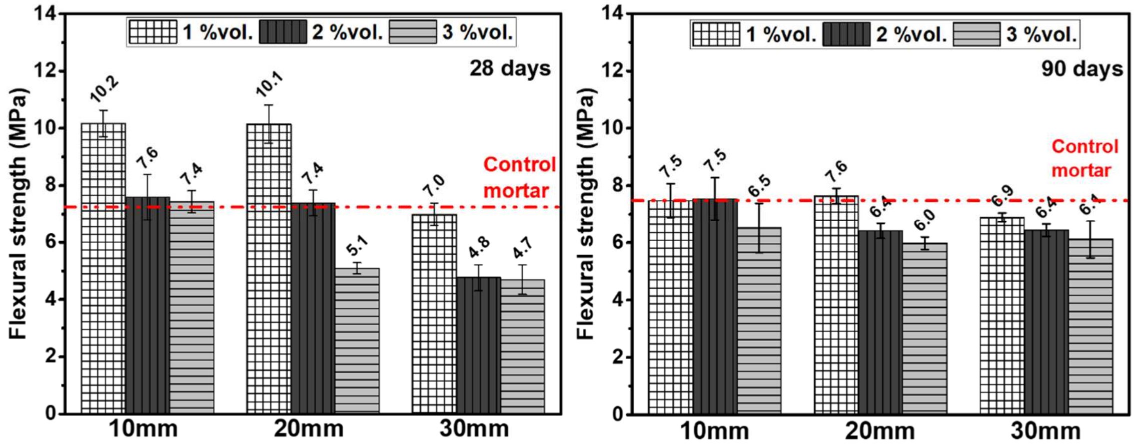


Fig. 10: Flexural strength of mortars reinforced with cut fibers at 28 and 90 days of cure

The compressive strengths after 28 and 90 days of curing various fiber-reinforced mortars are presented in **Fig. 11**. Compared to the control mortar (CM), the introduction of Alfa fibers reduces the compressive strength of the hardened composite. The CM exhibits a compressive strength of 83.2±0.34 MPa at 28 days and 85.7±0.10 MPa at 90 days. After 28 days of curing, the $RM(CF10)_1$ has a compressive strength of 68.6 MPa, which is the highest value of any fiber reinforced composition, showing a reduction of roughly 17% compared with CM. As depicted in **Fig. 11**, the increase in fiber content leads to a lower composite compressive strength compared to $RM(CF10)_1$, by 15% and 38% at 2% vol. and 3% vol., respectively, for a 10-mm length. This observation can be made for all Alfa fiber lengths. Otherwise, the variation in fiber length reduces the composite compressive strength. For a 30-mm length, the composite compressive strength also decreases with an increase in the addition rate: $RM(CF30)_1$ has a compressive strength of 59.4 MPa, while that of $RM(CF30)_2$ is 40.4 MPa and $RM(CF30)_3$ just 28.5 MPa. Consequently, these figures reveal a reduction of 29%, 51% and 66%, respectively, in comparison with the CM. Increasing fiber length thus seems to exert a more significant influence on compressive strength. These compressive strength decreases have also been highlighted by other authors on bio fiber-reinforced concretes [34,35], as attributed to greater concrete air content, which consequently reduces its compactness and hence its compressive strength [4]. These previous studies have also noted that long fibers produced lower compressive strengths; these fibers would further disrupt the granular packing, in turn reducing the mixture compactness.

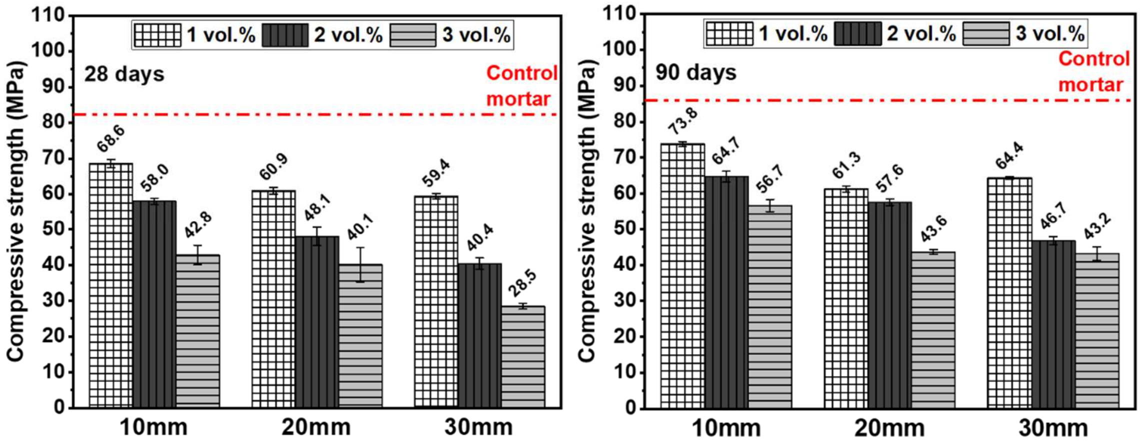


Fig. 11: Compressive strength of mortars reinforced with cut fibers at 28 and 90 days of cure

V. Comparative study between ground and cut Alfa fibers

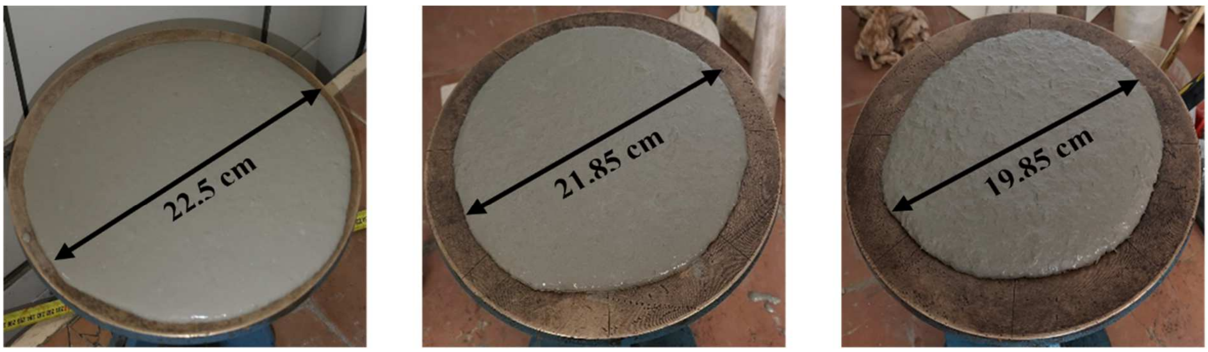
The results of the previous section indicate the effectiveness of incorporating cut fibers into a cementitious matrix. An improvement in the flexural strength of reinforced mortar was definitely observed, at least for $RM(CF10)_1$ and $RM(CF20)_1$ formulations; however, this finding was coupled with a loss of strength after 90 days of curing. Such behavior is most likely related to fiber deterioration over time. Several works have tied fiber degradation to the presence of calcium hydroxide and, consequently, fiber mineralization inside the matrix [36–38]. Wei and Meyer (2015) reported that the water released from fibers is captured by the cement matrix during the hardening process, leading to the formation of a highly alkaline pore solution, which promotes fiber deterioration [33]. In this context, the objective herein is to incorporate the ground Alfa fibers in order to study their behavior in comparison with cut fibers. Grinding makes it possible to both shorten the Alfa fibers and increase their specific surface area. A comparative study between the two morphologies will now be conducted to examine the difference in behavior inside the matrix. The ground fibers were incorporated into the cement mortar, in maintaining the same addition rate previously studied (i.e. 1, 2 and 3% vol.). The cement mortar composition also remains the same (W/C = 0.35 and S/C = 1), as do the test specimen storage conditions (RH > 90%, T = 20°C).

V.1. Effect of Alfa fiber morphology on mortar workability

The appearance of fresh mixtures produced using ground Alfa fibers is presented in **Fig. 12**. The ground fibers were added to the mixture at three addition rates (1, 2 and 3% vol.). The various formulations are denoted as follows: **RM(GF)x** stands for Reinforced Mortar with ground fibers at an x% vol. addition rate.

Compared to the control mortar (CM), with a flow diameter of 22.7 cm, introducing ground Alfa fibers up to a 2% vol. rate did not significantly affect workability on the reinforced mortar. A slight variation of about 1% and 4% was measured for $RM(GF)_1$ and $RM(GF)_2$, respectively; however, an $RM(GF)_3$ flow diameter of 19.8 cm was measured on the $RM(GF)_3$ mixture, thus corresponding to a 12% reduction relative to the CM.

