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Mechanical properties of date palm fibres and concrete reinforced with date palm fibres in hot-dry climate

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Abstract

The study examines four types of date palm surface fibres and determines their mechanical and physical properties. In addition, the properties of date palm fibre-reinforced concrete, such as strength, continuity index, toughness and microstructure, are given as a function of curing in water and in a hot-dry climate. The volume fraction and the length of fibres reinforcement were 2–3% and 15–60 mm respectively. Increasing the length and percentage of fibre-reinforcement in both water and hot dry curing, was found to improve the post-crack flexural strength and the toughness coefficients, but decreased the first crack and compressive strengths. In hot-dry climate a decrease of first crack strength with ageing was observed for each concrete type. Water curing decreased the global degree of the voids and cracks with time for each concrete type, but increased it in hot-dry climate.

Keywords: Date palm fibres; Vegetable fibres; Fibre-concrete; Curing; Hot-dry environment; Strength; Elongation; Modulus of elasticity; Continuity index; Voids; Toughness

1. Introduction

The date palm (*phoenix dactylifera*) is the one of the most cultivated palms around the world. It is commonly found in the Afro-Asiatic dry-band, which stretches from North Africa to the Middle East. It has a good tolerance to cold and dry-hot climates. The phoenix is a dioïque organism with male and female palm [1,2]. Algeria has more than 10 million date palms that yield over 800 date varieties in its oases in the south. The more common date varieties are Deglette-Nour, Elghers and Degla-Bida (local names) [3]. Date palms have a fibrous structure, with four types of fibre: leaf fibres in the peduncle, baste fibres in the stem, wood fibres in the trunk and surface fibres around the trunk.

Surface fibre was chosen in this study as it seemed most suitable for exploitation. After annually trimming operations, enormous quantities of palm fibre wastes are thrown away, except in smaller scales for artisan products. The aim of this study is to investigate the properties of date palm fibres and of concrete reinforced with these fibres in hot-dry climate. It also endeavours to examine the possibility for utilising these natural resources in local construction.

In fact, most materials used for construction, especially the concrete, are sensitive and adapted with difficulties to hot-dry climatic conditions. As an example Table 1 provides average climatic data of Ouargla, the Algerian oasis where a part of the tests reported here were made. During summer, the temperature in the day is very high (up to 43 °C), the daily amplitude between day and night regularly reaches about 18 °C, and the humidity level of air stays very low. Research [4–6]

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Table 1
The monthly mean climatic data of Ouargla Algeria region [26]

	June	July	August	September	October	November
T_{max} (°C)	39.8	43.2	42.2	37.6	30.7	23.6
T (°C)	31.5	34.3	33.6	29.8	23.4	16.6
T_{min} (°C)	23.2	25.3	25.0	22.0	16.0	9.6
RH (%)	28.5	24.4	26.4	34.4	47.6	56.5
WV (km/h)	16.02	13.43	10.80	10.33	08.86	08.06

T_{max}, the maximum temperature; T_{min}, the minimal temperature; RH, the relative humidity; WV, the wind velocity; T, the average temperature.

indicates that mechanical properties of concrete, particularly the flexural strength, decrease with time under similar climatic conditions. Furthermore, previous work [7,8] indicates that conventional concretes and mortars exhibit a high level of shrinkage and cracking in this type of environment.

According to the results of various researches on more common vegetable fibres [9–21], the presence of natural fibres in concrete is beneficial for flexural properties. Thus a research project to reinforce concrete with date palm fibres was launched, to explore a technical alternative for a suitable local solution for improving the qualities of concrete. This paper provides further information about the date palm fibres, and presents a range of results on the behaviour of date palm fibre-reinforced concrete, like, strength, toughness, global degree of voids or cracks and scanning electron micrographs at fibre–matrix interface zone.

2. Materials and methods

2.1. Materials

The natural fibres used in this research are from the surface of the turn of date palm. Four types of date palm surface fibres (DPSF) were tested, corresponding to the four principal palms: male palm, Deglette-Nour, Degla-Bida and Elguers palms (local names). The date palm surface fibre are naturally weaved, and are pulled out from trunk in the form of nearly rectangular mesh (length 300–500 mm, width 200–300 mm) formed with tree superposing layers. It is easy to separate them out of individual fibres of diameter 0.2–0.8 mm in water.

According to standards NFP 15-301 [22] two cement types were used: the Composite Portland Cement (CPJ-CEM II/A 32.5) and the Portland Cement (CPA-CEM I 52.5). Table 2 gives chemical and physical properties of the two cements.

Two natural sands with maximum size 5 mm were used:

- Sand 1 with bulk density 1660 kg/m^3,
- Sand 2 with bulk density 1600 kg/m^3.

Two aggregates with maximum size 10 mm and minimum size 5 mm were used:

- Aggregate 1: A crushed slice-lime stone with bulk density 1600 kg/m^3,
- Aggregate 2: Natural, with bulk density 1610 kg/m^3.

The cement CPJ-CEM II/A 32.5, Sand 1 and Aggregate 1 were used in concrete (referenced Concrete 1) prepared at the university of Ouargla in Algeria for compressive strength and sound velocity tests. The cement CEM I 52.5, Sand 2 and Aggregate 2 were used in concrete (referenced Concrete 2) prepared at INSA of Lyon in France, for the flexural properties test. In each case, the local cement and aggregates were used.

2.2. Specimens and curing conditions

2.2.1. Specimens fabrication

Specimens of concrete with dimensions 70 × 70 × 280 mm were used for flexural strength and pulse velocity tests concrete. 100 mm cubes sides were used for compressive strength tests.

