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RESEARCH **Open Access**

Date and doum palm natural fibers as renewable resource for improving interface damage of cement composites materials

Khaled Bendahane[1], Mohammed Belkheir[1], Allel Mokaddem[1*], Bendouma Doumi[1,2] and Ahmed Boutaous[3]

Abstract

Background Various recent studies have investigated the use of traditional fibers (metallic or synthetic) as reinforcement in mortar. In recent times, there has been growing interest in using natural fibers as reinforcement in cement composites. This study was conducted to assess the impact of date palm, doum palm, and sisal fibers on the mechanical properties of cement composites. Genetic modeling was chosen to find the shear damage at the fiber-matrix interface of the three cement composites using genetic crossing operator, which allows us to calculate the damage at the interface using two damages of the matrix and the fibers, respectively.

Results Our objective is to examine and evaluate the interface damage of date palm/mortar, doum palm/mortar and sisal/mortar under different mechanical tensile stresses ranging from 25 to 37 MPa with fiber volume fraction from 1 to 5%. It was found that the interface damage of date palm/mortar and doum palm/mortar cement composites was minimal compared to that of sisal/mortar. However, several researchers found that an increase in fiber volume fraction leads to decrease in mechanical properties and density in cement composites what we confirmed in this study that interface damage increases when the volume fraction increases.

Conclusions The results are in line with the findings of a recent experimental study on the use of other plant fibers. Their results showed that incorporating ramie fibers resulted in a 27% increase in compressive strength, whereas the use of synthetic fibers resulted in 4% decrease in tensile strength in compression. It is recommended the use of doum and date palm natural fibers in the composition of mortars with a fiber volume fraction of 1 to 5% in order to reduce and avoid interface damage and limit the negative impact of synthetic fibers on the environment.

Keywords Interface, Shear damage, Genetic operators, Doum palm, Date palm, Sisal fiber, Cement composites

1 Background

The incorporation of fibers, metallic or synthetic, in cement composites materials has shown better prospects for improving their performance by limiting the propagation of cracks, improving mechanical resistance (tension and bending) and increasing the hardness of the final product [1]. Cementitious composite materials incorporate different phases to improve their overall mechanical, physical and chemical properties, while maintaining the ease of the manufacturing process [2]. However, the cost of these synthetic fibers is not affordable and their production results in the emission of CO_2 and the use of non-renewable resources [3]. Therefore, current research

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*Correspondence:
Allel Mokaddem
mokaddem.allel@gmail.com
[1] Laboratoire d'Instrumentation et Matériaux Avancés, Centre Universitaire Nour Bachir El-Bayadh, 32000 El-Bayadh, Algeria
[2] Faculty of Sciences, Department of Physics, Dr Tahar Moulay University of Saïda, 20000 Saïda, Algeria
[3] Département Technologie des Matériaux, Faculté de Physique, Université des Sciences et de la Technologie, USTO-MB, Oran, Algeria

is exploring the possibility of replacing them with natural fibers from plants or animals.

Generally natural fibers are classified as primary and secondary fibers. Primary fibers include jute, sisal, kenaf, palm and hemp fibers, where these fibers are grown for their fiber content. Secondary fibers include agroresidues, coir fibers, and pineapple fibers, which are fibers obtained from plants by products. These fibers can be classified into six types: bast fibers (flax, jute, etc.), leaf fibers (sisal, pineapple leaf fibers), seed fibers (cotton, coconut), kernel fibers (hemp, kenaf), grass and reed fibers (wheat, maize and rice), and all other types (wood and roots) [4–7]. The biodegradability of natural fibers is associated with physical, chemical, mechanical, thermal and humidity conditions which have widened their field of use in many applications [8–12].

Several research studies were investigated the use of plant fibers as reinforcement in the development of composite materials. Ahmed Sabryin [13] demonstrated that the incorporation of 2 kg/m^3 of flax fibers in concrete led to an increase of 8.3% in compressive strength and 17.6% in tensile strength. In [14], Elie Awwad et al. found that adding 0.5% hemp fiber to cement-based mixes resulted in a 15–30% increase in its flexural strength. In addition, sisal fiber is widely used around the world and is an important source of textile fibers [15]. Thus, numerous and important studies [16–20] have been conducted on the application of sisal fibers as reinforcement for cement composites matrices. Another method of using these wastes is to incorporate them into construction materials in the form of fibers to reinforce the cementitious matrix. A number of researchers have taken advantage of fibers from various sections of the palm, including palm trunk [21], date palm fruit stem fibers [22], date palm leaf sheath fibers [22, 23] and the fibers surrounding the trunk or base of the palm [24, 25]. Despite considerable efforts to study the behavior and characterization of natural fiber reinforced cementitious composites, most research focuses only on short-term properties [18–20, 26–28]. However, considering their potential use in construction, it is still imperative to study their long-term behavior. The use of innovative materials based on natural fibers can reduce construction costs [29, 30].