Based on the observations shared in a previous section (IV.1), the cut Alfa fibers do not exert any significant effect on the reinforced mortar workability. Results show that incorporating Alfa fibers up to 2% vol., whether cut or ground, lead to an acceptable workability of the fresh mixture. Nevertheless, a high addition rate does reduce mortar workability, yielding an agglomeration of fibers inside the matrix. Similar observations have been reported in other studies [4,39]. However, unlike other plant fibers (e.g. flax), Alfa fibers exert less influence on the workability of fresh mixtures. This outcome might stem from the large Alfa fiber diameter (approx. 1-2 mm), which for example is much greater than that of flax fibers (10-20 μm) [40]. Flax fibers do in fact significantly modify the rheology of the blends, due to their high specific surface area [12,41]. In our case, the Alfa fibers, given their larger diameter, have a much smaller specific surface area, hence reducing the effect of these fibers on workability.



$RM(GF)_1$ **$RM(GF)_2$** **$RM(GF)_3$**

Fig. 12: Slump diameter of grinded Alfa fiber-reinforced mortar

RM(GF)x : Reinforced Mortar with ground fibers at an x% vol. addition rate (%).

V.2. Influence of Alfa fiber morphology on hydration kinetics

Given the setting or hydration issues highlighted in the literature when incorporating plant fiber particles in cementitious materials, it becomes necessary to assess the influence of Alfa fibers on cement hydration. This step can be quantified by following the hydration kinetics of

Alfa-based mixtures with a calorimeter. This test was conducted on the following formulations: CM, RM(CF10) and RM(GF) with 1, 2 and 3% vol. fibers.

The cement hydration process is constituted of several steps beginning with setting, followed by hardening, crystallization and, lastly, release of heat of hydration [42,43]. Generally speaking, the heat flow curve is characterized by three distinct times, such as the minimal flux time (t1), the first peak time (t2) and the second peak time (t3) [42]. **Fig. 13a** presents the heat flow released during the hydration reaction of the cementitious composite. The heat flow curve of the CM exhibits a two-step evolution. A rapid exothermic peak is observed during the first 30 min, due to the dissolution of various clinker phases and the initial hydration of aluminates [44]. Then the minimum flux time t_1, corresponding to the induction period or dormant period associated with relatively low chemical reactivity, lasts between roughly 30 minutes and 2 hours, depending on the cement type [45]. After this period, the hydration step carries into an acceleration period, characterized by an increase in heat evolution over approximately 10 hours until reaching a maximum heat flow corresponding to the main exothermic peak (t_2), which is mainly due to alite (C3S in cement chemistry notation) hydration to calcium silicate hydrate (CSH), i.e. the principal cementing reaction product. The second peak (t_3) reported above did not appear in the CM heat flow curve, as the authors attributed the appearance of this peak to the C3A content in cement when exceeding 12%, which is not the case for the Portland cement used in this study [42]. Finally, the deceleration period starts up, leading to a slow reaction period due to C3S consumption and aluminates. In comparison to CM, a decrease in the main peak intensity can be observed when adding Alfa fibers into the mixture. The induction periods of the Alfa-reinforced mortars are extended by a time ranging between 30 min and 8 hours for RM(CF)$_1$ and RM(CF)$_2$ and between 30 min and 16 hours for RM(GF)$_1$. The main hydration peak is therefore shifted to the right and delayed; consequently, the main peak is observed at 18 h for both RM(CF)$_1$ and RM(CF)$_2$ and at 25 h for RM(GF)$_1$, corresponding to a delay of 2 h and 9 h, respectively. A clear relationship can be drawn between the Alfa fiber addition rate and heat flow. In fact, the increased addition rate leads to a decrease in the maximum heat flow of Alfa fiber-based mixtures. The change observed in hydration kinetics of the reinforced mortars could be caused by soluble organic matter from Alfa fibers passed into solution in the mixture during the mixing process. It has indeed been reported that extractive components from plant fibers, such as saccharides, could significantly delay cement setting, even with a low content of these carbohydrates [46–48]. Moreover, other studies have also highlighted that pectin is a chelating agent of calcium ions that is capable of entrapping the cement ions inside its structure [49,50]. Alfa fibers undoubtedly retain the calcium ions inside the pectin structure, which could explain the delay observed in the hydration peaks of Alfa fiber-reinforced mortars. The lower calcium ion concentration serves to create deficiencies in the cement hydration reaction, thus inhibiting the formation of silica calcium gel, which is chiefly responsible for the mechanical properties of cementitious materials. However, mortars reinforced with ground fibers show a different behavior compared to mortars made with cut fibers. For a 1% vol. of fibers, the main exothermic peak of $RM(GF)_1$ is more intense than the same mortar containing cut fibers ($RM(CF)_1$). The increase in addition rate therefore leads to lower heat flow peaks for the remainder of mortar compositions. Also, $RM(GF)_2$ did not reveal any evolution during the 48 hours of calorimetry monitoring. The lack of $RM(GF)_2$ heat flow could be correlated with fiber composition. This behavior was pronounced for $RM(GF)_3$, no significant evolution was detected after the 48 hours of measurement.

The presence of sugar in the fiber structure strongly influences the setting mechanism, a finding which is in agreement with certain studies. Delannoy *et al.* (2020) for instance reported that hemp concrete did not show an exothermic peak during six days of monitoring [51]. Garci Juenger and Jennings (2002) also confirmed that cement hydration in the presence of a powerful delayer, e.g. sucrose, characterizes an exothermic peak corresponding to the hydration of tricalcium silicate (C3S) that becomes visible after 90 days of monitoring [52].

The cumulative heat release during the hydration reaction was determined by integrating the heat flow curve. **Fig. 13b** displays the curve variations of the various mortars, with CM showing the highest cumulative heat release, at 157.6 J/g. The inclusion of Alfa fibers, either cut or ground, leads to a decrease in the heat release of the composite. This effect becomes more pronounced when using a higher addition rate. For instance, decreases of about 78% and 60% were recorded for $RM(GF)_2$ and $RM(CF)_3$, respectively; nevertheless, $RM(GF)_1$ has a cumulative heat release of 141.9 J/g, which represents a slight decrease (roughly 9%) compared to the CM. Moreover, $RM(CF)_1$ has a cumulative heat release of 116.4 J/g, which represents a decrease of about 26%, again compared to the CM. This behavior was related to the hypothesis that fibers could inhibit the formation of calcium silicate hydrate, which acts as the most fundamental element in obtaining good mechanical properties. It is clearly observed that including Alfa fibers reduces the heat flow values, which might also be correlated with a reduced amount of calcium silicate hydrate in the composite; consequently, the compressive strength has decrease.