For the mix design of concrete without fibres, the experimental method recommended by Baron-Lesage [23] and Gorisse [24] was used to obtain the optimum sand/aggregate ratio. For all mixes of fibre concretes, the mass of cement and sand was kept equal to that of concrete without fibres. The percentage of fibres was

Table 2
The chemical and the physical properties of cementing material

Cement	Chemical properties									Physical properties		
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	SO_3	K_2O	Loss on ignition	Fineness (m^2/kg)	Setting time (initial-min)	σ_c, 28 days (MPa)
CPJ-CEM II/A	21.90	5.73	3.13	1.85	60.18	0.19	2.22	0.83	4.07	370	175	30
CPA-CEM I	20.29	4.60	2.98	1.66	65.24	0.30	2.70	0.99	2.80	385	200	50

Table 3
Mix design proportion

Materials	Mix 1 (0%)	Mix 2 (2%)	Mix 3 (3%)
Cement (kg/m^3)	400	400	400
Aggregate (kg/m^3)	1000	982	973
Sand (kg/m^3)	750	750	750
Water (kg/m^3)	240	270	290
MDPSF (kg/m^3)	0	18	27

varied but the mass of fibres plus aggregates was maintained constant. With a workability of VB time equal 20 ± 5 s and slump equal to 70 ± 10 mm, the water quantity was adjusted to adapt the mix with the fibre percentage. The fibre percentages in the reinforced concrete were 2% and 3% by volume. In fact, when the percentage of fibre increased, the demand for water also increased due to absorption by the fibres. For each mix the fibre lengths were 15 and 60 mm. The variation of workability with fibre length was slight. Table 3 gives the mix design proportions of concretes.

A conventional Zyklos mixer with a horizontal axis was used to mix the concrete composites. The fibres used in the concretes were washed beforehand with tap water and dried in free air.

The composites production was carried out as follows: The fibres were initially immersed in 10% of the total volume of water required for 5 min, in order to facilitate their separation. At this stage the rate of saturation of fibres was about 56%. The sand, aggregates, plus 30% of water were mixed for 30 s in a running mixer. Then, the fibres were added together with 30% of the water and mixed for 3 min. This was done slowly in order to obviate the possible clumping of fibres. After adding all cement quantity, the remaining water was added during 2.5 min.

As function of volume and length fibre variation, four types of fibre concretes were prepared in addition to concrete without fibre. The concretes were referenced by the following notation: N%–L, where N is the percentage in volume and L is the length in mm of fibres. For example 2%–60 that is $N = 2\%$ and $L = 60$ mm.

The filling of the moulds and the vibration using a vibrating table were carried out in accordance with standards NFP18-409 [25].

2.2.2. Curing conditions

The specimens were initially cured in the laboratory for 24 h under normal climatic conditions: $T = 20 \pm 2$ °C, and RH = 65 ± 5%. After demoulding, they were cured until test in three types of environment. For the first type of environment, fibre concrete specimens were placed in water at temperature of 20–25 °C (referenced Curing 1). For the second type of environment, they were placed in ambient atmosphere under uncontrolled hot-dry climate (referenced Curing 2) with severe field conditions as shown in Table 1. During 6 months (June–November) the mean monthly maximum temperature varied from 43.2 °C in July to 23.6 °C in November, the mean monthly minimum temperature varied from 9.6 °C in November to 25.3 °C in July. The percentage of relative humidity varied between 24.4% in July to 56.5% in November. Furthermore, the site is located in a zone at average wind velocity of 8–16 km/h [26]. For the third type of environment, they were placed in a steam room in the laboratory at 32 ± 2 °C and 28 ± 2 of RH (referenced Curing 3). This case was used to simulate Curing 2.

The concrete was tested at the following ages: 7, 28, 90, and 180 days for the pulse velocity test, and at 28, 90, and 180 days for compressive and flexural strength. Six specimens were used for each test.

2.3. Test methods

The bulk density of fibres was determined by the gravimetric method, according to NF EN ISO 1973 standard [27], on a balance Mettler PM 200 with a precision of ±0.1%. Sixty fibres of length 50 mm of different diameters were tested, under the following climatic conditions, $T = 20 \pm 2$ °C and RH = 65 ± 2%.

The absolute density of fibres was measured by a Micrometrics 9300 mercury porosimeter, equipped with two low-pressure devices for degasification and analysis and one high-pressure analysis device, which can reach 210 MPa.

The water absorption of the fibres was measured in accordance with ASTM C127/88, using 10 samples.

The mechanical properties (tensile strength, elongation and the modulus of elasticity) of fibres were determined in accordance with standards NF EN ISO 5079 [28], under the following climatic conditions, $T = 20 \pm 2$ °C and RH = 65 ± 2%, and using an Instron universal testing machine equipped with a 250 N load-sensor and two LVTD displacement transducers at a cross-head speed of 0.5 mm/min. Test data were digitally recorded and reduced using a numerical chain data acquisition system connected to a device that plotted the force/deformation curve.

Each fibre extremity (30 mm length) was moulded in an epoxy resin cylinder. The central part between the two cylinders and hence the tensile test lengths were 20, 60 or 100 mm. The cylinders were used to fix the fibre in the tensile device as shown in Fig. 1.

Thirty fibres for each length and for each treatment (dry, wet) were tested, first the natural dry fibre and second the fibre placed for 24 h in water (saturation).

A Hitachi S 800 scanning electron microscope was used to study fibre surface topographies and to examine the section of fibres and the fibre–matrix interface. The fibres and the fibre–matrix samples were fractionated and stuck on conducting silver plates, then were sputter coated with a layer of gold 20–30 nm thick in a vacuum

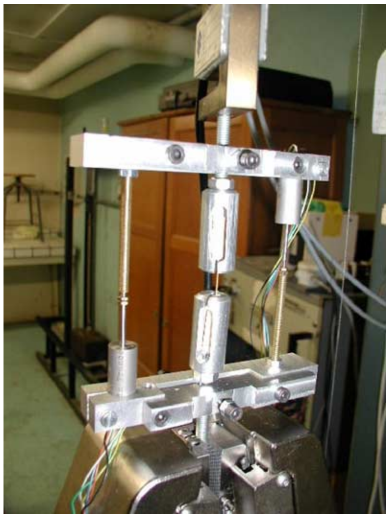

Fig. 1. The set-up tensile strength test.

chamber. The images on scanning electron microscope were obtained by the secondary electron imaging method, with a tension of acceleration of the beam of 15 kV.