In this study, we will study the fiber-matrix interface damage, however the behavior of this interface is very complex, and experimental tests are very expensive to determine the resistance interface and therefore a resistant material. It is necessary to provide a numerical model to understand the mechanical behavior of the interface in as much detail as possible in order to provide the experimenters with a very rich theoretical data base. Few theoretical studies have described fiber-matrix interface damage of a composite material. The methods for characterizing the interface have limits, either in the methodology (preparation of the specimens), or in the experimental protocol. For these reasons, we have chosen a genetic modeling in order to find and calculate the interface damage by using the genetic crossing operator between the fiber damage and the matrix damage defined by Weibull formalism [31]. Our aims is to study, examine and evaluate the interface damage of date palm/ mortar, doum palm/mortar and sisal/mortar by using genetic algorithm and under different mechanical tensile stresses ranging from 25 to 37 MPa and with a fiber volume fraction of 1% to 5%.

2 Methods

In this section, the different equations and numerical models used in our genetic modeling will be presented. At the end of this section a detailed explanation of the data presented in this part is illustrated on flowchart of the genetic program.

2.1 Statistical approach of Weibull

Matrix damage was developed by Weibull [31], where he assumed that the stress applied to composite materials follows a uniform law. The damage matrix is given by Eq. (1) [31]

$$D_m = 1 - \exp\left\{-\frac{V_{\mathrm{eff}}}{V_0}\left(\frac{\sigma_f}{\sigma_0}\right)^m\right\} \tag{1}$$

With: σ_f: applied stress; V_{eff}: matrix volume; $m$andσ_0 Weibull parameters. V_0 : Initial volume of the matrix.

The fiber breakage probability in composite materials was developed by Weibull [31], where he assumed that the fiber is considered as an isolated part of the system. Weibull therefore defined the probability of fiber breakage by Eq. (2).

$$D_f = 1 - \exp\left\{-A_f * L_{\mathrm{equi}} * \left(\frac{\sigma^f_{\mathrm{max}}}{\sigma_{\mathrm{of}}}\right)^{m_f}\right\} \tag{2}$$

With: σ^f_{max}: the maximum stress applied to the fiber; $\sigma_{0\mathrm{f}}$: the initial stress applied to the fiber; m_f: Weibull parameters; $A_f = \pi^* a^2$; L_{equi}: the length of the fiber at equilibrium.

2.2 Pull-out numerical theory

Composite materials have been the subject of numerous experimental and theoretical tests, including tensile testing at a specific angle relative to the fiber direction, interlaminar shear testing over a short distance, and bending testing with three or four points. Among tests on single fiber specimens, there are the tear or micro-drop test, fragmentation test, and indentation test [32, 33]. In our numerical simulation, Eq. (3) was obtained from the tear test, which involves applying a tensile force to partially or fully lift a fiber immersed in a micro-sample [32, 33], The same conditions were used in our genetic program to determine the variations of properties for the three types of cement composites materials, which used date palm, doum palm, and sisal fibers. The pull-out test was used to study the materials. Figure 1 shows the schematic for the tensile test system for the same cement matrix.

The average shear stress τ_{app} at the interface is determined by [32, 33]:

$$\tau_{\text{app}} = \frac{F_{\max}}{2\pi r l_e} \tag{3}$$

$F_{\max}$: the maximum force measured; r:average radius of the fiber; l_e: the length of the fiber inserted into the matrix (length of the interface).

2.3 Volume and mass fraction of reinforcement

In a composite, we write:

$$V_f + V_m + V_v = 1 \tag{4}$$

where the subscripts V_f, V_m, and V_v relate, respectively, to the volume of fiber, matrix, and void volume. In practice, V_f and V_m are mainly conditioned by the nature of the reinforcement, the matrix, and the method of implementation [34, 35]. The orders of magnitude are common (10^{-2}) to make the numbers size of V_f and V_m more understandable.

In this study, the voids volume has not been taken into account for the rest of the demonstration because we have used natural fibers which have undergone chemical treatment and for this reason, we can neglect the voids volume [4, 36–39].

The volume of a composite is the sum of the volumes of the fiber V_f and matrix V_m.

$$W_i = \frac{W_i}{W_c} \tag{5}$$

where

W_i: weight of component i. W_c: total weight of the composite.