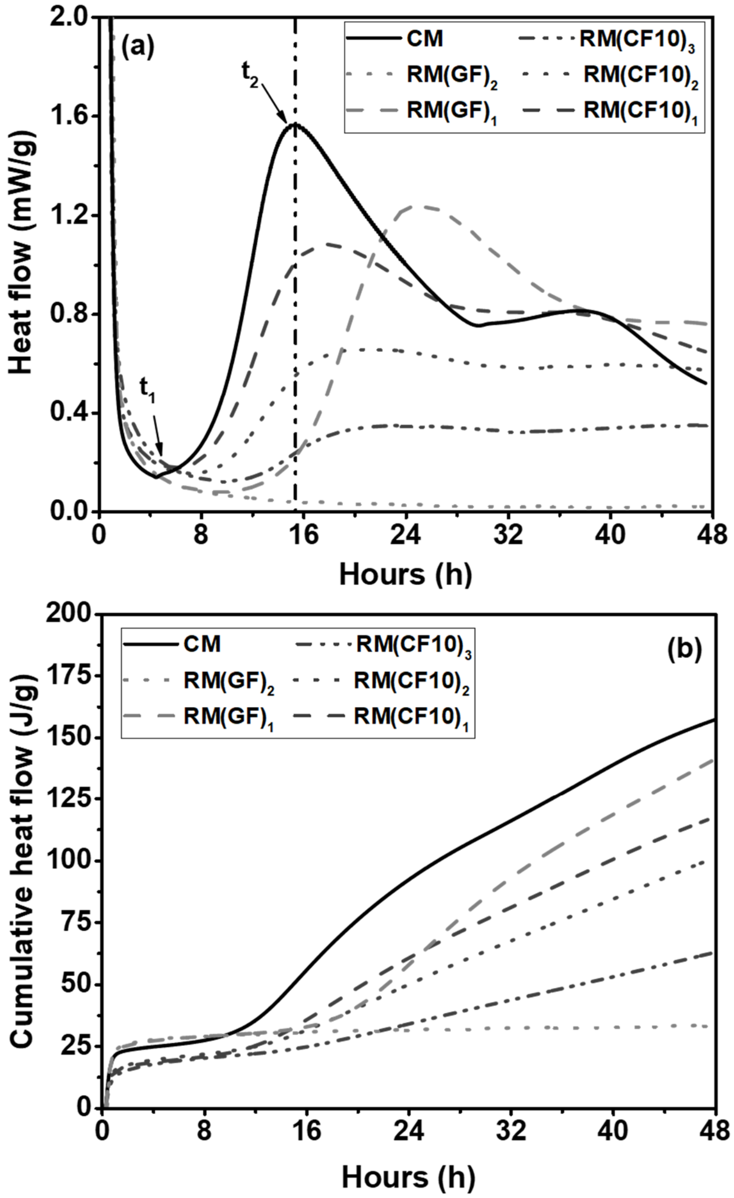


Fig. 13: Instantaneous heat flow (a) and cumulative heat released (b) for Alfa reinforced mortars

RM(CFX)y : Reinforced Mortar with cut fibers, where X = length (mm) and Y = addition rate (%)
RM(GF)x :Reinforced Mortar with ground fibers at an x% vol. addition rate (%)

V.3. Physical properties of Alfa fiber-reinforced mortar: Water-accessible porosity and dry density

Porosity is an essential parameter capable of influencing the mechanical properties of a cementitious material. Thus, the incorporation of Alfa fibers would likely exert an influence on the porosity of the hardened composite. Moreover, porosity commonly serves as an indicator of durability for cementitious materials since it determines the penetrability of aggressive agents into the material [53].

Fig. 14 presents the water-accessible porosity of the reinforced mortar vs. Alfa fiber addition rate. It should first be pointed out that the water-accessible porosity of the various mortars depends on the fiber addition rate: increased fiber addition leads to higher mortar porosity. The evolution of mortar porosity with ground fibers is somewhat similar to mortar with cut fibers, by virtue of displaying a linear evolution with respect to fiber content. Compared to the control mortar (CM), a 61 % relative increase in water-accessible porosity for RM(CF10)$_3$ and 54 % for RM(GF)$_3$ have been recorded. Furthermore, RM(CF20) and RM(CF30) exhibit a similar curve, trending up to 2% vol. of fibers, with a maximum relative increase of 67% compared to the CM. Beyond 2% vol., the water-accessible porosity remains nearly constant for RM(CF20) and slightly increases for RM(CF30). These results are in agreement with the literature. Previous works have confirmed that the inclusion of natural fibers in a cement-based matrix increases the porosity of the composite [54,55]. The additional porosity created inside the matrix is mainly due to the volumetric changes of the natural fibers from casting to curing of the reinforced mortar. Plant fiber hydrophilicity does indeed heavily contribute to an increased level of porosity. It has been reported that natural fibers absorb water during the mixing step, thus leading to a volume variation with shrinkage/swelling phenomena of the fiber [56]. This variation disturbs the cement hydration reaction while also promoting the creation of pores.

The difference observed in the water-accessible porosity of cut fiber-reinforced mortars (RM(CF)) and ground fiber-reinforced mortars (RM(GF)) could be explained by the different fiber morphology. During composite curing, the cut fibers exhibit a major volume change, leading to more voids within the matrix. This behavior is more pronounced for RM(CF30), when taking the workability value of this composite into account. The formation of a cluster along with reduced workability were observed, resulting in a potential change to composite capacity and consequently an increase in its porosity. This outcome could explain the high water-accessible porosity for the mortar with cut fibers. Moreover, regarding the water absorption of Alfa fibers (**Fig. 4**), ground fibers have shown a lower absorption rate compared to cut fibers, which might also explain the difference observed in composite porosity. The lower absorption capacity of ground fibers would in fact reduce the volume variation due to the swelling/shrinkage phenomena [57].

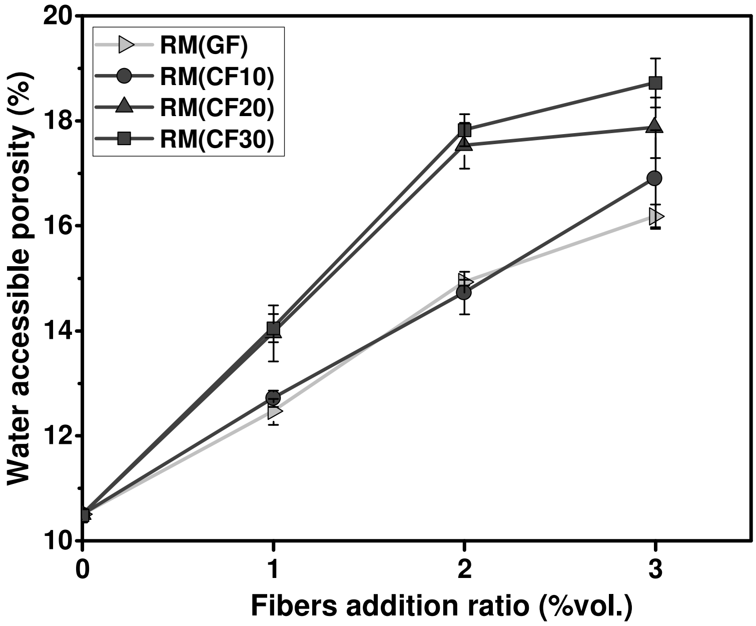


Fig. 14: Porosity of Alfa fiber-reinforced mortars according to fiber addition ratio

RM(CFX)y : Reinforced Mortar with cut fibers, where X = length (mm) and Y = addition rate (%)
RM(GF)x :Reinforced Mortar with ground fibers at an x% vol. addition rate (%)

The addition of Alfa fibers, either cut or ground, in mortars leads to increased porosity inside the cementitious matrix. This finding could be due to the increased amount of entrapped air inside the mixture, which probably reduces the composite compactness [4]. **Fig. 15** presents the correlation between water-accessible porosity and composite density. It can be observed that increasing fiber length and addition rate serves to increase composite porosity, as a result of decreasing and reducing the density. For instance, with a 3% vol. of ground Alfa fibers, a density reduction in RM(GF)$_3$ on the order of 3% compared to the CM is noted. Similarly, lower densities are obtained with mortars containing the highest Alfa content, i.e. 3% vol., regardless of fiber length. However, the 1% vol. addition rate yields a composite with a density near that of the CM. According to Djelal *et al.* (2020), comparable results have been presented, with similar changes being recorded for sawdust-based mortars. The authors linked the difference observed in results to the morphology of wood aggregates. Due to the wood fiber morphology, in its slender form, these natural fibers are capable of entrapping a high air volume [1].

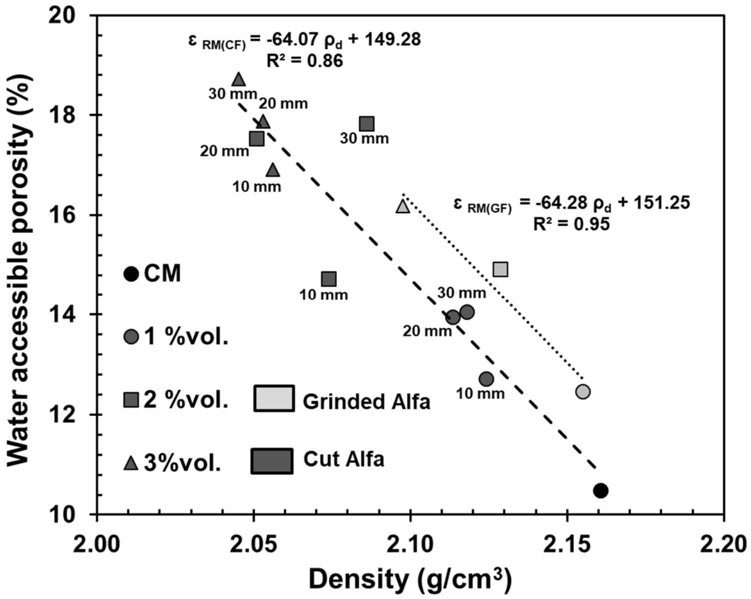


Fig. 15: Water absorption porosity and density correlation of Alfa fiber-reinforced mortars