The propagation of sound velocity across concrete was measured by the transparency technique in accordance with standards NFP 18-418 [29]. The apparatus used consisted of an electric pulse generator, equipped with a transmitter and several receivers. The transmitter and the receiver were placed on either side of specimen. The sound velocity across concrete is given by Eq. (1):

$$V = l/t \ (\mathrm{m/s}) \tag{1}$$

where l is the distance which separates transmitter and receiver (m) and t is the propagation time read by the apparatus (s). The continuity index (CI) proposed by Gorisse [24] is given by Eq. (2):

$$\mathrm{CI} = \frac{V}{V_\mathrm{r}} * 100 \tag{2}$$

where V is the sound velocity across concrete (m/s) and V_r is the reference sound velocity ($V_\mathrm{r} = 4500$ m/s). So, the CI was calculated to deduce the compactness and the global degree of voids and cracks. In fact, the CI is proportional to the compactness and inversely proportional to the global degree of voids and cracks.

The compressive strength of concrete was measured in accordance with standards NF EN 12390-4 [30], using a Maurice Perrier et C^{ie} machine with a rate loading of 3 ± 0.5 kN/s.

The flexural strength properties were determined with an experimental set-up in accordance with standard NFP 18-409 [25], using an Instron universal testing machine and four-point test configuration, with 210 mm span and cross-head rate of 0.1 mm/min. The system was equipped with a load-sensor of 50 kN and two LVDT displacement transducers. These continuously recorded to a numerical data acquisition system, which made it possible to determine the deflection at the mid-span of the specimen as function of loading.

The flexural properties were evaluated using three parameters:

1. The first crack strength (FCS) determined from the load at the first visible crack using Eq. (3).

$$\mathrm{FCS} = 6M_0/bd^2 \tag{3}$$

2. The maximum post-crack flexural strength of the composite (σ_f) determined from the maximum load carried by the composite after the first crack using Eq. (4):

$$\sigma_\mathrm{f} = 6M_\mathrm{f}/bd^2 \tag{4}$$

where M_0 and M_f are the failure moments of the test specimen of the load at the first visible crack and the maximum post-crack load respectively and b and d are the width and depth of the specimen respectively.

3. The French toughness coefficient (D_n):

$$D_n = P_n/P_0 \tag{5}$$

with P_n is the applied load at deflection of 0.7, 1.4 and 2.8 mm and P_0 is the load at the first visible crack [25].

3. Test results and discussion

3.1. Physical and mechanical properties of DPSF

Table 4 presents the mechanical properties of individual date palm surface fibres (DPSF). The results show that wet fibres were marginally stronger than dry fibres. The total elongation was slightly increased by humidification but the modulus of elasticity was significantly reduced. The male date palm surface fibre (MDPSF) was found to have the highest tensile strength and elongation, and for this reason, such fibres were selected to reinforce concrete. Compared to the mechanical properties of natural fibres reported in literature [9,16–21], the MDPSF has average tensile strength. In addition, the MDPSF ranges among the fibres, which have weak modulus of elasticity. This can be explained by the physical structure of the natural fibres [16]. In fact, these fibres do not have a role of resistance, but rather have a thermal role of protection in the palm tree.

However, it should be mentioned that the tensile strength depends on the fibre length, which is of prime importance regarding reinforcing efficiency. As shown in Table 4, the tensile strength increases with decreasing fibre length. The latter observation was also reported by Beledzeki et al. [16], who calculated the actual tensile strength of a single fibre by extrapolation to zero length

Table 4
Mechanical properties of DPSF

Palm types (local names)	Fibre length (mm)	Condition					
		Dry			Wet		
		Tensile strength (MPa)	Elongation (%)	Modulus of elasticity (GPa)	Tensile strength (MPa)	Elongation (%)	Modulus of elasticity (GPa)
Male	100	170 ± 40	16 ± 3	4.74 ± 2	175 ± 30	17.4 ± 2	3.78 ± 2
	60	240 ± 30	12 ± 2	5.00 ± 2	250 ± 25	13 ± 2	3.25 ± 1.5
	20	290 ± 20	11 ± 2	5.25 ± 3	300 ± 20	12 ± 2	3.55 ± 2
Elgers	100	88.15 ± 20	11.1 ± 2.5	3.50 ± 1.2	90.10 ± 18	12 ± 3	3.10 ± 1.5
Deglette-Nour	100	72.34 ± 18	8.7 ± 2.2	3.15 ± 1.5	74.34 ± 15	9.5 ± 2.5	2.30 ± 2
Degla-Bida	100	71.15 ± 16	7.5 ± 2.3	2.50 ± 1	73.19 ± 13	8.5 ± 2.7	2.10 ± 1

of the curve of tensile strength VS fibre length. This estimation method indicates a tensile strength of 320 MPa for the natural dry MDPSF. Compared with other results [16], the MDPSF is not so dependent on the fibre test length than is the case with other natural fibres. In fact, the specimen length generally affected the homogeneity of natural fibres, and hence the mechanical properties.

In the same way, the elongation also decreases with decreasing fibre length. However, the modulus of elasticity is not greatly influenced by the change in fibre length. The sensitivity to fibre length could be the main reason for the observed differences in the mechanical properties of natural fibres reported in literature, since the length of fibres tested is not constant. It was thus important to associate the length of the fibre in evaluating mechanical properties.

As will be shown later on, vegetable fibres have a porous structure. With DPSF, considering the section without the central channel as shown in Fig. 2(a) and (b), the real values of tensile strength and modulus of elasticity (Table 4) are in fact 10–20% higher then the predicted values.

