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Description of the Mechanical Behavior of Mortars Made out of Coconut Fibers and Rice Straw Treated with Homemade Solution

Ange Christine DJOHORE[1,*], Conand Honore KOUAKOU[2], Koffi Clement KOUADIO[2], Aka Alexandre ASSANDE[2], Edjikeme EMERUWA[2]

[1]Laboratoire de Politique Énergétique et Environnemental, Institut de Recherche sur les Energies Nouvelle, NANGUI ABROGOUA University, 02 BP 801 Abidjan 02, Côte d'Ivoire
[2]Laboratoire des Sciences du Sol, de l'Eau et des Géomatériaux, Félix HOUPHOUËT BOIGNY University, 22 BP 582 Abidjan 22, Côte d'Ivoire
*Corresponding author: drdjohore@gmail.com

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Abstract In recent years, the trend in the construction industry has been to gradually replace conventional materials by composite materials. In the same vein, this study suggests the addition of fibers in a mineral matrix in order to change the brittle behavior of a material in ductile behavior. It can be said, from the stress-strain curves of mortars in bending and compression tests made during this study that mortar strength increases with the fiber content up to 0.8%. The strength decreases beyond this rate. Likewise, the flexural strength of mortars containing treated fibers with potassium solution increases as the pH of the solution increases. But mortars containing treated fibers with high pH solutions (> 10) break faster than those containing treated fibers with lower pH solutions. Compared to mortars without fibers, the properties of mortars containing fibers treated with banana tree solution are excellent.

Keywords: *vegetable fibers, rice straw, mortar, kapok wood ash, banana tree juice, elastic modulus, ductile distortion*

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1. Introduction

For eco-design reasons, builders are more and more using materials associated to natural raw materials in building. For example, plant fibers are increasingly being used in materials development. These fibers make it possible to improve the properties of some materials. Thus, the addition of fibers in a mineral matrix allows to change the brittle behavior of a material in ductile behavior. The increase in ductility of soil-cement improved with flax fiber as did for soil-cement -sisal was reported by [1,2].

Some authors focused on the behavior of blocks made from soil-fiber mixtures. Thus tensile tests on blocks of stabilized soil with different fibers were carried out. [3] observed that samples degraded progressively with a multiplication of fine cracks and substantial distortion at final breaking. Some other authors studied the capacity of hemp soil mixtures. They showed that hemp significantly increased resistance to breaking, cracking and energy dissipation capacity of soil in static or dynamic stress [4].

However, until now, little attention has been paid to soil-water and fiber mixtures in a plastic state, sometimes called bauge. The role of fibers inside bauge walls is to [5]:

- ease mixing and handling,
- accelerate the drying process,
- distribute shrinkage cracks throughout walls mass,
- improve cohesion and shear strength of walls,
- improve weather resistance,
- reinforce walls corners.

Moreover, the using flax straw in the bauge allows to get mechanical performances superior to those obtained with wheat straw [6].

However, this rather molded bauge can be used, like earth-cement mortars reinforced with vegetable fibers, but these mortars have low mechanical resistance and a high water absorption capacity. For this reason, the fibers have been subjected to various treatments to improve their quality and that of composites. However, it should be pointed out that knowing the distortion of a material is essential to control its quality and it plays a key role in the behavior of a building. This study describes the behavior of fiber-reinforced cement-earth mortars. It's about determining the mechanical characteristics, the influence of fibers treatment with solutions from organic origin and the effect of nature and the role of fibers in the behavior of earth-cement mortars. Specimens of cement-earth mortars reinforced with coconut fibers and rice straw treated with or without solutions of banana tree juice and kapok wood ash were tested in bending and compression tests. The results obtained were analyzed and discussed in this article to highlight the improvement and the relationship between the nature of a fiber and its mechanical behavior.

2. Materials and Methods

2.1. Raw Materials

The raw materials used to make samples are cement, clay, coconut fiber and rice straw

2.1.1. Cement

The cement used is Compound Portland Cement (CPJ), with nominal resistance equal to 32.5 R. It is distributed by LAFARGE HOLCIM Company under the brand name “BELIER” which is one of the companies that manufacture and distribute cement commonly used in Côte d'Ivoire and in the sub-region.