RM(CFX)y : Reinforced Mortar with cut fibers, where X = length (mm) and Y = addition rate (%)
RM(GF)x :Reinforced Mortar with ground fibers at an x% vol. addition rate (%)

V.4. Influence of Alfa fiber morphology on mortar mechanical properties

V.4.1. Flexural strength

Flexural strength was measured for the reinforced mortars after 7, 28 and 90 days of curing. **Table 5** summarizes the compressive and flexural strength values of mortar reinforced with ground Alfa fibers. Compared to the CM (without fibers), ground Alfa fibers have a significant effect on the composite's mechanical properties. The addition of ground Alfa fibers, up to 2% vol., leads to a maximum increase in flexural strength of about 62% at 28 days of curing. Meanwhile, the 3% vol. addition also generates an 18% increase in flexural strength. The optimal Alfa fiber addition rate thus seems to be 1% vol. At this fiber content, the highest flexural and compressive strengths of mortars reinforced with ground fibers are indeed obtained. Moreover, it is necessary to take the workability discussed above into consideration. It has been noted that the increased addition rate could reduce mixture workability. Consequently, the addition of 3% vol. of ground Alfa fibers leads to a reinforced mortar with low workability, which is outside the scope of this work. At 90 days of curing, the flexural strength slightly decreases compared to 28 days. These results are in agreement with the literature. Krobba *et al.* observed that using Alfa fibers cut to 2-5 mm in length led to an exponential variation in flexural strength with an increase in the addition rate. A 16% enhancement was found in comparison to the reference mortar at 1.25% fiber content [19].

Table 5: Flexural and compressive strength of grinded Alfa fiber-reinforced mortars

	Compressive strength (MPa)				Flexural strength (MPa)			
Specimens	**CM**	**RM(GF)$_1$**	**RM(GF)$_2$**	**RM(GF)$_3$**	**CM**	**RM(GF)$_1$**	**RM(GF)$_2$**	**RM(GF)$_3$**
7 days	64.4±1.4	59.0±1.4	33.7±5.2	26.4±0.6	6..2±0.2	8.6±0.5	8.8±0.5	5.1±0.1
28 days	83.2±1.9	74.3±1.9	54.6±4.1	36.8±3.9	7.3±0.1	11.8±0.6	11.3±0.1	8.6±0.1
90 days	85.7±0.1	81.8±0.6	63.2±1.4	48.7±1.9	7.4±0.3	10.9±0.2	10.5±0.5	9.4±0.4

RM(CFX)y : Reinforced Mortar with cut fibers, where X = length (mm) and Y = addition rate (%)
RM(GF)x :Reinforced Mortar with ground fibers at an x% vol. addition rate (%)

Fig. 16 presents the effect of fiber morphology on the flexural strength of reinforced mortar. Using ground Alfa fibers serves to raise composite flexural strength compared to cut fibers. For instance, a 1% vol. addition results in a rise of approx. 17 % for RM(GF)$_1$ compared to RM(CF10)$_1$ and RM(CF20)$_1$. Even at a high addition rate, the flexural strength of ground Alfa fiber-reinforced mortar remains greater than that of the CM, as opposed to cut fiber-reinforced mortars. These results could be attributed to fiber morphology, which influences the adhesion between fiber and matrix. Morphology has also been found to exert a strong influence on the mechanical properties of fiber-reinforced cementitious composites [58,59].

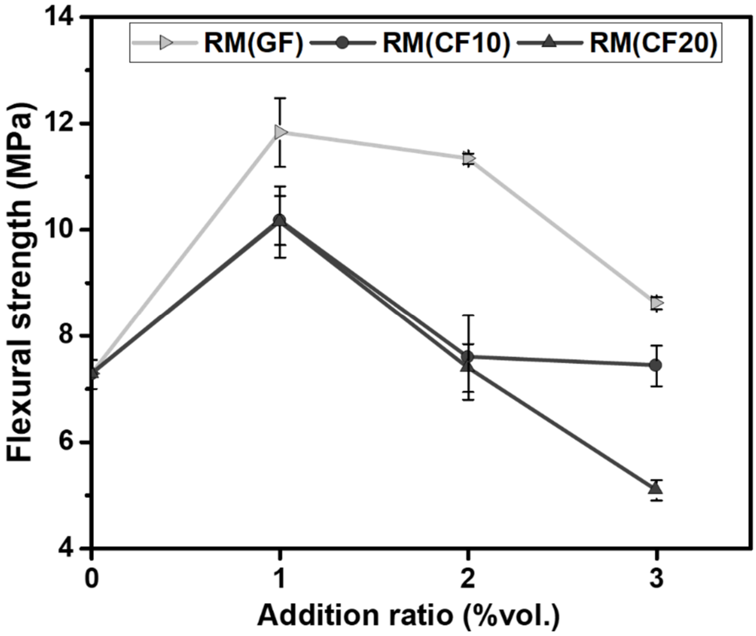


Fig. 16: Flexural strength comparison of RM(CF) and RM(GF)
at 28 days of curing

As regards the flexural behavior of mortars, **Fig. 17** shows the load vs. load point displacement curve of the CM and Alfa fiber-reinforced mortars. The flexural tests were carried out on the various mortars cured at 28 days with displacement-control at a rate of 0.5 mm/min. The mechanical properties of a fiber-reinforced composite depend mainly on fiber content and orientation, but also on the load transfer capability of the fiber-matrix interface [60,61]. Different phenomena acting simultaneously at different degrees, such as the physical and chemical adhesions between matrix and fibers at this interface, govern such load transfer capability [62]. The CM specimen exhibits a totally brittle behavior; however, the various fiber-reinforced materials exhibit the same failure mode, i.e. brittle fracture. This determination could be related to the shape and morphology of Alfa fibers. The cut Alfa fibers did not show any apparent flexibility, which likely influences their behavior inside the matrix; furthermore, their slippage out of the matrix could impact bending properties. Therefore, the fibers do not serve to overcome the stress applied in order to achieve the expected ductility. This hypothesis has already been reported in the literature. Zhang *et al.* (2020) specified that poor interfacial bonding led to a weak bridging effect; as a result, the fibers easily slip out and promote low composite ductility, with an appearance of deep crack widths [63]. Moreover, Belkadi *et al.* (2018) observed the same failure mode when using Alfa fibers and other natural fibers (Diss, palm date and hemp) as reinforcement of metakaolin-based mortars. These authors also exhibited that natural fiber types, length and texture directly influence the composite's mechanical behavior [11]. However, incorporating Alfa fibers improves the composite's reinforcement capacity before reaching the maximum breaking load. Ground fibers present a large peak area that could be tied to fiber morphology, as opposed to cut fibers. Olivito *et al.* (2014) reported that due to the larger fiber cross-sectional area, the composite samples measured a lower tensile strength [64].

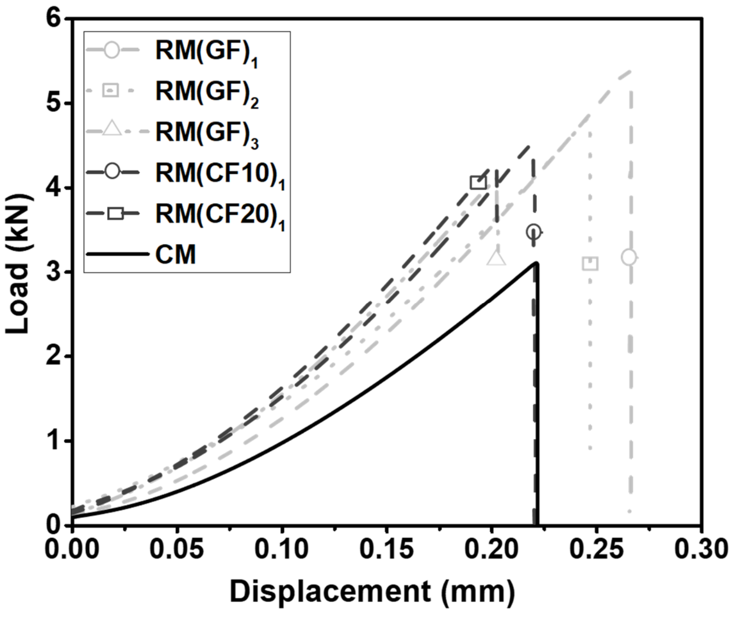


Fig. 17: Strain-displacement of Alfa reinforced mortar

RM(CFX)y : Reinforced Mortar with cut fibers, where X = length (mm) and Y = addition rate (%)