Table 5 presents the upper, lower, and mean physical properties of MDPSF as well as the coefficient of variation (CV). The results show that MDPSF has a porous structure capable of absorbing a great quantity of water. The mean porosity (P) of the DPSF can be calculated by Eq. (6):

$$P = 1 - (\text{Bulk density}/\text{Absolute density}) \quad (6)$$

Using this equation, the mean porosity of MDPSF was found to be 35%, the mean percentage of water absorbed by mass following 24 h (saturation) immersed was 132.5%. According to results reported by Tolêdo Filho et al. [18] relating to sisal and coconut fibres, the MDPSF absorption percentage ranges between 230% for sisal and 100% for coconut. The latter property affects the water–cement ratio of the concrete mixes. In mix design, a quantity of water needs to be added for absorption by fibres. This could have a beneficial effect on the concrete cured in dry-hot climate. In effect, the vegetable fibres act as a sponge that absorbs water and releases it when necessary.

Fig. 2 presents the scanning electron micrographs of DPSF; Fig. 2(a) and (b) show the typical transverse

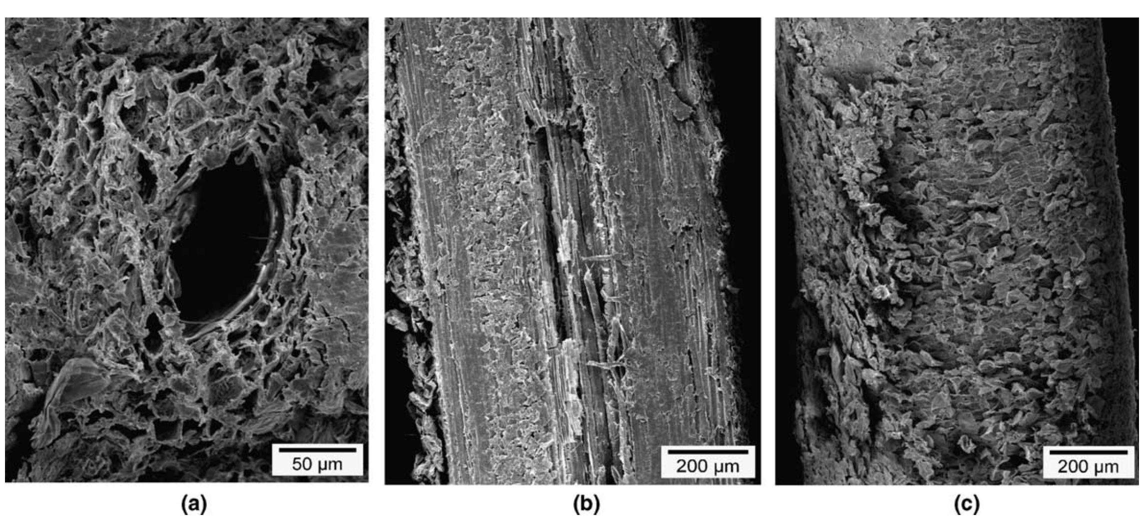

Fig. 2. (a) Scanning electron micrograph of typical transversal section of DPSF; (b) scanning electron micrograph of typical longitudinal section of DPSF; (c) scanning electron micrograph of longitudinal view of DPSF.

Table 5
Physical properties of MDPSF

Property	Lower–upper	Mean–CV (%)
Diameter (mm)	0.1–0.8	0.45–54.43
Bulk density (kg/m^3)	512.21–1088.81	900–17.64
Absolute density (kg/m^3)	1300–1450	1383.33–5.52
Natural moisture content (%)	9.5–10.5	10–5.00
Water absorption after 5 min (%) under water	60.05–84.12	74–14.02
Water absorption to saturation (%)	96.83–202.64	132.5–20.56

and longitudinal sections of DPSF. The DPSF section is dense with a small canal and many little pores for circulation of saliva. This confirms the porous structure and the observed absorption capacities of the DPSF. Fig. 2(c) presents the longitudinal view of MDPSF; its surface is irregular with many filaments, allowing good adhesion with the concrete matrix.

The study on the MDPSF, carried out in parallel on the MDPSF-reinforced concretes shows that these fibres have interesting physical and mechanical characteristics. However, the relatively weak elasticity modulus remains an element to be taken into account.

3.2. Properties of MDPSF-reinforced concrete

3.2.1. Continuity index

The mix used for these tests was Concrete 1. Figs. 3 and 4 show the mean values and the associated standard deviations of the CI for all concretes as a function of time and curing type.

The results show that in both Curing conditions at each age, the CI of fibre-concretes decreases with increasing fibre percentage. The maximum CI is thus obtained for 2%–15 fibre-concrete type. However, at early age (7 days) of curing in water, only two types of fibre-concretes (2%–15 and 2%–60) presented respectively a CI greater and equal to that of the concrete without fibres. All the fibre-concretes subjected to Curing 2 offered a CI larger than that of the concrete without fibres. After 7 days in both Curing 1 and 2, the CI of all fibre-concretes was lower than that of the concrete without fibres. However, the associated standard deviation for the CI for the 2%–15 concrete subjected to Curing 2 was closer to that of the concrete without fibres.

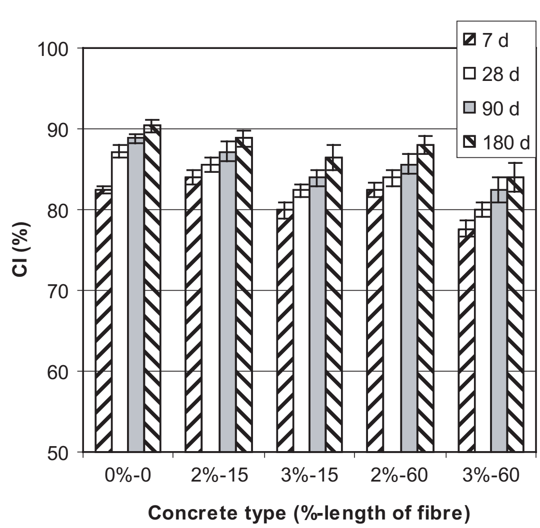

Fig. 3. Continuity index in water curing.

