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

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16 Abstract

17 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 18 valorize the Alfa plant into fiber-reinforced mortar based on a cement-glass composite mix 19 20 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 21 22 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 23 (CM), the introduction of Alfa fibers (either cut or ground), with ratios below 2% vol., leads 24 to a slight decrease in mixture workability. However, Alfa fibers do not significantly alter the 25 fresh material density. It was recorded a delay in setting time of the composites as a function 26 of fiber addition rate. In the hardened state, an improvement in flexural strength is noticed for 27 mortars reinforced with 1% vol. of fibers compared to the CM. However, results show that the 28 increase in either type of fiber (cut or ground) generates a decrease in compressive strength 29 compared to the CM. This outcome can be confirmed by both the decrease in heat released 30 during the hydration reaction and water-accessible porosity inside the matrix. 31

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

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- 36

38 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.

42 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 43 44 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 45 46 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 47 fact been reported that the incorporation of plant fibers results in a loss of workability, limited 48 49 crack propagation, improved tensile and flexural strength, and lastly a more resistant hardened concrete [4,11,12]. 50

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].

57 Several parameters will influence the composite's mechanical and rheological properties, led 58 by the poor level of fiber/matrix adhesion due to a fiber contraction effect subsequent to 59 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.

72 The behavior of Alfa fibers in a cementitious matrix could be influenced by both chemical 73 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 74 75 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 76 77 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 78 79 material.

80 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 81 82 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 83 84 both the endogenous shrinkage and drying shrinkage of the composite relative to the reference 85 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; 86 however, its incorporation did improve the composite's deformation capacity. These results 87 are in close agreement with the work performed by Khelifa et al. (2018) [17], which also 88 revealed that integrating Alfa fibers is able to reduce shrinkage during the early age and 89 provides a composite with characteristics basically similar to those of a structural concrete. 90 Krobba et al. (2018) assessed the effectiveness of adding Alfa microfibers, manually cut to a 91 length of 3-5 mm, to a patching mortar containing sand with a 0/0.5 mm particle size range. 92 Their results indicated that the incorporation of volume of 0.75 % served to limit drying 93 94 shrinkage while improving the composite's compressive strength, as compared to a reference 95 mortar devoid of Alfa fiber [19]. On the other hand, Ajouguim et al. (2020) included Alfa 96 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 97 alkaline solution. A set of interesting results were recorded, revealing a 39% gain in flexural 98 strength for the mortar containing 1% vol. of treated Alfa fibers [22]. The choices of 99

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.

103 The objective of this study is to make efficient use of fibers stemming from the Alfa plant, 104 which for the most part is found in North Africa and Spain. This plant grows spontaneously in 105 arid or semi-arid environments and moreover covers a land area estimated at 4,000,000 ha in 106 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 107 both lower production costs and mitigate serious pollution problems. The inclusion of these 108 fibers in a cementitious matrix requires a preliminary study of the fiber properties, especially 109 their hydrophilic and mechanical properties, as well as their interaction with the cementitious 110 matrix. 111

The originality of this work program consists in developing an Alfa fiber-reinforced mortar 112 based on a cement-glass composite mix design. According to the literature, this type of 113 114 formulation that makes use of Alfa fibers has never been officially catalogued. The most 115 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 116 117 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 118 119 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 120 121 examine the influence of both morphology and fiber addition rate on the properties of the 122 fiber-reinforced mortar. Two morphologies have been selected for this part of the study: 123 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 124 strength were measured at various time intervals. A final study will compare the different 125 effects of cut and crushed Alfa fibers on the properties of the resulting composite in both the 126 fresh and hardened state. 127

128 II. Materials and methods

129 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 cm²/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 cm²/g, and with a density of 2.7 g/cm³. A siliceous sand from "ULTIBAT" with a particle size distribution of 0-1 mm (**Fig.1**) and a density of 2.61 g/cm³ 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

142 II.2. Alfa fibers characterization

143 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 1.40 144 145 g/cm³. 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, 146 and 13.28% extractible elements [8]. The Alfa fibers were cleaned in order to remove any 147 dust and impurities deposited on the surface. In the present study, two Alfa fiber 148 149 morphologies have been considered: cutting at different lengths (10, 20 and 30 mm), and 150 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 151

- 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]

155



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 mt denoting the mass of fibers at time (t) and m₀ the initial dry mass of fibers:

163
$$WA_t(\%) = \left(\frac{m_t - m_0}{m_0}\right) \times 100$$
 (1)

The water absorption kinetics of cut and ground Alfa fibers are presented in Fig.4. It should 164 be noted that extending the immersion time leads to higher water absorption of both fiber 165 morphologies. The water absorption kinetics of cut and ground Alfa fibers can be 166 distinguished in two areas, separated by an intersection point at approximately 8 hours. The 167 168 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; 169 therefore, the cut fibers display a higher water absorption than ground fibers after 8 hours of 170 immersion. More specifically, the water absorption of ground fibers was approx. 55% after 8 171 hours of immersion, with a slow evolution reaching 62% at 48 hours. Cut Alfa fibers thus 172 173 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 174 175 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 176 typically correlated with fiber hydrophilicity, which depends on the fibers' chemical 177 composition and nature. These results are in accordance with the literature [4,27], with a 178 similar behavior observed for different types of fibers: the water absorption of fibers increases 179 the longer the water immersion time. 180



Fig. 4: Water absorption kinetics of Alfa fibers

181 **II.3. Preparation of specimens**

The sand and Alfa fibers were oven-dried at 60 °C to remove all traces of moisture. First, a 182 dry mixing of the various constituents (cement, filler and sand) at slow speed $(140 \pm 5 \text{ min}^{-1})$ 183 for 30 seconds. The 2/3 of the mixing water is introduced by mixing for 1 min 30 seconds. 184 The superplasticizer is introduced (mixing for 30 sec), followed by 1/3 of the remaining 185 mixing water (mixing for 60 sec), then, the VMA is added (mixing for 30 sec). Switch the 186 mixer to the high speed (285 \pm 10 min⁻¹) and continue the mixing for an additional 60 sec. 187 Finally, the Alfa fibers were added progressively with slow mixing for 180 sec. The addition 188 of Alfa fibers in the mixtures was based on volume. Specimens sized 40 x 40 x 160 mm were 189 190 generated and then cured in a humid room (RH > 90%, T = $\pm 20^{\circ}$ C) until testing.

191 **II.4. Methods**

192 II.4.1. Fresh properties

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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.

199 • Calorimetry

The cement hydration kinetics were thus measured by a two-channel (I-Cal 2000 HPC) 200 201 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. 202 203 The heat of hydration released by the reacting cementitious specimen is transferred and passes 204 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. 205 Since the heat is allowed to flow away from the specimen, this measurement will essentially 206 207 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 208 209 after mixing. Next, the heat evolution of the various formulations was monitored for the first 210 48 hours of hydration process.



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

211 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.

217

• Water accessible porosity

The measurement of water-accessible porosity was carried out according to Standard NF P18-218 459. After 90 days of curing, the various specimens were dried in an oven at 105°C for 24 219 hours, until attaining constant mass. After cooling in a desiccator, the specimens were 220 221 immersed in water under vacuum for 48 hours in order to reach saturation. The specimens 222 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 (mdry). The 223 224 porosity (ϵ) and specific gravity (ρ_d) were both calculated using Equations (2) and (3), 225 respectively:

226
$$\epsilon(\%) = \left(\frac{m_{air} - m_{dry}}{m_{air} - m_{water}}\right) \times 100$$
(2)

227
$$\rho_d = \frac{m_{dry}}{m_{air} - m_{water}} \times \rho_{water}$$
(3)

228 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 229 in defining the final properties of a cementitious material. Singh et al. (2015) exhibited that 230 the mechanical properties of cement mortar decreased with an increase in S/C ratio [28]. 231 Those authors also reported that a W/C ratio determination is required to make the mortar 232 workable; otherwise, the addition of natural fibers is widely known to greatly influence 233 composite workability and composite mechanical properties [29]. In this regard, when 234 choosing an adequate mix design, incorporating Alfa fibers has been essential to studying the 235 combination of the fiber effect with the variation in dosage of the set of constituents. 236

237 III.1. Cement composite mix design

To study the effect of incorporating Alfa fibers on the cement mortar properties, a major 238 preliminary step focused on optimizing the cement paste parameters. The rheological, 239 mechanical and physical properties of cementitious materials usually depend on the nature 240 241 and amount of its various constituents. Likewise, the addition of cellulosic fibers into a 242 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 = 243 244 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 245 246 length and content of Alfa fibers correspond to the median values tested in the next part of this study. 247