RM(GF)x :Reinforced Mortar with ground fibers at an x% vol. addition rate (%)

To evaluate Alfa/matrix adhesion, pictures were taken using digital video microscope on small fragment of 90 days cured mortar. **Fig. 18** illustrate the interfacial zone and distribution of Alfa fibers inside the matrix for both mortar formulation (grinded and cut fibers). A poor fiber/matrix adhesion is observed on mortars with fibers cut in different lengths, with a fiber slipping from the cement matrix (**Fig.18-a and Fig.18-b**). According to the literature, the SEM micrographs of the lateral view of Alfa fibers confirm that the Alfa fiber surface has a thick layer of impurities with a rough appearance, which in turn could affect the adhesive properties of the fibers [10]. Otherwise, an apparent homogeneous distribution of ground fibers in the matrix is observed (**Fig18-c**), which could improve the adhesion between fibers and matrix and therefore enhance the flexural strength of the reinforced mortar (**Fig18-d**). This change in Alfa fiber behavior is probably due to the different fiber morphology and specific surface area. Ground fibers do in fact possess a small fiber length compared to cut fibers, which leads to a high specific surface area and results in a larger contact surface area between fiber and cement matrix. According to the literature, Silva et al. (2011) corroborated that these fibers' cross-sectional area variation has a great influence on the adhesive force. Hence, the authors reported that fibers with arcuate or twisted shapes tend to more often display the highest adhesive stress values [12,62].

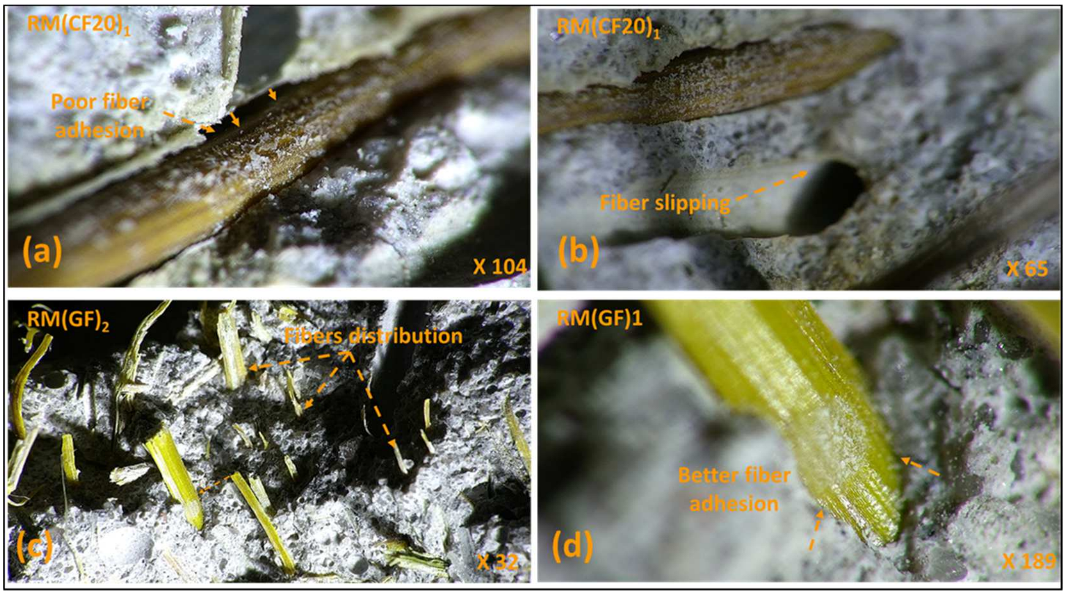


Fig. 18: Microscope observation of RM(CF) and RM(GF)

V.4.2. Compressive strength

Table 5 summarizes the compressive strengths of mortars reinforced by means of ground Alfa fibers. The evolution in strength is similar to mortar using cut fibers, with values increasing over time for all of the various mixes. Compared to CM, the inclusion of ground Alfa fibers reduces the compressive strength of the composite. The increase in addition rate leads to a significant decrease in compressive strength. For instance, at 28 days of curing, $RM(GF)_1$ and $RM(GF)_2$ indicate a decrease of 11% and 34%, respectively, compared with the CM. These results are similar to those of mortar made with cut fibers. **Fig. 19** presents the evolution in the relative compressive strength vs. fiber addition rate. Relative compressive strength is the ratio of the compressive strength of the fiber-reinforced mortar (RM(GF) or RM(CF)) to the compressive strength of the control mortar (CM). The incorporation of Alfa fibers, either cut or ground, reveals the same trend in the evolution of relative compressive strength when increasing the fiber content. This trend was also reported in a recent work; the authors noted a significant reduction in compressive strength when increasing the wood fiber substitution rate [1]. Also, it was reported by Boumhaout *et al.* that compressive strength significantly decreases with an increase in the addition rate of a date palm fiber (DPF) mesh. The authors attributed this behavior to the increased composite porosity and low DPF mesh mechanical strength [65].

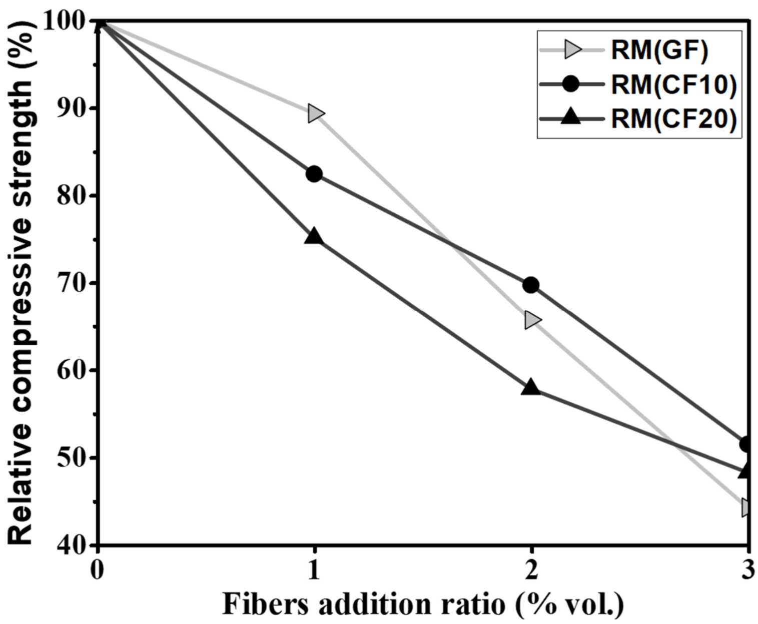


Fig. 19: Relative compressive strength of Alfa fiber-reinforced mortars at 28 days of curing

This decrease in the compressive strength of the reinforced mortar might be explained by two hypotheses. On the one hand, the modification of hydration kinetics has been corroborated by calorimetric tests previously performed on various formulations. The increase in the Alfa addition rate leads to a drop in the composite heat release; otherwise, the formation of silica calcium gels would be reduced, thus resulting in a decrease of compressive performance. On the other hand, the water-accessible porosity strongly influences the compressive strength of cement composites. **Fig. 20** presents the correlation between water-accessible porosity and the compressive strength of specimens after 90 days of curing. A clear linear correlation between compressive strength and porosity can be discerned. The increase in addition rate therefore leads to a higher water-accessible porosity; consequently, the composite compressive strength declines. This finding confirms the results discussed above, namely a high addition rate of Alfa fibers, either cut or ground, raises porosity while decreasing density, resulting in a compressive strength reduction. This increase in porosity with the incorporation of plant fibers has been noted by other authors [66,67]; it is attributed to increased porosity at the interfacial transition zone (ITZ) between plant fibers and matrix [68].