$$\sum_{i=1}^{N} W_i = 1 \tag{6}$$

The mass of the constituents of the composite is given by:

$$W_c = \rho_c Vc;$$

$$W_f = \rho_f V_f;$$

$$W_m = \rho_m V_m,$$

With ρ_c : thedensityofcomposite; ρ_f : densityoffiber; ρ_m : densityofthematrix

The total mass of the composite is:$\rho_c Vc = \rho_f V_f + \rho_m V_m$ which allows to derive the density of the composite as follows:

$$\rho_c = \frac{\rho_f V_f + \rho_m V_m}{V_c} \tag{7}$$

Similarly, one can express the density as a function of mass fraction on the basis of the total volume of the composite $V_c = V_m + V_f$:

$$\rho_c = \frac{\rho_f V_f + \rho_m V_m}{V_m + V_f}$$

$$\rho_c = \frac{W_f + W_c}{\frac{W_f}{\rho_f} + \frac{W_m}{\rho_m}}$$

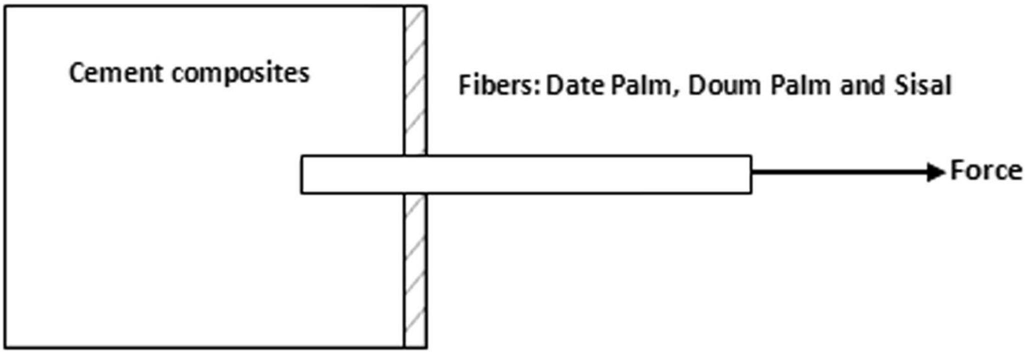

Fig. 1 Single fibers pull-out test [32, 33]

$$\rho_c = \frac{1}{\frac{W_f}{\rho_f}+\frac{W_m}{\rho_m}} \tag{8}$$

From the different values of the fiber (Date palm, Doum Palm and Sisal) and the cement composites matrix illustrated in the following section (Tables 1 and 2), we were able to calculate the interface damage using Eqs. (1) and (2). The fiber-matrix interface damage is achieved by crossing the damage to the fiber and the matrix, respectively, using the genetic operator crossing. Optimization of objective function is provided by Eqs. (3) and (4) (see Fig. 2).

3 Materials

3.1 Natural fibers

Nowadays, plant fibers are replacing conventional fibers as reinforcement in composite materials due to environmental and ecological issues. Currently, Jute, Ramie, Kenaf, Alfa, Sisal, Date palm and Doum palm natural fibers are used for various potential applications because of their physical and mechanical properties and their cost and more particularly the ecological and environmental characteristics they have [40–43]. Date palm, doum palm and sisal fibers have been used as reinforcement for composite materials based on a thermoplastic or thermosetting matrix [44–54]. In this study, we used the fibers of date palm, doum palm and sisal to reinforce cement composites with a volume fraction of 1–5% of each. The different properties of its fibers are mentioned in Table 1.

Table 1 The different mechanical properties of the fibers used in genetic simulation

Fibers	Density (Kg/m^3)	Modulus elasticity E (GPa)	Tensile strength (MPa)	References
Date palm	463	70	125	[55]
Doum palm	1260	11	180	[56, 57]
Sisal	1500	9	540	[58–60]

3.2 Cement composites

The cement composite reinforced with natural fibers can achieve mechanical characteristics superior to those of conventional materials already used in the industry. Fibers inhibit the initiation and propagation of cracks. They attenuate the progression of microcracks, thus preventing sudden rupture. As a result, the length of cracks in the hardened matrix is shorter, which considerably improves the impermeability and durability of composites exposed to the environment [61]. Figure 3 presents an image comparing concrete reinforced with vegetable fibers to one without incorporated fibers [61, 62].

The choice of mortar as a matrix in research is mainly due to the following reasons: (a) mortar is one of the most widely used materials in construction engineering. It is commonly used in brick- laying and plastering work. (b) the mortar test is simple and intuitive. Therefore, it is possible to select mortar as the research material which reflects the respective performance of concrete through the different properties of fiber mortar [63]. In our genetic modeling, we investigated the resistance of the fiber-matrix interface between the mortar matrix and the different fibers (date palm, doum palm and Sisal) in order to predict the best cement composites at the macroscopic scale and this following to the various old and recent studies which have demonstrated through experimental and theoretical tests that to develop composites with good properties, it is necessary to improve the fiber–matrix interface and reduce moisture absorption. To ensure the durability of composites reinforced with vegetable fibers, these fibers must undergo surface modifications in order to infer better characteristics as a reinforcing material [64, 65]. The incorporation of natural fibers in the cement mortar is modeled in order to improve the tensile strength and to reduce its fragility of the fiber-matrix interface under mechanical stresses ranging from 25 to 37 MPa. The physico-chemical characteristics of the mortar used in our genetic program are mentioned in Table 2.