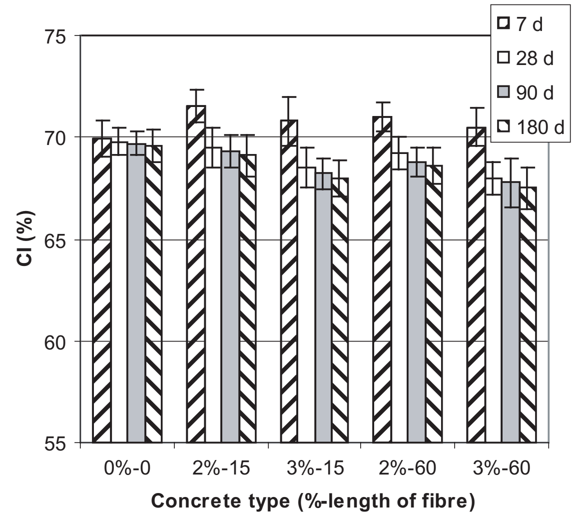

Fig. 4. Continuity index in hot-dry climate.

In Curing 1 (Fig. 3), for each concrete type, the CI increases with time, then the compactness increases and the global degree of the voids and cracks decrease with ageing. However, in the hot-dry environment, Fig. 4 shows a loss of CI with time for each concrete type. This loss was especially large for all fibre-concretes between 7 and 28 days. Then the global degree of the void and cracks increases with time for all concretes.

These results show that the presence of fibres in concrete promotes an increase in the CI at early age (7 days), implying an increase in the compactness and a decrease in the global degree of the voids and cracks. The retention of water by the fibre has a beneficial effect during this period and this is much more noticeable in air curing. However, after 7 days, the evaporation of water into concrete produces a slowing down of cement hydration processes and hence shrinkage of concrete. The high gradient of humidity inside the concrete induces cracks near the surface, which explains the difference in level of CI between water and hot-dry environment. Another effect of drying is the lateral shrinkage of the palm fibre, which debonds the fibre from the matrix. Thus the percentage of voids increases with time at the fibre–matrix interface, which explains the reduction of CI for all fibre-concretes with ageing.

3.2.2. Compressive strength

Concrete 1 was used in this test. Figs. 5 and 6 present the mean values and associated standard deviations for

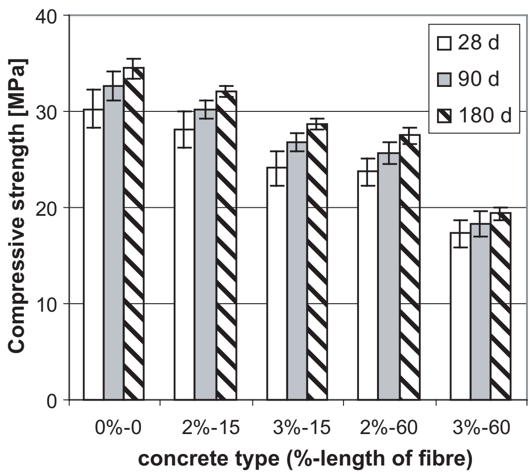

Fig. 5. Compressive strength in water curing.

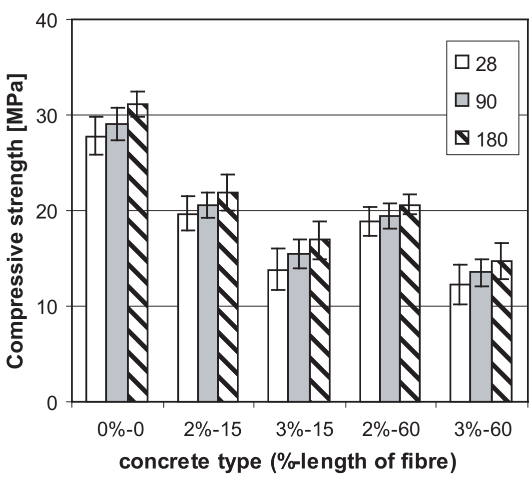

Fig. 6. Compressive strength in hot-dry climate.

compressive strength (σ_c) as a function of time, fibre percentage, fibre length and curing type.

For both Curing 1 and 2 the results (Figs. 5 and 6) show that the compressive strength decreases with age (28, 90, 180 days) with increasing fibre percentage and length. The maximum compressive strength of MDPSF-concrete was obtained for 2%–15 fibre concrete, which remained lower than that of the concrete without fibres (0%–0). For the fibre-concretes, the optimal compressive strength is obtained with lower percentage and shorter fibre length, as that introduces minimal flaws in the matrix, and gives more uniform distribution in the concrete. These results agree with other published findings [10,11]. In fact, in water curing, the vegetable fibre-reinforcement concrete can have limited beneficial effects on compressive strength. As shown in Fig. 5 at 28 and 180 days, the values of σ_c of 2%–15, the most resistant fibre-concrete, were respectively equivalent to about 90% of σ_c for 0%–0 concrete in water curing. In contrast, the values of σ_c of 2%–15 fibre-concrete were only about 70% of 0%–0 concrete in Curing 2. It should be mentioned that the mix of fibre-reinforced concrete (Mix 2 and 3) were made with more water then the mix without fibre (Mix 1). So the hardened fibre-reinforced concretes were more porous and hence less resistant then that of the concrete without fibre.

Although the compressive strength continues to increase with age in Curing 1 and 2, the strength observed for concretes cured outdoors is definitely lower than that stored in water. The reasons behind this will be detailed later on, but are largely due to the lack of hydration products due to rapid evaporation of water from the concrete at early ages, and to the development of drying cracks after long term. It is therefore noticeable that drying is disadvantageous for concrete strength, but more critical to natural fibre concrete.