Constituents (g)	Cement	Sand 0/1	Limestone (filler)	Superplasticizer	VMA	Water	Alfa fibers
FRM(0.3)1						259.7	28.6
FRM(0.4)1	900	900	225	9	4.5	349.7	31.1
FRM(0.5)1						439.7	33.7
FRM(0.3) ₂						173.1	25.6
FRM(0.4) ₂	600	1200	150	6	3	233.1	27.3
FRM(0.5) ₂						293.1	29.1
FRM(0.3)3						129.8	24.1
FRM(0.4)3	450	1350	112.5	4,5	2.3	174.8	25.4
FRM(0.5)3						219.9	26.7

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

249 **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 252 higher composite workability. For S/C = 1, workability increases according to the W/C ratio. 253 FRM(0.3)₁ and FRM(0.4)₁ display a respective workability of 19.5 and 20.9 cm and moreover 254 present a homogeneous appearance, which is indicative of good fiber distribution in the 255 256 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. 257 For this mixture, segregation has been observed, with a conglomeration of fibers in the middle 258 259 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 267 several studies. Singh et al. (2015) reported that insufficient water content leads to poor 268 269 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) 270 271 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 272 causes a decrease in solid concentration inside the matrix. An excessive injection of water 273 actually causes segregation phenomena to appear in the fresh state [31]. 274



Fig. 6: Slump flow diameter of mortars



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

278 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.

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

283 **Table 2:** Mechanical strength of different paste mortar

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

285 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 286 287 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. 288 289 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 290 291 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 292 293 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 294 strength of the reinforced mortar. For instance, for the composite with W/C=0.5, increasing 295 the S/C ratio from 1 to 3 leads to an increase of 9.3%. FRM $(0.3)_1$ has the highest flexural 296 strength, i.e. 6.3 MPa, compared to the other formulations. 297



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

298 The workability measurements and mechanical testing were complementary in the effort to 299 choose a basic formulation. Based on analysis of the various results, $FRM(0.3)_1$ shows the 300 best mechanical properties. However, the slump diameter and apparent fiber distribution in 301 fresh mixtures were high enough to confirm the relevance of this mix design in satisfying the 302 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 303 design candidate with slightly better workability than $FRM(0.3)_1$. However, its mechanical 304 performance is lower than that of $FRM(0.3)_1$. As such, to limit cement content and preserve 305 good workability and mechanical performance, it is preferable to select a W/C ratio ranging 306 between 0.3 and 0.4. The basic formulation used in this work was therefore set at: W/C =307 0.35, and S/C = 1. 308

309 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:

316 **RM(CFX)y** stands for Reinforced Mortar with cut fibers, where X = length (mm) and Y =317 addition rate (%). **Table 3** summarizes the previously chosen mortar mix design.

1 able 5: Composition of the control morta

319

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

320 IV.1. Properties of fresh mixes

The measured flow diameters of mortars reinforced with cut Alfa fibers are given in Table 4. 321 The introduction of Alfa fibers does not significantly affect the workability of fresh mixtures, 322 323 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 324 slump flow of 22.7 cm. Mixtures with 3% vol. of Alfa fibers exhibit a relative reduction of 325 6% in workability for fiber lengths of 10 and 20 mm, and of 15% for fibers 30 mm long. The 326 increase in fiber length with a high volume content leads to the formation of clusters (i.e. 327 RM(CF30)₃), which strongly influences the fluidity of fiber mortars (Fig. 9). This same 328 329 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 330 slump of flax-reinforced concrete was observed for a fiber length ranging from 12 to 36 mm 331 332 [4].