Table 2 The physico-chemical characteristics of the Mortar [63]

Cement characteristics (%) CEM II/B-V 42.5R [63]									
SiO_2	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**Na_2O**	**K_2O**	**TiO_2**	**$Cl^{(-)}$**
25.1	8.8	3.2	54.0	1.2	2.4	0.19	0.67	0.18	0.059
Compressive strength (MPa) CEM II/B-V 42.5R				Blaine fineness (cm^2/g) CEM 42.5		Loss on ignition (%) CEM 42.5		Water demand (%) CEM 42.5	
47.8				4411		4.1		28.5	
Sand (40% of aggregate volume)				Water, type: tap water				Date palm, Doum Palm and Sisal fibers (2.5 cm in length)	

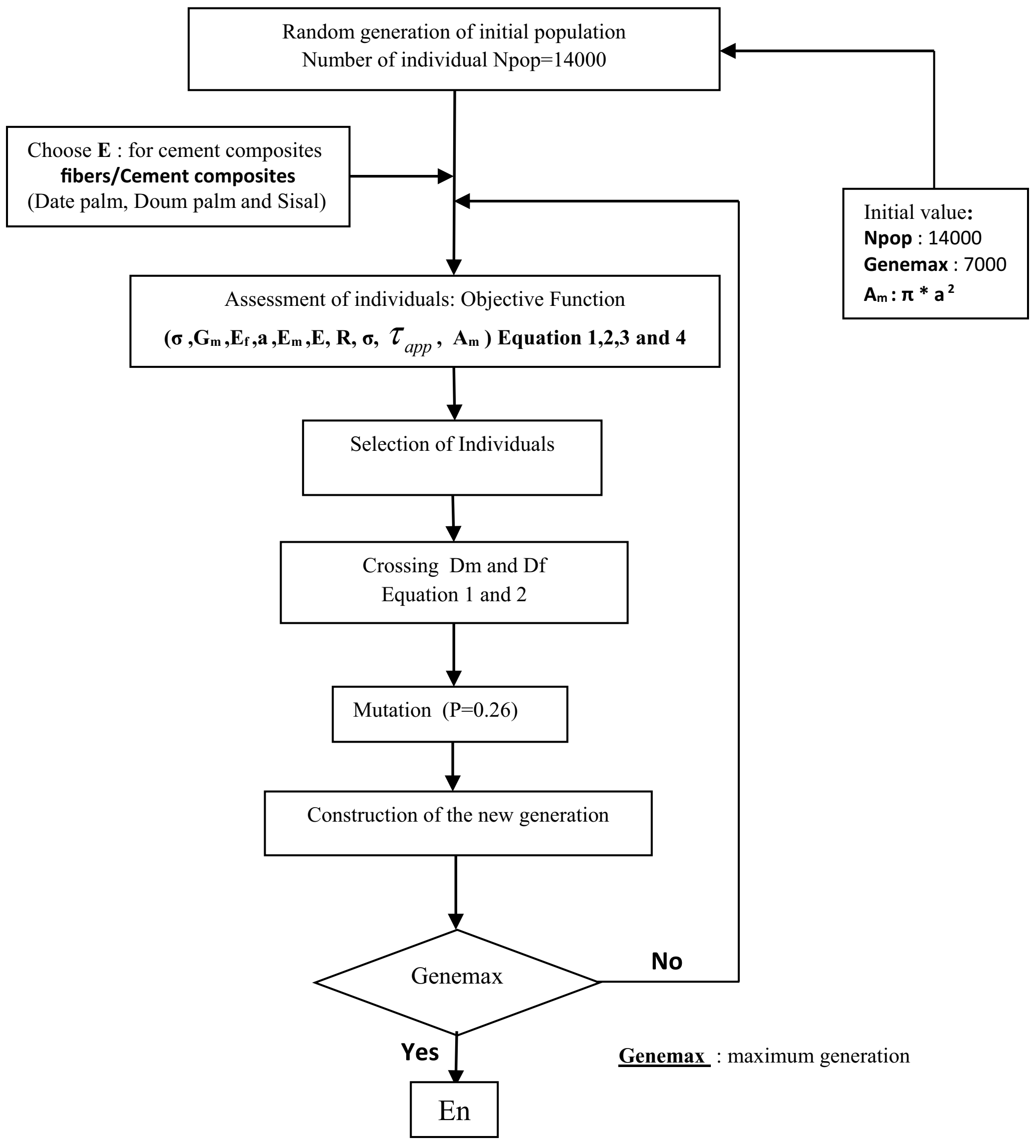

Fig. 2 The flowchart of genetic program

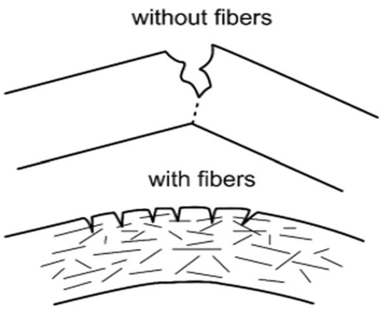

Fig. 3 Difference between vegetable-fiber-reinforced concrete and one without incorporated fibers [61, 62]

4 Results

Renewable natural materials have become an appropriate alternative to fit with the regulatory requirements and a recommended best for reducing carbon emissions [66]. A special focus on materials made from plants that absorb CO_2 from the atmosphere, which could result in a reduction in carbon emissions [67]. The aim of this study is to reinforce mortar made primarily of CEM II/B-V 42.5R cement (as shown in Table 2 [63]) using date palm, doum palm, and sisal fibers (as listed in Table 1 [55–60]).