3.2.3. Flexural strength properties

Concrete 2 was used in this part. Typical examples of bending load-deflection of MDPSF-reinforced concretes cured 28 days in water (Curing 1) and in steam room (Curing 3) are presented in Figs. 7 and 8. At the beginning of loading, the behaviour is elastic until the first crack strength (FCS). This limit was linked with the quality of concrete and the matrix flaws induced by the presence of fibres. Beyond the first crack strength the recorded deflection around 0.05 mm, the initiated crack had an unstable growth leading either to separation of the body into parts when there is no fibre, or to a macro-crack beam with a deflection around 0.5 mm when the fibres could stop the crack growth. This crack instability could be connected with MDPSF-fibre elasticity modulus. In fact to have an activation of the mechanical reinforcement, the crack must have a slight opening. After that the load became nearly constant with the increasing bending deflection.

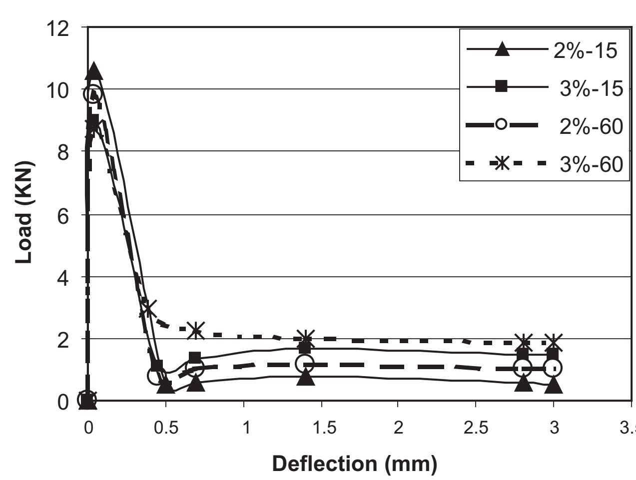

Fig. 7. Load–deflection curves at 28 days in water curing.

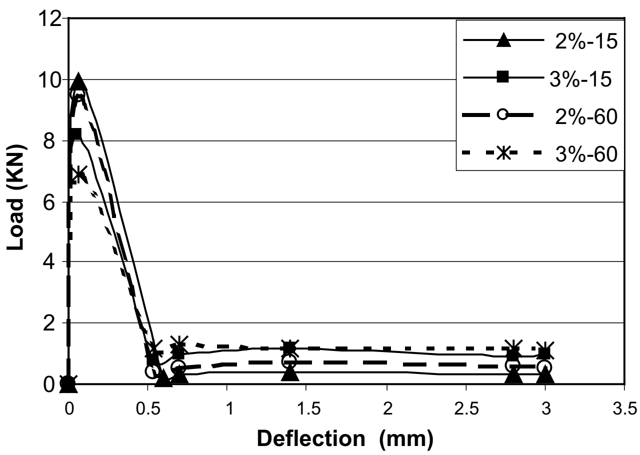

Fig. 8. Load–deflection curves at 28 days in Curing 3.

Table 6 provides the mean and the coefficient of variation of the first crack strength (FCS), the maximum post-crack flexural strength (σ_f) and the French toughness coefficient (D_n). In Curing 1, for each period (28, 90, 180 days), although the FCS continues to increase with time, a reduction in FCS for the fibre-reinforcement concretes compared to the concrete without fibre was observed. For the fibre-reinforcement concretes the maximum of FCS is obtained with the less percentage-length fibre (2%–15). Looking at the maximum post-crack flexural strength behaviour, an increase in σ_f is registered for an increase of fibre percentage-length in concrete. The maximum value of σ_f is then obtained with 3%–60 fibre-concrete. Increasing the percentage and the length of fibres ameliorates the toughness.

After the first crack in water curing, examination of the results given in Table 6, and Fig. 7 show that the MDPSF-concretes are relatively weak compared to the more common vegetable fibre concretes reported in the literature [9–21]. The σ_f for the most resistant fibre-concretes (3%–60), was only about 35% of the FCS at 28 days. In the same way toughness coefficient represented by $D_{0.7}$, $D_{1.4}$ and $D_{2.8}$ for the most ductile MDPSF-concretes (3%–60) remains relatively low compared to that found for the sisal and coconut fibre-concretes reported by Tolêdo Filho et al. [18]. That is probably due to three reasons: firstly, to the mediocre mechanical performance of the MDPSF; secondly, to the high resistance of the cement used (CPA-CEM I 52.5) which gave very high FCS and consequently a great energy of rupture at the first crack; thirdly, to the fibre–matrix interface strength bond. In fact, some researchers [31–33] have reported that treatment of vegetable fibres by chemical processes to improve their mechanical properties and adherence to the matrix and hence increase the flexural strength properties of vegetable fibre-concretes. These three causes shall be investigated in more detail in a following work.

The results in Table 6 show that, for each period in Curing 3, the FCS decreases with increasing fibre percentage and length. The high value of FCS was then obtained for 2%–15 fibre-concrete, but remaining lower than that of concrete without fibres. After first crack, at 28 days, increasing the percentage and the length of fibres ameliorates the toughness the maximum σ_f was then obtained with 3%–60.