333 334

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

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

³³⁵ 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

336 IV.2. Mechanical properties

Fig. 10 presents the flexural strength of Alfa fiber-reinforced mortar with different lengths 337 338 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 7.3 339 340 \pm 0.3 MPa and 7.4 \pm 0.3 MPa after 90 days of curing. The introduction of Alfa fibers into 341 cement mortar leads to an increase in the flexural strength of cementitious materials. At 28 342 days of curing, a 39~40% gain in flexural strength was observed for RM(CF10)1 and 343 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, 344 respectively. Moreover, it was noted that mortar containing cut fibers 30 mm long (denoted 345 RM(CF30)) has a lower flexural strength, regardless of fiber content. This finding confirms 346 347 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, 348 349 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 350 fiber length and addition rate were found to significantly influence the flexural strength of 351

flax-reinforced concrete. It was noted that for each fiber length, the higher the flax fiber 352 content, the greater the flexural strength. Moreover, these authors confirmed that the flexural 353 strength of the composite increased when decreasing fiber length. Similarly, Comak et al. 354 (2018) [32] corroborated this same correlation between hemp fibers and the mechanical 355 properties of cement-based mortars. It was reported that an increase in fiber content leads to 356 an increase in flexural strength of between 1% and 17%. The difference observed by these 357 two authors could be related to the actual fiber length studied. Page et al. used flax fibers cut 358 to 12, 24 and 36 mm, which presents a rather high average length. In contrast, the highest 359 360 length studied by Comak 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 361 362 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 363 364 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. 365

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 372 matrix. According to Wei et al., the degradation of natural fibers in a cement matrix could 373 occur in four steps: (i) lignin and hemicellulose degradation, which serves to expose the 374 holocellulose; (ii) reduction in cell wall stability due to hemicellulose degradation; (iii) 375 dispersion of some cellulosic fiber components in the pore solution of the matrix, thereby 376 promoting cellulose degradation; and (iv) a complete degradation of the natural fibers due to 377 alkaline hydrolysis of their amorphous part [33]. Based on this hypothesis, the decrease in 378 379 flexural strength ascribed to the addition of Alfa fibers could be correlated with fiber hydrolysis taking place inside the matrix over time. 380



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 382 presented in Fig. 11. Compared to the control mortar (CM), the introduction of Alfa fibers 383 384 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, 385 386 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 387 388 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 389 390 a 10-mm length. This observation can be made for all Alfa fiber lengths. Otherwise, the 391 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: 392 $RM(CF30)_1$ has a compressive strength of 59.4 MPa, while that of $RM(CF30)_2$ is 40.4 MPa 393 and RM(CF30)₃ just 28.5 MPa. Consequently, these figures reveal a reduction of 29%, 51% 394 and 66%, respectively, in comparison with the CM. Increasing fiber length thus seems to exert 395 a more significant influence on compressive strength. These compressive strength decreases 396 397 have also been highlighted by other authors on bio fiber-reinforced concretes [34,35], as 398 attributed to greater concrete air content, which consequently reduces its compactness and 399 hence its compressive strength [4]. These previous studies have also noted that long fibers 400 produced lower compressive strengths; these fibers would further disrupt the granular 401 packing, in turn reducing the mixture compactness.



403 V. Comparative study between ground and cut Alfa fibers

404 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 405 definitely observed, at least for RM(CF10)1 and RM(CF20)1 formulations; however, this 406 finding was coupled with a loss of strength after 90 days of curing. Such behavior is most 407 likely related to fiber deterioration over time. Several works have tied fiber degradation to the 408 presence of calcium hydroxide and, consequently, fiber mineralization inside the matrix [36– 409 410 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 411 solution, which promotes fiber deterioration [33]. In this context, the objective herein is to 412 incorporate the ground Alfa fibers in order to study their behavior in comparison with cut 413 414 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 415 examine the difference in behavior inside the matrix. The ground fibers were incorporated 416 417 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 418 do the test specimen storage conditions (RH > 90%, $T = 20^{\circ}C$). 419

420 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. 425 Compared to the control mortar (CM), with a flow diameter of 22.7 cm, introducing ground 426 Alfa fibers up to a 2% vol. rate did not significantly affect workability on the reinforced 427 mortar. A slight variation of about 1% and 4% was measured for RM(GF)₁ and RM(GF)₂, 428 respectively; however, an RM(GF)₃ flow diameter of 19.8 cm was measured on the RM(GF)₃ 429 mixture, thus corresponding to a 12% reduction relative to the CM.