The main disadvantages of natural fiber are poor adhesion between the fiber and the matrix, the presence of cellulose content, moisture absorption and voids at the interface between the fiber and the matrix, which lead to inaccuracy dimensional, thus affecting the mechanical properties [4, 36–39], the presence of high moisture content in the fiber leads to fiber and matrix swelling in composites, leading to dimensional instability. This drawback and this limitation can be overcome by chemical treatments. Chemical treatments are performed to reduce the hydrophilicity of the fiber but surface treatments not only modify the surface of the fiber but also increase the strength of the fiber leading to improved adhesion between the fiber and the matrix [4, 68–70]. Fiber and matrix optimization aims to improve adhesion, surface tension, interfacial resistance and wettability which provide good surface roughness leading to good adhesion [4, 71]. Several recent studies have shown that several works have been published on different natural fibers extracted from renewable sources which are used as reinforcement on a large dimension of applications. These studies describe various surface treatments performed to improve fiber properties and to enrich the mechanical properties of composites, unlike untreated fiber reinforced materials.

The objective is to examine and evaluate the damage to the mortar-fiber interface of the three cement composites under different mechanical tensile stresses ranging from 25 to 37 MPa and with a fiber volume fraction of 1% to 5%. This study follows the methodology proposed by Cox [72], when a tensile stress is applied to a representative elementary volume (REV), it creates shear at the interface, which is strong at the ends and weak in the middle (as depicted in Fig. 4). The shear damage at the fiber-matrix interface of the three cement composites was calculated using the cross genetic operator of matrix and fiber damage, which were expressed by Eqs. (1) and (2) [73–80]. The objective function was calculated by incorporating the values of the materials listed in Tables 1 [55–60] and Table 2 [63]. The interface shear damage is represented by the black, blue and red dots for the different cement composites materials constituted by date palm, doum palm and sisal fibers, respectively. These points were obtained by crossing the damage of the three fibers and mortar damage using the genetic operator crossing. The results presented in Figs. 5, 6 and 7 were determined as a function of fiber length for the cementitious composite materials studied. Figure 5 demonstrates that the "D" shear damage interface of the mortar/Date Palm starts at a threshold of 0.021 when $\sigma = 25$ MPa and increases to a peak value of 0.098 when $\sigma = 37$ MPa. The damage appears symmetrical, with weaker damage in the middle and stronger damage at the ends of the fiber. The increase in interface damage can be attributed to the increase in mechanical stress, and for this material, we can see that the degradation at the interface is relatively low (less than 0.1). Figure 6 displays that the "D" shear damage interface of the mortar/Doum Palm begins at a threshold of 0.12 when $\sigma = 25$ MPa and increases to a maximum value of 0.192 when $\sigma = 37$ MPa. Just like in the previous case, the damage in this material is symmetrical, with weaker damage in the middle and stronger damage at the ends of the fiber. The higher level of damage is a result of the concentration of mechanical stress, indicating that the degradation at the interface of the mortar/Doum palm is more severe compared to the interface of the mortar/Date palm cement composites. Figure 7 shows that the "D" shear damage interface of the mortar/Sisal begins at a level of 0.208 when $\sigma = 25$ MPa and increases to a maximum value of 0.278 when $\sigma = 37$ MPa.

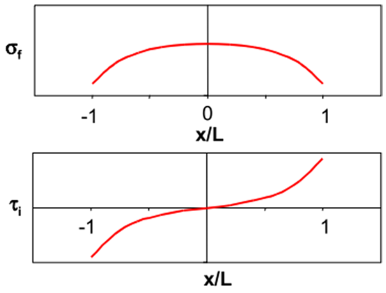

Fig. 4 Cox model; Stress profiles in the fiber (σ_f) and at the interface (τ_i)

5 Discussions

As depicted by the aforesaid results, the damage is symmetrical, with weaker damage in the middle and stronger damage at the ends of the fiber. The increase in the level of interface damage is a result of the concentration of mechanical stress, and it can be seen that the degradation at interface of mortar/Sisal is more severe compared to the other cement composites (mortar/Date palm and mortar/Doum palm). Alawar et al. [81] found that an increase in fiber volume fraction leads to decrease in mechanical properties and density in cement composites, what we confirmed in this study that interface damage increases when the volume fraction increases.