For the aforementioned curing, a remarkable reduction in FCS was recorded with ageing for each concrete type. Moreover, the FCS, σ_f and toughness coefficient of these MDPSF-concrete types are remarkably lower than for those subjected to water curing. The principal elements responsible for this loss were lack of hydration products caused by the rapid evaporation of water during early stages and hence the development of voids and micro-cracks. To explain, Fig. 9 presents a comparison

Table 6
The FCS, σ_f and D_n for MDPSF-concretes at function of time and cures type

Flexural properties	Ageing condition	Age (days)	Concretes type (%–length of fibre)				
			0%–0	2%–15	3%–15	2%–60	3%–60
FCS (CV %) (MPa)	Curing 1	28	7.60 (7.11)	6.47 (11.59)	5.50 (14.54)	6.02 (10.82)	5.34 (12.47)
	Curing 1	90	8.06 (4.96)	7.00 (11.00)	6.00 (14.66)	6.50 (10.66)	5.95 (11.76)
	Curing 1	180	8.35 (5.98)	7.40 (8.78)	6.30 (11.11)	6.82 (8.95)	6.21 (12.86)
	Curing 3	28	7.07 (7.77)	6.09 (4.59)	5.00 (6.00)	5.81 (3.61)	4.20 (7.14)
	Curing 3	90	6.80 (7.35)	5.19 (7.70)	3.89 (11.56	5.00 (8.00)	3.45 (11.59)
	Curing 3	180	5.82 (7.87)	3.82 (7.85)	2.86(15.00)	3.00 (16.66)	1.94 (14.48)
σ_f (CV %) (MPa)	Curing 1	28	–	0.49 (19.32)	1.04 (11.77)	0.72 (11.06)	1.81 (2.57)
	Curing 3	28		0.24 (9.98)	0.70 (19.32)	0.43 (24.98)	0.79 (7.15)
$D_{0.7}$ (CV %)	Curing 1	28	–	0.06 (19.64)	0.15 (57.58)	0.09 (11.68)	0.26 (66.60)
	Curing 3	28	–	0.04 (24.17)	0.12 (25.00)	0.05 (26.95)	0.19(14.78)
$D_{1.4}$ (CV %)	Curing 1	28	–	0.08 (2.85)	0.19 (38.03)	0.11 (13.84)	0.23 (24.20)
	Curing 3	28	–	0.04 (9.24)	0.14 (14.28)	0.07 (28.98)	0.17 (28.36)
$D_{2.8}$ (CV %)	Curing 1	28	–	0.05 (18.64)	0.17 (20.00)	0.09 (17.69)	0.21 (10.23)
	Curing 3	28	–	0.03 (39.14)	0.11 (20.20)	0.06 (24.69)	0.17 (11.11)

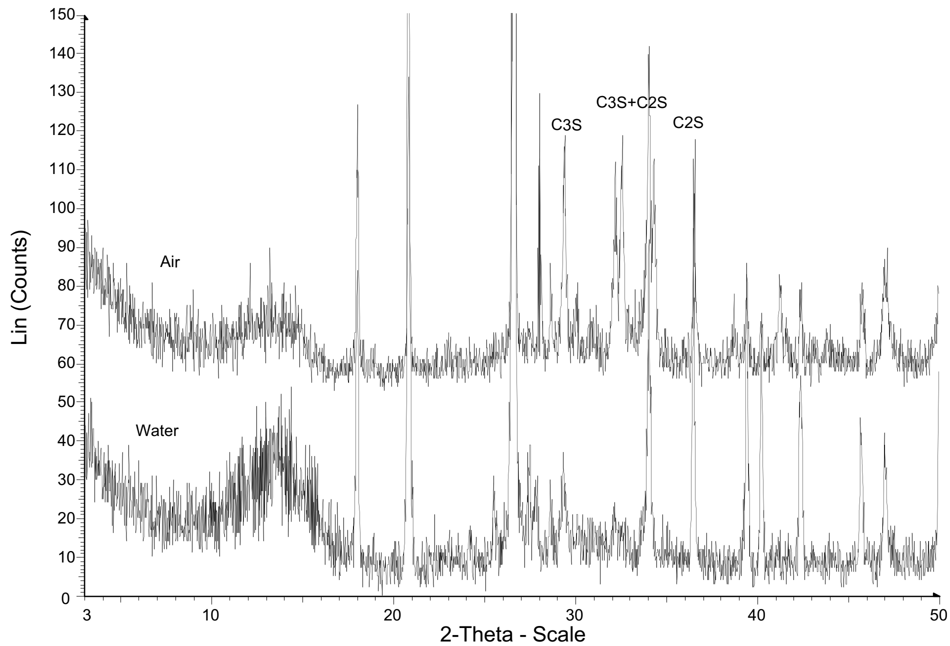

Fig. 9. Rayon X diffraction of cement-mortar in hot-dry and water curing.

of X-ray diffraction of cement mortar cured in water and in hot-dry environment (Curing 3) for 3 months. It clearly shows that the percentages of C_3S and C_2S remain very high in the dry environment, which confirms the low level of cement hydration processes. This also, explains the drop in compressive and flexural strengths for this curing. The observation indicates that a suitable treatment is then necessary to retain a moist environment during early stages, to improve the performance of concrete. To clarify the development of voids and micro-cracks after long time, Fig. 10 presents a scanning electron micrograph of the fibre–matrix interface for the specimens conserved in Curing 3 for 3 months. Observing this microstructure of the fibre–matrix interface, it can be seen that the voids around the fibres are large. Fig. 11 presents a scanning electron micrograph of the hole left by some fibres after pullout. It is without any fragments or traces of adhesion between the fibre and the matrix. This could confirm the presence of voids around some fibres and difficulties to have fibre–matrix adhesion. It also confirms the decrease of CI with time in the Curing 2.

It is important to specify that the concretes in this case were cured in a steam room in the laboratory at

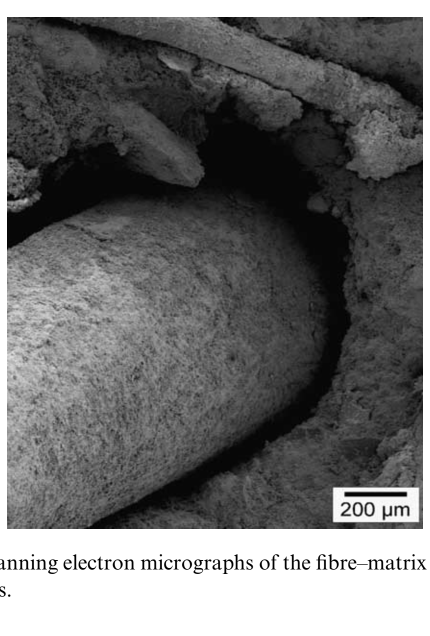

Fig. 10. Scanning electron micrographs of the fibre–matrix in Curing 3 at 3 months.