430 Based on the observations shared in a previous section (IV.1), the cut Alfa fibers do not exert 431 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 432 fresh mixture. Nevertheless, a high addition rate does reduce mortar workability, yielding an 433 agglomeration of fibers inside the matrix. Similar observations have been reported in other 434 studies [4,39]. However, unlike other plant fibers (e.g. flax), Alfa fibers exert less influence 435 on the workability of fresh mixtures. This outcome might stem from the large Alfa fiber 436 diameter (approx. 1-2 mm), which for example is much greater than that of flax fibers (10-20 437 μ m) [40]. Flax fibers do in fact significantly modify the rheology of the blends, due to their 438 high specific surface area [12,41]. In our case, the Alfa fibers, given their larger diameter, 439 have a much smaller specific surface area, hence reducing the effect of these fibers on 440 workability. 441

442



RM(GF)1RM(GF)2RM(GF)3Fig. 12: Slump diameter of grinded Alfa fiber-reinforced mortar

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

444 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 450 by hardening, crystallization and, lastly, release of heat of hydration [42,43]. Generally 451 speaking, the heat flow curve is characterized by three distinct times, such as the minimal flux 452 453 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 454 curve of the CM exhibits a two-step evolution. A rapid exothermic peak is observed during 455 456 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 457 458 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 459 460 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 461 462 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 463 464 second peak (t₃) 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%, 465 which is not the case for the Portland cement used in this study [42]. Finally, the deceleration 466 467 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 468 fibers into the mixture. The induction periods of the Alfa-reinforced mortars are extended by a 469 time ranging between 30 min and 8 hours for RM(CF)₁ and RM(CF)₂ and between 30 min 470 and 16 hours for RM(GF)₁. The main hydration peak is therefore shifted to the right and 471 delayed; consequently, the main peak is observed at 18 h for both RM(CF)₁ and RM(CF)₂ and 472 at 25 h for RM(GF)₁, corresponding to a delay of 2 h and 9 h, respectively. A clear 473 relationship can be drawn between the Alfa fiber addition rate and heat flow. In fact, the 474 475 increased addition rate leads to a decrease in the maximum heat flow of Alfa fiber-based 476 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 477 the mixing process. It has indeed been reported that extractive components from plant fibers, 478 such as saccharides, could significantly delay cement setting, even with a low content of these 479 carbohydrates [46-48]. Moreover, other studies have also highlighted that pectin is a 480 chelating agent of calcium ions that is capable of entrapping the cement ions inside its 481

structure [49,50]. Alfa fibers undoubtedly retain the calcium ions inside the pectin structure, 482 which could explain the delay observed in the hydration peaks of Alfa fiber-reinforced 483 mortars. The lower calcium ion concentration serves to create deficiencies in the cement 484 hydration reaction, thus inhibiting the formation of silica calcium gel, which is chiefly 485 responsible for the mechanical properties of cementitious materials. However, mortars 486 reinforced with ground fibers show a different behavior compared to mortars made with cut 487 fibers. For a 1% vol. of fibers, the main exothermic peak of RM(GF)₁ is more intense than the 488 same mortar containing cut fibers (RM(CF)1). The increase in addition rate therefore leads to 489 490 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)₂ 491 492 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. 493

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 500 heat flow curve. Fig. 13b displays the curve variations of the various mortars, with CM 501 502 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 503 more pronounced when using a higher addition rate. For instance, decreases of about 78% and 504 60% were recorded for RM(GF)₂ and RM(CF)₃, respectively; nevertheless, RM(GF)₁ has a 505 cumulative heat release of 141.9 J/g, which represents a slight decrease (roughly 9%) 506 507 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 508 509 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 510 that including Alfa fibers reduces the heat flow values, which might also be correlated with a 511 reduced amount of calcium silicate hydrate in the composite; consequently, the compressive 512 strength has decrease. 513



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

514RM(CFX)y : Reinforced Mortar with cut fibers, where X = length (mm) and Y = addition rate (%)516RM(GF)x :Reinforced Mortar with ground fibers at an x% vol. addition rate (%)

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

518 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 524 rate. It should first be pointed out that the water-accessible porosity of the various mortars 525 depends on the fiber addition rate: increased fiber addition leads to higher mortar porosity. 526 The evolution of mortar porosity with ground fibers is somewhat similar to mortar with cut 527 fibers, by virtue of displaying a linear evolution with respect to fiber content. Compared to the 528 control mortar (CM), a 61 % relative increase in water-accessible porosity for RM(CF10)₃ 529 and 54 % for RM(GF)₃ have been recorded. Furthermore, RM(CF20) and RM(CF30) exhibit 530 a similar curve, trending up to 2% vol. of fibers, with a maximum relative increase of 67% 531 532 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 533 534 literature. Previous works have confirmed that the inclusion of natural fibers in a cementbased matrix increases the porosity of the composite [54,55]. The additional porosity created 535 536 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 537 538 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 539 540 fiber [56]. This variation disturbs the cement hydration reaction while also promoting the 541 creation of pores.