The results obtained indicate that the degreasing of the fibers enhances their mechanical properties and results in composites that are less brittle compared to composites made from raw fibers. These conclusions are consistent with those of a recent experimental study by Marzena Kurpińska et al. [63] where they found that the use of ramie fibers improved compressive strength and resulted in a 27% increase in strength, while the use of synthetic fibers led to a 4% decrease in tensile strength and compression. As results, the use of fibers in cement composites also reduced the expansion of samples stored in water. The smallest deformation was noted on the sisal

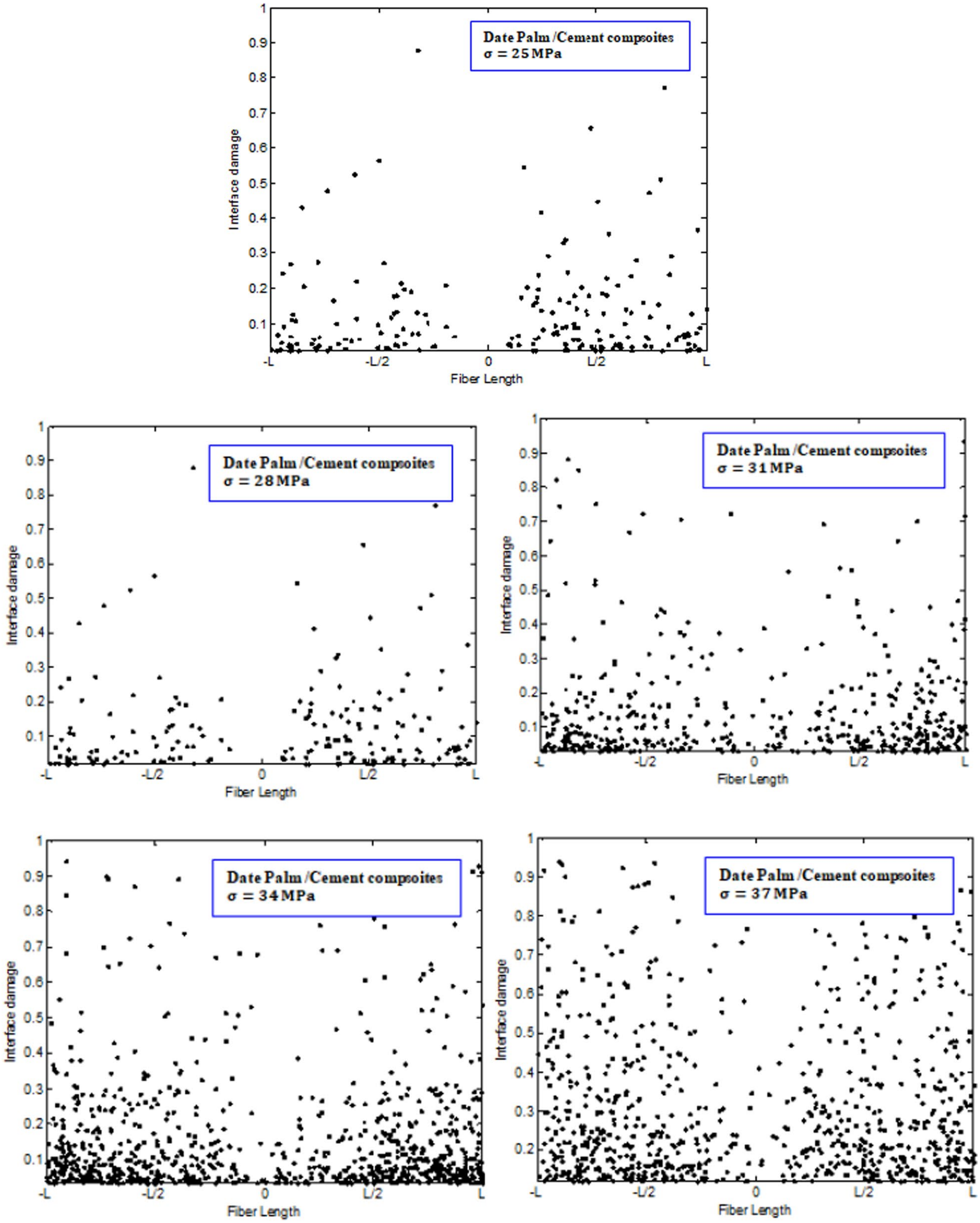

Fig. 5 Fiber-mortar interface damage of Date Palm/Cement composites

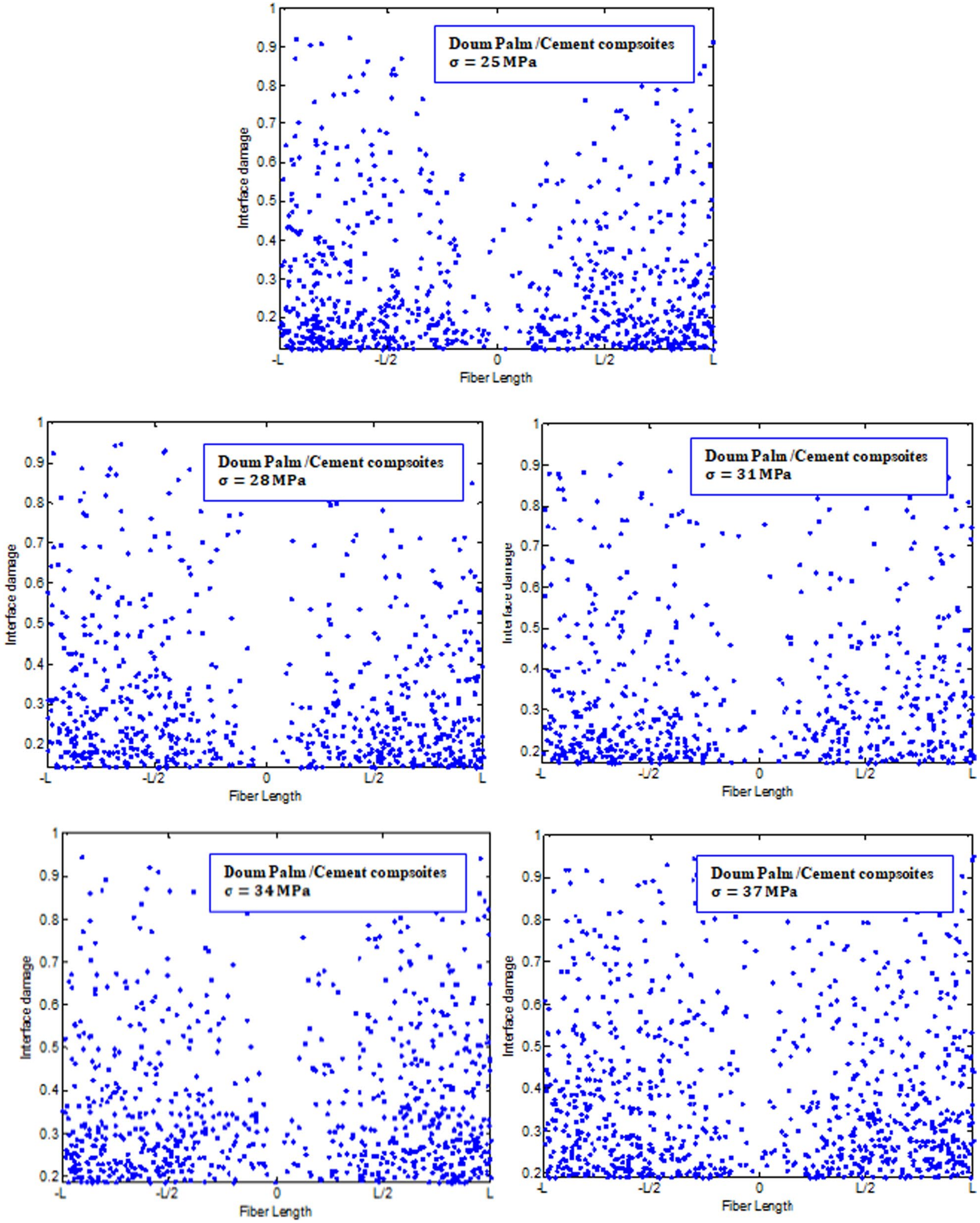

Fig. 6 Fiber-mortar interface damage of Doum Palm/Cement composites

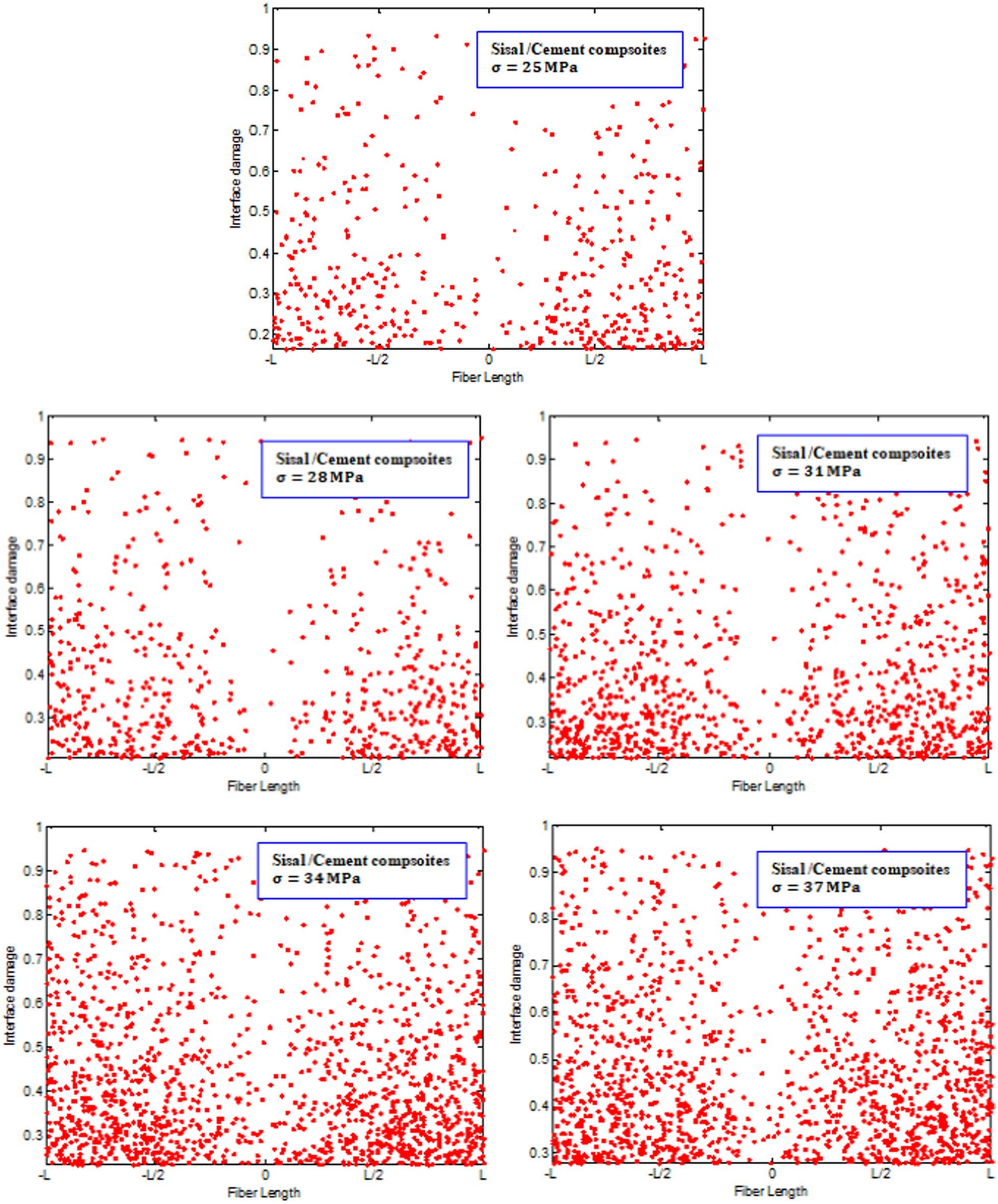

Fig. 7 Fiber-mortar interface damage of Sisal/Cement composites

fiber samples. It has been observed that the expansion or shrinkage is influenced by the fiber structure, diameter, cellulose content and total fiber length in the element. Cement composites containing natural and synthetic fibers showed 2–8% higher water absorption compared to absorption of non-fibrous samples. An exception is represented by ramie fibers, which lower water