2.1.2. Clay

The clay used comes from crushed raw clay extracted from a site in Dabou city (Ivory Coast). The geographical coordinates of this city are 5°19'70" N and 4°22'80" W. That clay has been assessed [7,8]. It is brown kaolinic clay. The basic raw material was the clay power passing through a 1 mm mesh size sieve.

2.1.3. Fibers

Two vegetable fibers are used: coconut fiber and rice straw. These fibers have been chosen because they are agricultural waste with little economic value for farmers and are available in large quantities.

Coconut fibers come from the husk (wadding or coir) of a fruit called *Cocos nuciféra*. These fibers are between 10 and 35 cm long with diameters varying from 0.5 to 1 mm.

The rice straw used comes from dry stems of *Oriza* stripped of their leaves. These stems are about 2 to 45 cm long with diameters varying from 1 to 4 mm.

2.2. Methods

2.2.1. Fibers Treatment

The fibers are treated with different potash solutions and a banana tree juice solution.

Table 1. Formulation of potash solutions and their pH

Mass (g)	60	80	100	120	140
Distilled water (ml)	1000	1000	1000	1000	1000
pH	9.1	9.5	10	10.5	11

Potash solutions are obtained by dissolving potash pellets (crystals) from kapok wood ash (***scientific name***). The kapok wood stems are dried in the sun and then burnt to ashes. The ash obtained is sieved using a 500 µm sieve. It is then dissolved in distilled water and left to rest for 24 hours. The resulting solution is filtered with a cloth and the filtrate collected in a bowl is finally heated until complete water evaporation leaving a deposit of potash pellets. Table 1 shows for the different solutions, the different masses of potash pellets dissolved in 1000 ml of distilled water as well as their pH.

As for banana tree juice, it is obtained after boiling 200 g of a banana tree trunk in 1000 ml of distilled water for 4 hours. The liquid obtained is cooled and filtered with a cloth. This filtrate, which is the banana tree juice solution, has a pH of 5.2.

For processing, the coconut and rice straw fibers are cut manually into 100 mm long pieces. These pieces are then dried in an oven at 60°C for 24 hours to ensure a constant moisture content. These raw fibers are then immersed either in the different potash solutions or in the banana tree juice solution for 24 hours. Finally, they are rinsed with distilled water to remove excess solution and then dried in an oven at 60°C.

The fibers treated with potash are called MPx with x as the pH of the treatment solution. On the other hand, fibers treated with banana tree juice solution are called MBA while fibers treated with no solution are called MF.

2.2.2. Sample Preparation

Various samples were prepared according to the procedure explained in Figure 1. For each sample, the cement content is kept constant at 8 %, and the 92 % content left is made up of clay and fiber. The coconut fibers and rice straw are cut into 30 mm long pieces. Their proportions in the different samples vary from 0; 0.2; 0.4; 0.6; 0.8 and 1 %.