The difference observed in the water-accessible porosity of cut fiber-reinforced mortars 542 (RM(CF)) and ground fiber-reinforced mortars (RM(GF)) could be explained by the different 543 fiber morphology. During composite curing, the cut fibers exhibit a major volume change, 544 545 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 546 547 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 548 549 water-accessible porosity for the mortar with cut fibers. Moreover, regarding the water 550 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 551 lower absorption capacity of ground fibers would in fact reduce the volume variation due to 552 553 the swelling/shrinkage phenomena [57].

554



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 (%)

558 559 560

561 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 562 563 inside the mixture, which probably reduces the composite compactness [4]. Fig. 15 presents 564 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 565 of decreasing and reducing the density. For instance, with a 3% vol. of ground Alfa fibers, a 566 density reduction in RM(GF)₃ on the order of 3% compared to the CM is noted. Similarly, 567 lower densities are obtained with mortars containing the highest Alfa content, i.e. 3% vol., 568 regardless of fiber length. However, the 1% vol. addition rate yields a composite with a 569 density near that of the CM. According to Djelal et al. (2020), comparable results have been 570 presented, with similar changes being recorded for sawdust-based mortars. The authors linked 571 the difference observed in results to the morphology of wood aggregates. Due to the wood 572 fiber morphology, in its slender form, these natural fibers are capable of entrapping a high air 573 volume [1]. 574



Fig. 15: Water absorption porosity and density correlation of Alfa fiberreinforced mortars

575
576
577 RM(CFX)y : Reinforced Mortar with cut fibers, where X = length (mm) and Y = addition rate (%)
577 RM(GF)x :Reinforced Mortar with ground fibers at an x% vol. addition rate (%)

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

579 V.4.1. Flexural strength

Flexural strength was measured for the reinforced mortars after 7, 28 and 90 days of curing. 580
 Table 5 summarizes the compressive and flexural strength values of mortar reinforced with
 581 ground Alfa fibers. Compared to the CM (without fibers), ground Alfa fibers have a 582 significant effect on the composite's mechanical properties. The addition of ground Alfa 583 fibers, up to 2% vol., leads to a maximum increase in flexural strength of about 62% at 28 584 days of curing. Meanwhile, the 3% vol. addition also generates an 18% increase in flexural 585 586 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 587 588 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 589 590 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, 591 592 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 593 594 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]. 595

	Compressive strength (MPa)				Flexural strength (MPa)			
Specimens	СМ	RM(GF)1	RM(GF) ₂	RM(GF) ₃	СМ	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	62±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

Table 5: Flexural and compressive strength of grinded Alfa fiber-reinforced mortars
 596

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

597 598 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. 599 Using ground Alfa fibers serves to raise composite flexural strength compared to cut fibers. 600 For instance, a 1% vol. addition results in a rise of approx. 17 % for RM(GF)₁ compared to 601 RM(CF10)₁ and RM(CF20)₁. Even at a high addition rate, the flexural strength of ground Alfa 602 603 fiber-reinforced mortar remains greater than that of the CM, as opposed to cut fiber-reinforced 604 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 605 mechanical properties of fiber-reinforced cementitious composites [58,59]. 606



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 607 displacement curve of the CM and Alfa fiber-reinforced mortars. The flexural tests were 608 carried out on the various mortars cured at 28 days with displacement-control at a rate of 0.5 609 mm/min. The mechanical properties of a fiber-reinforced composite depend mainly on fiber 610

content and orientation, but also on the load transfer capability of the fiber-matrix interface 611 612 [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 613 capability [62]. The CM specimen exhibits a totally brittle behavior; however, the various 614 fiber-reinforced materials exhibit the same failure mode, i.e. brittle fracture. This 615 determination could be related to the shape and morphology of Alfa fibers. The cut Alfa fibers 616 did not show any apparent flexibility, which likely influences their behavior inside the matrix; 617 furthermore, their slippage out of the matrix could impact bending properties. Therefore, the 618 619 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 620 621 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, 622 623 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 624 625 authors also exhibited that natural fiber types, length and texture directly influence the composite's mechanical behavior [11]. However, incorporating Alfa fibers improves the 626 627 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 628 fibers. Olivito et al. (2014) reported that due to the larger fiber cross-sectional area, the 629 composite samples measured a lower tensile strength [64]. 630