absorption by a margin of 3.5%. Due to the numerous benefits of utilizing natural plant fibers, including their lightweight, cost-effectiveness, readily accessible nature, and decomposability, their integration into composites aligns with the increasing global demands for sustainable cement composites and resilient concrete materials.

6 Conclusions

This work presents a comprehensive study of the effect of plant fibers on the mechanical characteristics of cement composites, conducted through genetic modeling with a volume fraction ranging from 1 to 5%. The results reveal that the interface damage of cement composites made from Date Palm and Doum Palm fibers is minor in comparison with that of Sisal/mortar composite. Several researchers found that an increase in fiber volume fraction leads to decrease in mechanical properties and density in cement composites, what we confirmed in this study that interface damage increases when the volume fraction increases. The results suggest that degreased fibers lead to improved mechanical properties, resulting in more robust composites compared to those made from raw fibers. These conclusions are consistent with the findings of a recent experimental study on various vegetable fibers. The inclusion of natural fibers in cement composites was found to reduce the expansion of samples stored in water. The lowest deformation was observed in samples made from sisal fibers. Given the numerous benefits of using natural plant fibers, such as their light weight, affordability, accessibility, and eco-friendly decomposition, their utilization in composites reflects the growing global demand for sustainable cement composites and durable concrete materials.

Abbreviations

τ	Shear stress of the interface
R	Distance between fibers
$F_{\max}$	The maximum force measured
l_e	The length of the fiber inserted into the matrix (length of the interface)
(r_f)	The distance between fiber and the matrix
σ_f	Applied stress
V_{eff}	Matrix volume
$m\mathrm{and}\sigma_0$	Weibull parameters
V_0 :	Initial volume of the matrix
$\sigma_{\max}$	The maximum stress applied to the fiber
σ_{0f}	The initial stress applied to the fiber
m_f	Weibull parameters
A_f	π*A^2
L_{equi}	The length of the fiber at equilibrium

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Author contributions
All authors contribute, read and approved the final manuscript.

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Availability of data and materials
The data used in the present study are available on request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
On behalf of all authors, the corresponding author states that there is no conflict of interest.

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