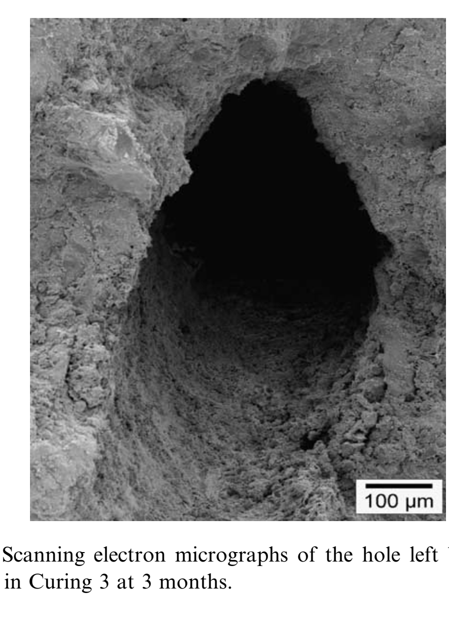

Fig. 11. Scanning electron micrographs of the hole left by the fibre interface in Curing 3 at 3 months.

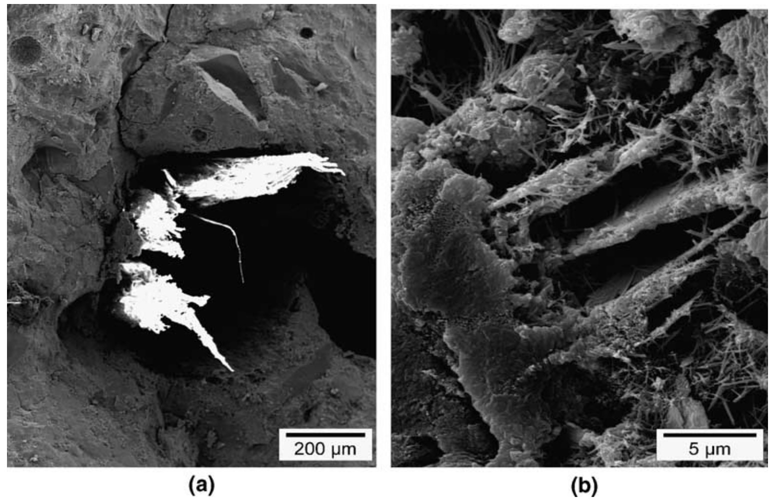

Fig. 12. (a) Scanning electron micrographs at the interface fibre–matrix in water curing at 3 months; (b) scanning electron micrographs of deposit of the calcium hydroxide products at the interface fibre–matrix in Curing 3 at 3 months.

relatively high temperature and low humidity. This environment contributed to the acceleration of concrete drying and some loss of the flexural properties. For this reason the Curing 3 was probably more severed than Curing 2.

On the other hand, Fig. 12 presents the scanning electron micrograph at the fibre–matrix interface for the specimens cured in water for 3 months. Fig. 12(a) shows traces of adhesion between the fibre and the matrix, and some fragment fibres to stick to the matrix, whilst Fig. 12(b) illustrates the deposit of the calcium hydroxide products at the interface. Consequently, the void between the fibres and the matrix is very much reduced with hydration products in water environment. This confirms the findings of Tolêdo Filho et al. [18] and Bentur and Akers [19], regarding mineralisation of vegetable fibres due to migration of hydration products, especially calcium hydroxide after natural ageing. It also confirms the increase of CI with time in this curing type.

The variation of σ_f with ageing and the durability aspects of the fibres in the cement matrix will be developed in a later publication.

4. Conclusion

1. The Afro-Asiatic dry band is rich in date palm fibres that could be utilized in local material construction products.
2. The male date palm surface fibre (MDPSF) has the most tensile strength amongst the other types of date palm surface fibres.
3. Regarding the mechanical performance of more common vegetable fibres, the MDPSF has average tensile strength and weak elastic modulus.
4. For each concrete type, the CI in water curing increases with time. Thus the global degree of the voids and cracks decreases.
5. At 7 days in hot-dry environment, according to the CI, the global degree of voids and cracks for most fibre-concretes is smaller then the concrete without fibres. The presence of fibre in concrete favours the decrease in global degree of the voids and cracks at early ages.
6. In free atmospheric environment the CI decreases with time for each concrete type. This loss was especially large for all fibre-concretes between 7 and 28 days. Thus the global degree of the voids and cracks increases with ageing. In this curing type the CI is lower than that in water curing.
7. In water curing, compared to the concrete without fibres, the increase in percentage and length of MDPSF in concrete has a beneficial effect on the ductile behaviour, but no benefit for the first crack strength (FCS) and the compressive strength.
8. In dry-hot environment, the first crack strength of fibre-concretes decreases with time and with increasing fibre reinforcement percentage and length. But at 28 days increasing the percentage and the length of fibres ameliorates the toughness. The maximum of toughness coefficient and σ_f was obtained for 3%–60 concrete type.
9. Observing the micro-structure of the fibre–matrix interface cured in hot-dry and water environments, it can be seen that the voids around the fibres are large for the dry environment.
10. The mechanical compressive strength and the flexural properties for the concretes conserved outdoors or in Curing 3 are definitely lower than for those conserved in water curing.

11. Based on the results and observations presented in this paper, further research should be developed on the treatment of MDPSF and MDPSF-concretes to improve their mechanical performance using local industrials wastes, especially in hot-dry climate. The results of this further research will be published in a forthcoming paper.

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