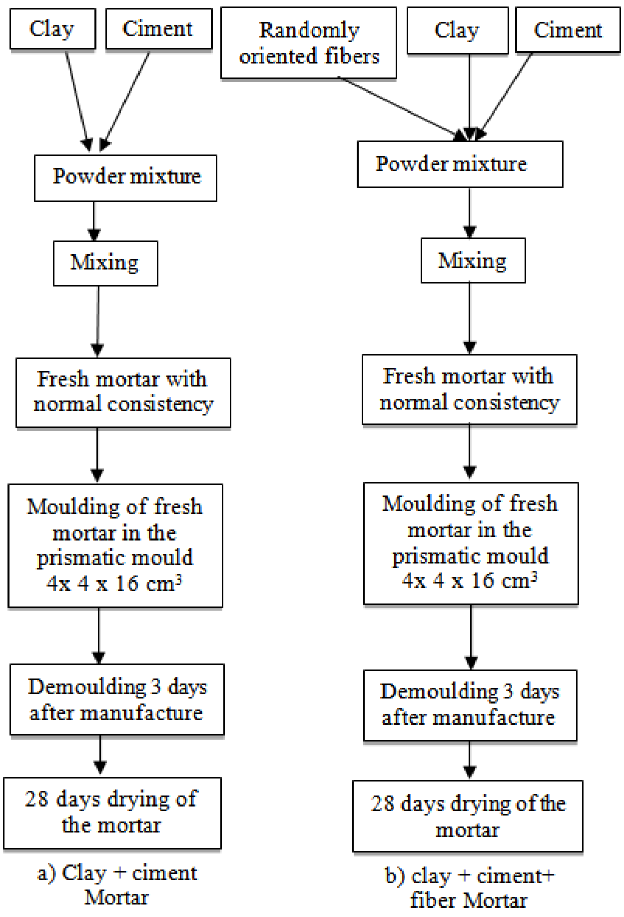

Figure 1. Diagram of mortar specimens’ preparation procedure

Water contents are measured so that the consistency of fresh mixture with or without fibers should match with a slump with the 12.6 cm mini Abram cone according to **EN 206-1**.

2.2.3. Experimental Technique

To determine the mechanical properties, three point flexural and compression test were performed.

- **Three point Flexural test**

The flexural test consists in subjecting a 4 x 4 x 16 cm^3 prismatic specimen test piece on two single supports to a vertical force (F) acting in the middle of the specimen. The bending load causes the test piece to bend, resulting in tension and compression. The test is performed according to ASTM D 790. During the test, a force transducer and LVDT displacement transducers are used to read the applied force and the deflection (D) in the middle of the specimen, respectively. The stress at breaking (σf), distortion (εf) and flexural modulus (Ei) are determined by the following ratios:

$$\sigma_f = 3.F.L / 2.b.d^2 \quad (1)$$

$$\varepsilon_f = 6.D.d / L^2 \quad (2)$$

$$E_i = \left(m.L^3\right) / \left(4.b.d^3\right) \quad (3)$$

With F: force applied or load (KN); L: length between the two supports (mm); b: width (distance at 1/4 of the length in mm) of a specimen; d: thickness of a specimen in mm; m: linear slope of a stress-deflection curve.

Five specimens of each mortar formulation were tested.

- **Compression Test**

The compression test consists in placing half a prism of the 4x4x16 cm^3 prismatic specimen between the press platens and a load is applied to it. The press allows to apply up to 250 KN maximum loads with a 5000 N/s speed. During the test, a force transducer and LVDT displacement transducers are used to read the force applied and the longitudinal shrinkage of the specimen. The Stress (σc), longitudinal distortion (εc) and compressive modulus (Ec) are determined by the following expressions:

$$\sigma_c = F / b.d \quad (4)$$

$$\varepsilon_c = \Delta l / l \quad (5)$$

$$E_c = \sigma / \varepsilon \quad (6)$$

With F: force applied to the surface of the mortar specimen (KN); b: width of the specimen (distance at 1/4 of the length in mm); d: thickness of the specimen in mm. Five specimens of each mortar formulation were tested.

In practice, the moduli Ec and Ei are determined respectively from the slope from the beginning of the stress-strain curves in compression and bending test. Similarly, the m value corresponds to the slope at the beginning of the stress-strain curve. These values are assumed to be acceptable when the ratio coefficient (R2) between the curve and the line is greater than 95%. In addition, the stress and strain values at breaking in compression test or bending test are saved if the coefficient of variation is less than 0.05.

3. Results and Discussion

3.1. Influence of Fiber Content on Mechanical Behavior

3.1.1. Mechanical Behavior in Flexural and Compression Tests

Mortars mechanical behavior in three point flexural test and compression test as dependent on the fiber content is given in Figure 2.

In flexural test, mortar without fibers is characterized by linear elastic behavior with brittle breaking and in compression test by pseudo-elastic behavior. This pseudo-elastic behavior is explained by the fact that along the loading and unloading cycles carried out on earth blocks in the compressive elastic range, a permanent distortion is recorded [9].