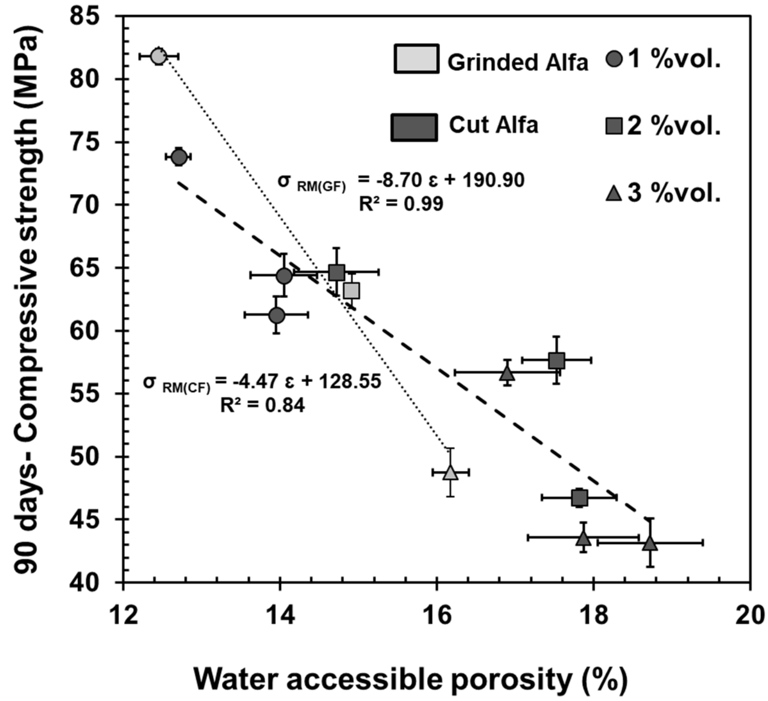


Fig. 20: Correlation between the water accessible porosity and the compressive strength after 90 days of curing

VI. Conclusion

This work has aimed to investigate the efficiency of Alfa fiber incorporation into a cementitious material. Two Alfa fiber morphologies were studied: cut Alfa fibers with three different lengths (10, 20 and 30 mm); and ground Alfa fibers (shorter than 2 mm). The post-saturation water absorption rate equaled 86% and 62% for cut and ground fibers, respectively.

A preliminary study was performed to select the appropriate mix design from both workability and mechanical property specifications. It was confirmed that W/C = 0.35 and

S/C = 1 were the optimal parameters with respect to these properties. The incorporation of fibers 10 mm and 20 mm in length at up to 1% vol. allows improving the flexural strength of the composite by about 28% at 28 days of curing, compared to the control mortar. Nevertheless, at 90 days, the flexural strength has decreased, most likely due to fiber degradation over time, although the values remain close to those of the CM. As regards ground fibers, the reinforced mortar exhibits similar behavior, as the addition of ground Alfa fibers up to 2% vol. leads to a maximum increase in flexural strength by approx. 62% at 28 days of curing. The addition of cut or ground Alfa fibers did not however improve the compressive strength of the composite.

A comparative study was conducted to compare the effect of a fiber morphology change on composite properties. The addition of Alfa fibers increases the composite's water-accessible porosity; this effect is more pronounced for cut fibers than ground fibers. The longer fiber contributes to creating more voids between fibers and matrix, which in turn raises the level of water-accessible porosity and consequently decreases composite density. This finding was also confirmed by the failure cross-section observations. It was noted that cut fibers were slipping out from the matrix after the flexural test, which indicates poor fiber/matrix adhesion. A modification in the hydration process was indeed recorded as a function of fiber addition rate. An increased addition rate extends the induction period and decreases the main peak intensity, which was mainly due to fiber composition. Based on these results, the compressive strength reduction can be explained by both hypotheses; Fiber addition leads to a composite with high porosity and low cumulative heat flow, compared with the control mortar.

Lastly, the addition of Alfa fibers might be effective when using ground or cut fibers up to 20 mm long at an addition rate of 1% vol. The delay observed in hydration kinetics could be a positive during fabrication of the final product, which allows for sufficient time before setting. By virtue of this work, it is recommended to modify the Alfa fiber surface in order to enhance its adhesive properties.

Acknowledgments

The authors gratefully acknowledge the University of Artois for its financial support of this thesis research program. Moreover, special thanks are expressed to CNRST (National Center for Scientific and Technical Research - Morocco) for their award of Merit Scholarship No. 16UCA2017.

Figure Caption

Fig. 1: Grain size distribution of sand aggregates

Fig. 2: SEM micrograph of the external surface of Alfa fiber [8]

Fig. 3 : Cut and grinded Alfa fiber

Fig. 4: Water absorption kinetics of Alfa fibers

Fig. 5: Isothermal calorimeter I-Cal 2000-HCP

Fig. 6: Slump flow diameter of mortars

Fig. 7: Pictures of the table test for different mortars

Fig. 8: Flexural and compressive strength evolution of mortar after 7 days of curing

Fig. 9: Flow table test of cut Alfa fiber-reinforced mortar

Fig. 10: Flexural strength of mortars reinforced with cut fibers at 28 and 90 days of cure

Fig. 11: Compressive strength of mortars reinforced with cut fibers at 28 and 90 days of cure

Fig. 12: Slump diameter of grinded Alfa fiber-reinforced mortar

Fig. 13: Instantaneous heat flow (a) and cumulative heat released (b) for Alfa reinforced mortars

Fig. 14: Porosity of Alfa fiber-reinforced mortars according to fiber addition ratio

Fig. 15: Water absorption porosity and density correlation of Alfa fiber-reinforced mortars

Fig. 16: Flexural strength comparison of RM(CF) and RM(GF) at 28 days of curing

Fig. 17: Strain-displacement of Alfa reinforced mortar

Fig. 18: Microscope observation of RM(CF) and RM(GF)

Fig. 19: Relative compressive strength of Alfa fiber-reinforced mortars at 28 days of curing

Fig. 20: Correlation between the water accessible porosity and the compressive strength after 90 days of curing

Table Caption

Table 1: Composition of fiber-reinforced mortar with variation of the W/C and S/C ratios

Table 2: Mechanical strength of different paste mortar

Table 3: Composition of the control mortar

Table 4: Slump flow of cut Alfa fiber-reinforced mortar

Table 5: Flexural and compressive strength of grinded Alfa fiber-reinforced mortars

References

[1] C. Djelal, J. Page, H. Kada, Y. Vanhove, Feasibility study of using poplar wastes as sand in cement mortars, J Mater Cycles Waste Manag. 22 (2020) 488–500. https://doi.org/10.1007/s10163-019-00946-x.

[2] K.L. Pickering, M.G.A. Efendy, T.M. Le, A review of recent developments in natural fibre composites and their mechanical performance, Composites Part A: Applied Science and Manufacturing. 83 (2016) 98–112. https://doi.org/10.1016/j.compositesa.2015.08.038.

[3] O. Faruk, A.K. Bledzki, H.-P. Fink, M. Sain, Progress Report on Natural Fiber Reinforced Composites, Macromolecular Materials and Engineering. 299 (2014) 9–26. https://doi.org/10.1002/mame.201300008.

[4] J. Page, F. Khadraoui, M. Boutouil, M. Gomina, Multi-physical properties of a structural concrete incorporating short flax fibers, Construction and Building Materials. 140 (2017) 344–353. https://doi.org/10.1016/j.conbuildmat.2017.02.124.

[5] F. Pacheco-Torgal, S. Jalali, Cementitious building materials reinforced with vegetable fibres: A review, Construction and Building Materials. 25 (2011) 575–581. https://doi.org/10.1016/j.conbuildmat.2010.07.024.

[6] J. Page, C. Djelal, Y. Vanhove, Optimisation of vibrocompaction process for wood-based concrete blocks, Int J Adv Manuf Technol. 109 (2020) 1189–1204. https://doi.org/10.1007/s00170-020-05674-3.

[7] A.B. Mabrouk, H. Kaddami, S. Boufi, F. Erchiqui, A. Dufresne, Cellulosic nanoparticles from alfa fibers (Stipa tenacissima): extraction procedures and reinforcement potential in polymer nanocomposites, Cellulose. 19 (2012) 843–853. https://doi.org/10.1007/s10570-012-9662-z.

[8] S. Ajouguim, K. Abdelouahdi, M. Waqif, M. Stefanidou, L. Saâdi, Modifications of Alfa fibers by alkali and hydrothermal treatment, Cellulose. 26 (2019) 1503–1516. https://doi.org/10.1007/s10570-018-2181-9.

[9] S. Hamza, H. Saad, B. Charrier, N. Ayed, F. Charrier-El Bouhtoury, Physico-chemical characterization of Tunisian plant fibers and its utilization as reinforcement for plaster based composites, Industrial Crops and Products. 49 (2013) 357–365. https://doi.org/10.1016/j.indcrop.2013.04.052.