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 633 small fragment of 90 days cured mortar. Fig. 18 illustrate the interfacial zone and distribution 634 of Alfa fibers inside the matrix for both mortar formulation (grinded and cut fibers). A poor 635 fiber/matrix adhesion is observed on mortars with fibers cut in different lengths, with a fiber 636 slipping from the cement matrix (Fig.18-a and Fig.18-b). According to the literature, the 637 SEM micrographs of the lateral view of Alfa fibers confirm that the Alfa fiber surface has a 638 thick layer of impurities with a rough appearance, which in turn could affect the adhesive 639 properties of the fibers [10]. Otherwise, an apparent homogeneous distribution of ground 640 641 fibers in the matrix is observed (Fig18-c), which could improve the adhesion between fibers 642 and matrix and therefore enhance the flexural strength of the reinforced mortar (Fig18-d). 643 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 644 645 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 646 647 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 648 649 display the highest adhesive stress values [12,62].



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

650 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 654 significant decrease in compressive strength. For instance, at 28 days of curing, RM(GF)₁ and 655 RM(GF)₂ indicate a decrease of 11% and 34%, respectively, compared with the CM. These 656 results are similar to those of mortar made with cut fibers. Fig. 19 presents the evolution in 657 the relative compressive strength vs. fiber addition rate. Relative compressive strength is the 658 ratio of the compressive strength of the fiber-reinforced mortar (RM(GF) or RM(CF)) to the 659 compressive strength of the control mortar (CM). The incorporation of Alfa fibers, either cut 660 or ground, reveals the same trend in the evolution of relative compressive strength when 661 662 increasing the fiber content. This trend was also reported in a recent work; the authors noted a 663 significant reduction in compressive strength when increasing the wood fiber substitution rate 664 [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 665 666 attributed this behavior to the increased composite porosity and low DPF mesh mechanical 667 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 673 cement composites. Fig. 20 presents the correlation between water-accessible porosity and the 674 compressive strength of specimens after 90 days of curing. A clear linear correlation between 675 compressive strength and porosity can be discerned. The increase in addition rate therefore 676 leads to a higher water-accessible porosity; consequently, the composite compressive strength 677 declines. This finding confirms the results discussed above, namely a high addition rate of 678 Alfa fibers, either cut or ground, raises porosity while decreasing density, resulting in a 679 compressive strength reduction. This increase in porosity with the incorporation of plant 680 681 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]. 682



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

683 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 postsaturation water absorption rate equaled 86% and 62% for cut and ground fibers, respectively.

688 A preliminary study was performed to select the appropriate mix design from both 689 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 690 fibers 10 mm and 20 mm in length at up to 1% vol. allows improving the flexural strength of 691 the composite by about 28% at 28 days of curing, compared to the control mortar. 692 Nevertheless, at 90 days, the flexural strength has decreased, most likely due to fiber 693 degradation over time, although the values remain close to those of the CM. As regards 694 ground fibers, the reinforced mortar exhibits similar behavior, as the addition of ground Alfa 695 fibers up to 2% vol. leads to a maximum increase in flexural strength by approx. 62% at 28 696 days of curing. The addition of cut or ground Alfa fibers did not however improve the 697 698 compressive strength of the composite.

A comparative study was conducted to compare the effect of a fiber morphology change on 699 700 composite properties. The addition of Alfa fibers increases the composite's water-accessible 701 porosity; this effect is more pronounced for cut fibers than ground fibers. The longer fiber 702 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 703 704 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. 705 706 A modification in the hydration process was indeed recorded as a function of fiber addition 707 rate. An increased addition rate extends the induction period and decreases the main peak 708 intensity, which was mainly due to fiber composition. Based on these results, the compressive 709 strength reduction can be explained by both hypotheses; Fiber addition leads to a composite 710 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.

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749	Table 3: Composition of the control mortar
750	Table 4: Slump flow of cut Alfa fiber-reinforced mortar
751	Table 5: Flexural and compressive strength of grinded Alfa fiber-reinforced mortars
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