Mortar containing fibers has elasto-plastic behavior in flexural and compression tests. Its behavior, prior to its breaking in bending test, can be described in two parts, starting from a critical value of the loading stress (Fi), whereas in compression test, the behavioral development shows three ranges with ductile failure (Figure 2)

- Range I has a linear elastic behavior. It ends at the point where the tangent to the original stress-strain curve separates from the latter. In bending test, it corresponds to the crack initiation on the mortar's tensile surface.
- Range II describes a plastic behavior characterized by a no (or almost) linear curve. It corresponds to the multiplication of the micro cracks initiation points and their progression in the matrix, as well as fibers decohesion in the matrix. The end of this range is equivalent to the breaking point of the mortar in flexural test.
- Range III only visible on compression curves is characterized by a straight line of practically zero slope. It perfectly deciphers a plastic behavior corresponding to certain micro cracks closure and the matrix fibers detachment which leads to the mortar breaking. This same elasto-plastic behavior in compression test was obtained on hemp concrete [10]. But this mechanical behavior of hemp concretes in compression test must be qualified as very ductile even though the hemp fibers have low ductility [11]. Thus, in compression, mortars containing fibers have an elasto-plastic behavior with ductile breaking.

Identical bending behavior curves were made during work on epoxy fibers composites [12,13]. Similarly, a similar behavior curves in compression test on fiber composites were obtained [14]. This type of behavior marked by the shape of curves does not depend on fibers' nature and/or the matrix but only on their presence and the fibers content in the composite.