[10] R. Hajj, B. Otazaghine, R. Sonnier, R. El Hage, S. Rouif, M. Nakhl, J.-M. Lopez-Cuesta, Influence of monomer reactivity on radiation grafting of phosphorus flame retardants on flax fabrics, Polymer Degradation and Stability. 166 (2019) 86–98. https://doi.org/10.1016/j.polymdegradstab.2019.05.025.

[11] A.A. Belkadi, S. Aggoun, C. Amouri, A. Geuttala, H. Houari, Effect of vegetable and synthetic fibers on mechanical performance and durability of Metakaolin-based mortars,

Journal of Adhesion Science and Technology. 32 (2018) 1670–1686. https://doi.org/10.1080/01694243.2018.1442647.

[12] J. Page, F. Khadraoui, M. Gomina, M. Boutouil, Influence of different surface treatments on the water absorption capacity of flax fibres: Rheology of fresh reinforced-mortars and mechanical properties in the hardened state, Construction and Building Materials. 199 (2019) 424–434. https://doi.org/10.1016/j.conbuildmat.2018.12.042.

[13] Y. Li, Y.W. Mai, L. Ye, Sisal fibre and its composites: A review of recent developments, Composites Science and Technology. 60 (2000) 2037–2055. https://doi.org/10.1016/S0266-3538(00)00101-9.

[14] S.S. Munawar, K. Umemura, S. Kawai, Characterization of the morphological, physical, and mechanical properties of seven nonwood plant fiber bundles, Journal of Wood Science. 53 (2007) 108–113. https://doi.org/10.1007/s10086-006-0836-x.

[15] O. Onuaguluchi, N. Banthia, Plant-based natural fibre reinforced cement composites: A review, Cement and Concrete Composites. 68 (2016) 96–108. https://doi.org/10.1016/j.cemconcomp.2016.02.014.

[16] S.R. Ferreira, F.D.A. Silva, P.R.L. Lima, R.D. Toledo Filho, Effect of fiber treatments on the sisal fiber properties and fiber-matrix bond in cement based systems, Construction and Building Materials. 101 (2015) 730–740. https://doi.org/10.1016/j.conbuildmat.2015.10.120.

[17] M.R. Khelifa, N. Leklou, T. Bellal, R.L. Hebert, B.A. Ledesert, Is alfa a vegetal fiber suitable for making green reinforced structure concrete?, European Journal of Environmental and Civil Engineering. 22 (2018) 686–706. https://doi.org/10.1080/19648189.2016.1217792.

[18] A.-B. Tahar, Effet de l'incorporation des fibres d'Alfa sur le comportement des bétons autoplaçants, JMPE. 4 (2016) 5–10.

[19] B. Krobba, M. Bouhicha, S. Kenai, L. Courard, Formulation of low cost eco-repair mortar based on dune sand and Stipa tenacissima microfibers plant, Construction and Building Materials. 171 (2018) 950–959. https://doi.org/10.1016/j.conbuildmat.2018.03.200.

[20] S. Hanana, A. Elloumi, V. Placet, H. Tounsi, H. Belghith, C. Bradai, An efficient enzymatic-based process for the extraction of high-mechanical properties alfa fibres, Industrial Crops and Products. 70 (2015) 190–200. https://doi.org/10.1016/j.indcrop.2015.03.018.

[21] A.A. Belkadi, Contribution à l'étude de la durabilité et les performances des bétons autoplaçants (fibres végétales, milieu agressif, formulation, modélisation, PhD Thesis, Universé Mohamed Khider Biskra, 2018. http://thesis.univ-biskra.dz/3989/ (accessed March 31, 2020).

[22] S. Ajouguim, M. Stefanidou, K. Abdelouahdi, M. Waqif, L. Saâdi, Influence of treated bio-fibers on the mechanical and physical properties of cement mortars, European Journal of Environmental and Civil Engineering. 0 (2020) 1–15. https://doi.org/10.1080/19648189.2020.1782773.

[23] B. Youssef, A. Soumia, E.A. Mounir, C. Omar, L. Abdelaziz, E.B. Mehdi, Z. Mohamed, Preparation And Properties Of Bionanocomposite Films Reinforced With Nanocellulose Isolated From Moroccan Alfa Fibres, Autex Research Journal. 15 (2015) 164–172. https://doi.org/10.1515/aut-2015-0011.

[24] M.C. Paiva, I. Ammar, A.R. Campos, R.B. Cheikh, A.M. Cunha, Alfa fibres: Mechanical, morphological and interfacial characterization, Composites Science and Technology. 67 (2007) 1132–1138. https://doi.org/10.1016/j.compscitech.2006.05.019.

[25] Z. Marrakchi, H. Oueslati, M.N. Belgacem, F. Mhenni, E. Mauret, Biocomposites based on polycaprolactone reinforced with alfa fibre mats, Composites Part A: Applied Science and Manufacturing. 43 (2012) 742–747. https://doi.org/10.1016/j.compositesa.2011.12.027.

[26] J. Page, M. Sonebi, S. Amziane, Étude expérimentale des propriétés d'un béton de chanvre incorporant un adjuvant viscosant, Revue Des Composites et Des Matériaux Avancés. 26 (2016) 349–366. https://doi.org/10.3166/RCMA.26.349-366.

[27] S.R. Ferreira, F. de A. Silva, P.R.L. Lima, R.D. Toledo Filho, Effect of fiber treatments on the sisal fiber properties and fiber–matrix bond in cement based systems, Construction and Building Materials. 101 (2015) 730–740.https://doi.org/10.1016/j.conbuildmat.2015.10.120.

[28] S.B. Singh, P. Munjal, N. Thammishetti, Role of water/cement ratio on strength development of cement mortar, Journal of Building Engineering. 4 (2015) 94–100. https://doi.org/10.1016/j.jobe.2015.09.003.

[29] R. Ralegaonkar, H. Gavali, P. Aswath, S. Abolmaali, Application of chopped basalt fibers in reinforced mortar: A review, Construction and Building Materials. 164 (2018) 589–602. https://doi.org/10.1016/j.conbuildmat.2017.12.245.

[30] V.G. Haach, G. Vasconcelos, P.B. Lourenço, Influence of aggregates grading and water/cement ratio in workability and hardened properties of mortars, Construction and Building Materials. 25 (2011) 2980–2987. https://doi.org/10.1016/j.conbuildmat.2010.11.011.

[31] N.-E. Bouhamou, N. Belas, H. Mesbah, A. Jauberthie, A. Ouali, A. Mebrouki, Influence des rapports eau/ciment et fines/ciment sur le comportement à l'état durci du béton autoplaçant à base de matériaux locaux algériens N. Bouhamou, N. Belas, H. Mesbah, R. Jauberthie, A. Ouali, A. Mebrouki, Canadian Journal of Civil Engineering. (2009) 1195–1206.

[32] B. Çomak, A. Bideci, Ö. Salli Bideci, Effects of hemp fibers on characteristics of cement based mortar, Construction and Building Materials. 169 (2018) 794–799. https://doi.org/10.1016/j.conbuildmat.2018.03.029.

[33] J. Wei, C. Meyer, Degradation mechanisms of natural fiber in the matrix of cement composites, Cement and Concrete Research. 73 (2015) 1–16. https://doi.org/10.1016/j.cemconres.2015.02.019.

[34] Z. Li, X. Wang, L. Wang, Properties of hemp fibre reinforced concrete composites, Composites Part A: Applied Science and Manufacturing. 37 (2006) 497–505. https://doi.org/10.1016/j.compositesa.2005.01.032.

[35] D. Sedan, C. Pagnoux, A. Smith, T. Chotard, Mechanical properties of hemp fibre reinforced cement: Influence of the fibre/matrix interaction, Journal of the European Ceramic Society. 28 (2008) 183–192. https://doi.org/10.1016/j.jeurceramsoc.2007.05.019.

[36] M. Ardanuy, J. Claramunt, J.A. García-Hortal, M. Barra, Fiber-matrix interactions in cement mortar composites reinforced with cellulosic fibers, Cellulose. 18 (2011) 281–289. https://doi.org/10.1007/s10570-011-9493-3.

[37] G.H.D. Tonoli, S.F. Santos, H. Savastano, S. Delvasto, R. Mejía de Gutiérrez, M. del M. Lopez de Murphy, Effects of natural weathering on microstructure and mineral composition of cementitious roofing tiles reinforced with fique fibre, Cement and Concrete Composites. 33 (2011) 225–232. https://doi.org/10.1016/j.cemconcomp.2010.10.013.