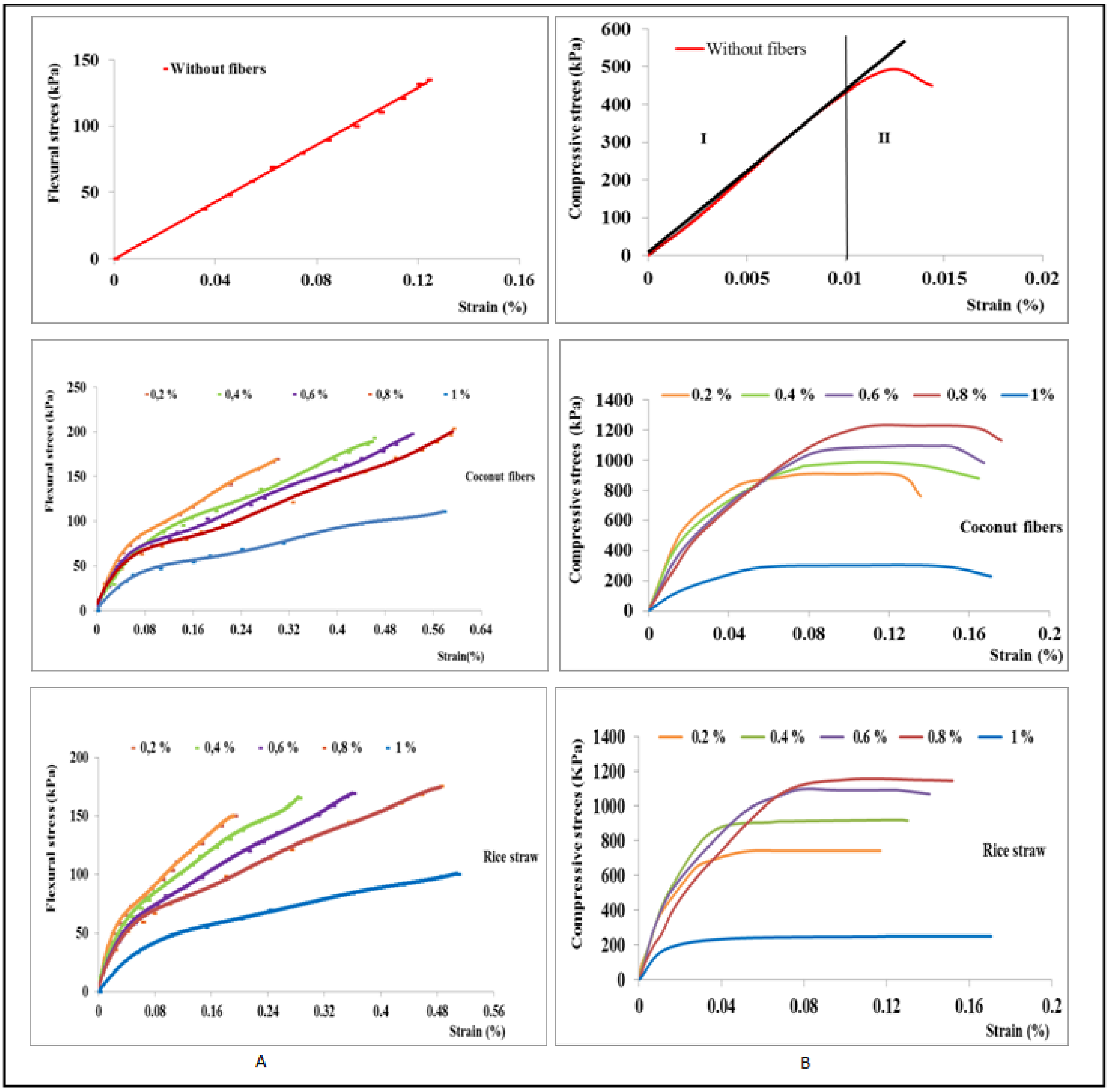

Figure 2. Evolution of curves strain-stress - mortars distortion; A) in flexural test; B) in compression test

Table 2. Compressive mechanical characteristics of earth mortars

Mortars	Fiber content (%)	Breaking strength (kPa)	Distortion at breaking (%)	E_c (kPa)
Without fibers	0	487	0.013	42002
	0.2	856	0.13	34519
	0.4	1043	0.14	28310
With coconut fibers	0.6	1153	0.15	24376
	0.8	1230	0.16	19414
	1	300	0.17	10241
	0.2	793	0.11	34797
	0.4	950	0.13	32316
With rice straw	0.6	1110	0.14	28449
	0.8	1150	0.15	24071
	1	250	0.17	18497

Table 3. Mechanical flexural characteristics of mortars

Mortars	Fiber content (%)	F_i (kPa)	F_f (kPa)	Distortion at breaking (%)	Slope (kPa)	
					Before F_i (E_i)	After F_i (E_f)
Without fibers	0	20	134.60	0.13	594860	
With coconut fibers	0.2	50	169.54	0.29	192910	39547
	0.4	54	193.00	0.46	159740	30449
	0.6	50	197.40	0.52	154610	27813
	0.8	55	204.00	0.57	119630	26044
	1	40	101.50	0.60	68249	13003
With rice straw	0.2	50	150.20	0.20	328420	56057
	0.4	50	165.20	0.30	255570	42239
	0.6	51	169.40	0.40	219970	34377
	0.8	50	175.30	0.50	173470	26823
	1	40	100.30	0.53	94270	13172

3.1.2. Mechanical Characteristics in Flexural And Compression Tests

Table 2 and Table 3 respectively show the mechanical characteristics in compression test and in bending test, i.e. the breaking stress, distortion and modulus of elasticity (E_c and E_i) obtained on the different mortar specimens containing fibers. These values were determined from stress-strain curves. The moduli E_f corresponds to the asymptotic line slope at the end of the stress-strain curve as proposed [15].

These tables show that both compressive and flexural breaking strength vary with the fiber content. It increases to a maximum value when the fiber content is 0.8%. This is due to a homogeneous distribution of fibers in the matrix and the adhesion of the fiber/matrix interface. Above this content, the low proportion of matrix between fibers leads to poor fiber/matrix adhesion, resulting in reduced strength.

These tables also show that slopes E_c, E_i and E_f of stress-strain curves (stiffness of mortars) decrease with increasing fiber content while distortion increases. This decrease in E_c and E_i and therefore in mortars initial stiffness is linked to matrix structure at the beginning of the test, a structure induced by the presence of fibers. The higher the fiber content in the mortar, the less dense and therefore looser its structure is, hence the decrease in stiffness with the fiber content. Furthermore, when the mortar is stressed, the stresses are first applied on the matrix and then transmitted to the fibers via the fiber/matrix interface. When the stress becomes more and more intense, micro cracks appear in the matrix but are stopped by fibers which are softer. They will therefore progress on fiber/matrix interfaces and cause their separation, hence reducing their stiffness (E_f) and increasing distortion at mortar failure with the fiber content. This result agrees with those of some authors [16,17]. They note that improvement in the flexural strength of the composite comes with a decrease in their stiffness which they attribute to an increase in their porosity.

Moreover, these tables also show that for the same fiber content, mortar with coconut fibers is stronger and more deformable but less stiff than mortar with rice straw.

This observation is justified by the intrinsic properties of each fiber and its ability to adhere to the clay cement matrix. Coconut fibers are stronger, stiffer and less absorbent than rice straw. In addition, their surface is rough unlike straw. They promote good adhesion between coconut fibers and the clay cement matrix.

3.2. Influence of Fiber Content on Mechanical Behavior

3.2.1. Mechanical Behavior in Flexural and Compression Tests of Mortars Containing Treated Fibers

The stress-strain curves of mortars containing fibers treated with the different solutions (kapok wood ash and banana tree juice) in bending test and compression test are shown in Figure 3, regardless of the nature of the solution used for treatment and the fibers, curves have the same appearance as those of mortars containing untreated fibers surface partially removes hemicellulose and amorphous cellulose [18]. This change in the chemical composition of fibers results in improved force transfer to the fiber-matrix interface and improved stiffness of the composites. In addition, having an optimal value of the flexural strength with the pH of the alkaline treatment solution is due to both improved adhesion and force transmission to the fiber matrix interface. Some authors who worked on composites based on aliphatic polyester and bagasse fibers obtained similar results [19]. They showed that the treatment of bagasse fibers with NaOH solutions destroys cell structures and causes the fiber to split into filaments (fibrillation). This change in fiber structure improves the adhesion of the fiber-matrix interface when the NaOH concentration is 1%, while for a 5% NaOH concentration the increase in fibrillation reduces stress transfer at the interface.

Similarly [20] who worked on hemp fiber cement composite claim that treatment with a 6% NaOH solution (by mass) roughens their surface by dissolving wax hemicellulose and surface impurities. This results in improved force transfer to the interface. In addition, [21] worked on composites based on cement and diss and doum fibers. Treating those composites with a 1% and 3%

NaOH solution improves fibers surface roughness which results in improved interfacial adhesion between the fiber and the cement matrix. The difference between the observations made by these authors can be explained by the purity of NaOH solutions used because the hydroxyl groups (OH-) brought by the alkaline solution reacts with the hydrogen ion (H+) released by the fiber [22]. These Table 4 and Table 5 also show that above pH 9.5, the resistance of composites containing treated fibers decreases as the pH increases. The treatment of fibers with strongly alkaline solutions causes fiber degradation (significant defibrillation) as also indicated by the work [16,23-28]. As a result, the breaking strength decreases. Furthermore, the effect of treating fibers with banana tree juice solution on the flexural and compression behavior of composites is hardly noticeable (Figure 3). However, a significant improvement in flexural strength is noted. It is due to impurities removal from the fiber's surface and therefore to their change in morphology and modification of their chemical composition.