[38] M. Ardanuy, J. Claramunt, R.D. Toledo Filho, Cellulosic fiber reinforced cement-based composites: A review of recent research, Construction and Building Materials. 79 (2015) 115–128. https://doi.org/10.1016/j.conbuildmat.2015.01.035.

[39] H. Savastan, V. Agopyan, A.M. Nolasco, L. Pimentel, Plant fibre reinforced cement components for roofing, Construction and Building Materials. 13 (1999) 433–438. https://doi.org/10.1016/S0950-0618(99)00046-X.

[40] J. Page, S. Amziane, M. Gomina, C. Djelal, F. Audonnet, Using linseed oil as flax fibre coating for fibre-reinforced cementitious composite, Industrial Crops and Products. 161 (2021) 113168. https://doi.org/10.1016/j.indcrop.2020.113168.

[41] J. Page, S. Amziane, M. Gomina, Optimization of the linseed oil treatment of flax fibres: influence on fresh properties of fibre reinforced mortars, Academic Journal of Civil Engineering. 37 (2019) 73–79. https://doi.org/10.26168/icbbm2019.10.

[42] N. Sauvat, R. Sell, E. Mougel, A. Zoulalian, A Study of Ordinary Portland Cement Hydration With Wood by Isothermal Calorimetry, Holzforschung. 53 (1999) 104–108. https://doi.org/10.1515/HF.1999.016.

[43] A. Govin, A. Peschard, R. Guyonnet, Modification of cement hydration at early ages by natural and heated wood, Cement and Concrete Composites. 28 (2006) 12–20. https://doi.org/10.1016/j.cemconcomp.2005.09.002.

[44] X.-M. Kong, H. Liu, Z.-B. Lu, D.-M. Wang, The influence of silanes on hydration and strength development of cementitious systems, Cement and Concrete Research. 67 (2015) 168–178. https://doi.org/10.1016/j.cemconres.2014.10.008.

[45] J. Bensted, Some applications of conduction calorimetry to cement hydration, Advances in Cement Research. 1 (1987) 35–44. https://doi.org/10.1680/adcr.1987.1.1.35.

[46] J. Page, F. Khadraoui, M. Gomina, M. Boutouil, Traitements des fibres de lin : influence sur l’hydratation d’un composite ciment-lin, Academic Journal of Civil Engineering. 34 (2016) 728–735. https://doi.org/10.26168/ajce.34.1.88.

[47] K. Kochova, K. Schollbach, F. Gauvin, H.J.H. Brouwers, Effect of saccharides on the hydration of ordinary Portland cement, Construction and Building Materials. 150 (2017) 268–275. https://doi.org/10.1016/j.conbuildmat.2017.05.149.

[48] Y. Diquélou, E. Gourlay, L. Arnaud, B. Kurek, Impact of hemp shiv on cement setting and hardening: Influence of the extracted components from the aggregates and study of the interfaces with the inorganic matrix, Cement and Concrete Composites. 55 (2015) 112–121. https://doi.org/10.1016/j.cemconcomp.2014.09.004.

[49] T. Le Hoang, Etude de caractérisation du comportement de composites cimentaires incorporant des fibres courtes de lin, PhD Thesis, Université de Caen Normandie, 2013. http://www.theses.fr/2013CAEN2042 (accessed March 31, 2020).

[50] D. Sedan, Etude des interactions physico-chimiques aux interfaces fibres de chanvre/ciment : influence sur les propriétés mécaniques du composite, PhD Thesis, Université de Limoges, 2007. http://www.theses.fr/2007LIMO4055 (accessed March 31, 2020).

[51] G. Delannoy, S. Marceau, P. Glé, E. Gourlay, M. Guéguen-Minerbe, D. Diafi, S. Amziane, F. Farcas, Impact of hemp shiv extractives on hydration of Portland cement, Construction and Building Materials. 244 (2020) 118300. https://doi.org/10.1016/j.conbuildmat.2020.118300.

[52] M.C. Garci Juenger, H.M. Jennings, New insights into the effects of sugar on the hydration and microstructure of cement pastes, Cement and Concrete Research. 32 (2002) 393–399. https://doi.org/10.1016/S0008-8846(01)00689-5.

[53] A.M. Neville, A.M. Neville, Properties of Concrete, Pearson, 2011.

[54] D.G. Soltan, P. das Neves, A. Olvera, H. Savastano Junior, V.C. Li, Introducing a curauá fiber reinforced cement-based composite with strain-hardening behavior, Industrial Crops and Products. 103 (2017) 1–12. https://doi.org/10.1016/j.indcrop.2017.03.016.

[55] A. Sellami, M. Merzoud, S. Amziane, Improvement of mechanical properties of green concrete by treatment of the vegetals fibers, Construction and Building Materials. 47 (2013) 1117–1124. https://doi.org/10.1016/j.conbuildmat.2013.05.073.

[56] K. Bilba, M.-A. Arsene, Silane treatment of bagasse fiber for reinforcement of cementitious composites, Composites Part A: Applied Science and Manufacturing. 39 (2008) 1488–1495. https://doi.org/10.1016/j.compositesa.2008.05.013.

[57] V. Nozahic, S. Amziane, Influence of sunflower aggregates surface treatments on physical properties and adhesion with a mineral binder, Composites Part A: Applied Science and Manufacturing. 43 (2012) 1837–1849. https://doi.org/10.1016/j.compositesa.2012.07.011.

[58] S.R. Ferreira, M. Pepe, E. Martinelli, F. de Andrade Silva, R.D. Toledo Filho, Influence of natural fibers characteristics on the interface mechanics with cement based matrices,

Composites Part B: Engineering. 140 (2018) 183–196. https://doi.org/10.1016/j.compositesb.2017.12.016.

[59] M.E.A. Fidelis, R.D. Toledo Filho, F. de Andrade Silva, B. Mobasher, S. Müller, V. Mechtcherine, Interface characteristics of jute fiber systems in a cementitious matrix, Cement and Concrete Research. 116 (2019) 252–265. https://doi.org/10.1016/j.cemconres.2018.12.002.

[60] S. Eve, M. Gomina, A. Gmouh, A. Samdi, R. Moussa, G. Orange, Microstructural and mechanical behaviour of polyamide fibre-reinforced plaster composites, Journal of the European Ceramic Society. 22 (2002) 2269–2275. https://doi.org/10.1016/S0955-2219(02)00014-6.

[61] American Concrete Institut, ACI Committee 544, Report on Fiber Reinforced Concrete (Reapproved 2009), 1996.

[62] A.M. Brandt, Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering, Composite Structures. 86 (2008) 3–9. https://doi.org/10.1016/j.compstruct.2008.03.006.

[63] D. Zhang, J. Yu, H. Wu, B. Jaworska, B.R. Ellis, V.C. Li, Discontinuous micro-fibers as intrinsic reinforcement for ductile Engineered Cementitious Composites (ECC), Composites Part B: Engineering. 184 (2020) 107741. https://doi.org/10.1016/j.compositesb.2020.107741.

[64] R.S. Olivito, O.A. Cevallos, A. Carrozzini, Development of durable cementitious composites using sisal and flax fabrics for reinforcement of masonry structures, Materials & Design. 57 (2014) 258–268. https://doi.org/10.1016/j.matdes.2013.11.023.

[65] M. Boumhaout, L. Boukhattem, H. Hamdi, B. Benhamou, F. Ait Nouh, Thermomechanical characterization of a bio-composite building material: Mortar reinforced with date palm fibers mesh, Construction and Building Materials. 135 (2017) 241–250. https://doi.org/10.1016/j.conbuildmat.2016.12.217.

[66] H. Savastano, P.G. Warden, R.S.P. Coutts, Microstructure and mechanical properties of waste fibre–cement composites, Cement and Concrete Composites. 27 (2005) 583–592. https://doi.org/10.1016/j.cemconcomp.2004.09.009.

[67] B. Madsen, A. Thygesen, H. Lilholt, Plant fibre composites – porosity and stiffness, Composites Science and Technology. 69 (2009) 1057–1069. https://doi.org/10.1016/j.compscitech.2009.01.016.

[68] V. Agopyan, H. Savastano, V.M. John, M.A. Cincotto, Developments on vegetable fibre–cement based materials in São Paulo, Brazil: an overview, Cement and Concrete Composites. 27 (2005) 527–536. https://doi.org/10.1016/j.cemconcomp.2004.09.004.