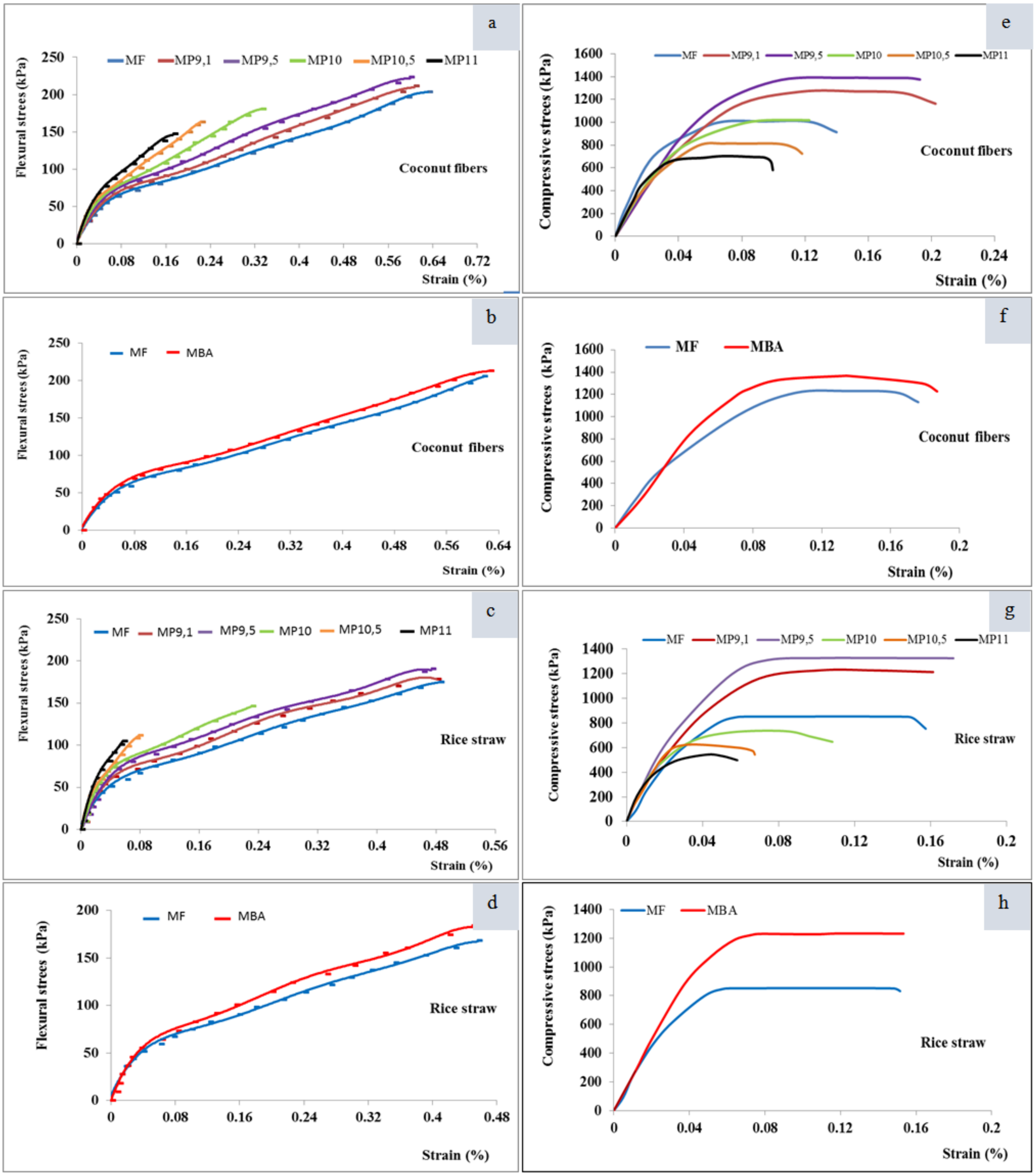

Figure 3. Stress-strain curves of mortars containing treated fibers: - in flexural test a) and c) treated fibers with potash solutions; b) and d) treated fibers with banana juice solution; - in compression test (e) and (g) treated fibers with potash solutions ; (g) and (h) treated fibers with banana juice solution

Table 4. Compressive mechanical characteristics of mortars containing treated fibers

Mortars	Name	Breaking strength (kPa)	Distortion at breaking (%)	E'_c (kPa)
With coconut fiber	MP	1230	0.16	19414
	MP9.1	1259	0.17	19718
	MP9.5	1386	0.20	20828
	MP10	1020	0.14	22306
	MP10.5	800	0.11	25389
	MP11	700	0.09	26622
	MBA	1246	0.18	18673
With rice straw	MP	1150	0.15	24071
	MP9.1	1226	0.16	25769
	MP9.5	1327	0.17	25697
	MP10	925	0.11	26730
	MP10.5	570	0.07	27098
	MP11	500	0.06	27589
	MBA	1232	0.17	24758

E'_c: modulus of elasticity.

Table 5. Mechanical flexural characteristics of mortars containing treated fibers

Mortars	Fiber content (%)	F_i (kPa)	F_f (kPa)	Distortion at breaking (%)	Slope (kPa) Before F_i (E_i)	After F_i (E_f)
With coconut fiber	MP	55	204	0.57	119630	26044
	MP9.1	65	211.5	0.59	121730	26217
	MP9.5	66	216	0.63	141170	27027
	MP10	69	181	0.43	157800	29261
	MP10.5	72	163.3	0.32	160272	31977
	MP11	75	147.2	0.20	247440	45949
	MBA	56	211	0.61	141490	26141
With rice straw	MP	50	175.30	0.50	173470	26823
	MP9.1	54	179	0.53	174010	27668
	MP9.5	62	191	0.62	174370	28832
	MP10	64	146	0.23	185340	42076
	MP10.5	69	108.4	0.09	239390	76778
	MP11	73	105	0.08	266960	77888
	MBA	55	174.50	0.52	184400	27236

F'_i: critical value F'_f: breaking strength.

3.3. Relationship between Compressive and Flexural Strength

Compressive and flexural strengths are the most widely used mechanical parameters for assessing the mechanical performance of building materials. In general, the compressive strength is overestimated because the slenderness (height/length ratio) of two is not always respected. Therefore, in order to deduce the value in compression test from the strength to bending, the correlation between these two parameters was sought. Figure 4 illustrates the evolution of bending strength as a function of compressive strength. It indicates that the curve of rice straw mortars is different from that of coconut fibers. However, the two curves look the same despite treatments to improve their quality. This difference can therefore be explained by the intrinsic characteristics of fibers.

Figure 4 further shows that the correlation between the two strengths is a power function. The smoothing functions have a coefficient of variation $R^2 = 0.96$ and $R^2 = 0.99$ respectively for mortars containing rice straw and treated or untreated coconut fibers. The relationship between the compressive and flexural strength of cement-earth mortars can be correctly approximated by the function $\sigma c = 0.025\sigma f^{2.08}$ and $\sigma c = 0.031\sigma f^{1.99}$ respectively for rice straw and coconut fibers. A similar expression (Rtf=mRcn) that relates the splitting tensile strength (Rtf) and the compressive strength (Rc) was obtained by [30]. These equations make it possible to predict the compressive strength of earth mortar containing fibers (rice straw or coconut fibers) with an error of less than 5% from the experimental value.

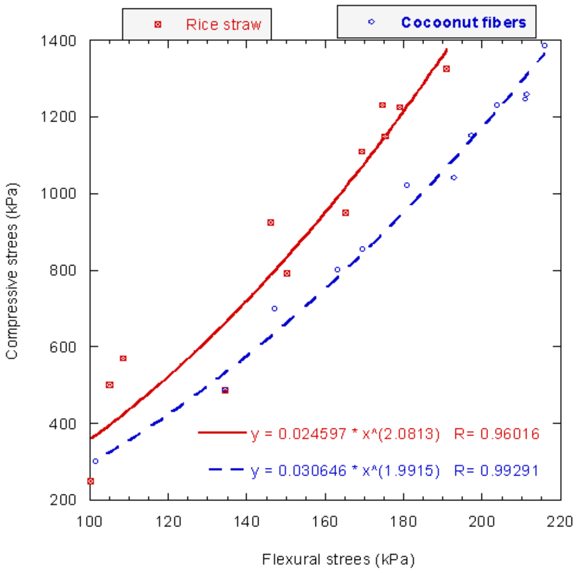

Figure 4. Relationship between the flexural and compressive strength of mortars containing treated and untreated fibers

4. Conclusion

The study of the influence of fibers rate and treatment with aqueous solutions of potash, kapok wood ash and banana tree juice on the mechanical properties of mortars led to these conclusions.

- Clay cement mortar has a brittle elastic behavior in bending test and pseudo-elastic behavior in compression test. The addition of plant fibers transforms these behaviors into elasto-plastic behavior in bending test and ductile (elasto-plastic) in compression. In addition, they lead to a decrease in mortar's stiffness. However, the highest compressive and flexural strength is achieved at a fiber content of 0.8% by mass of mixture.
- Adding fibers treated with potash solutions of kapok wood ash and banana tree juice in clay cement mortars hardly affects composites behavior. Only the extent of plastic distortion varies with the pH of the treatment solution. The compressive and bending strengths are greater when the pH of the potash solution is 9.5. Gain in strength compared to mortars containing the same untreated fibers is more than 6% and 15% in bending and compression test respectively. However, the composite containing fiber treated becomes stiffer than those containing untreated fibers.
- The compressive strength of clay cement mortars containing fibers is correlated by a power function with the flexural strength. The error rate with the experimental value is less than 8%.

Seeing these results, it would be interesting to valorize these natural fibers in designing building materials.

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