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Effect of aging process on mechanical performance of reinforced mortar with NaOH abaca fibers

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ABSTRACT

There is a high demand for bio composites due to its eco-friendliness, lightweight, availability, low cost and life-cycle superior. This bio composite was prepared by reinforcing the cementitious matrix with alkali treated abaca fiber. However, one of the major concerns about this material is its durability in the cementitious matrix. This study gives an insight into the comparison of alkali treated fiber reinforced mortar (MFTHS) vs reference mortar with no fiber (MSF) through flexural, compressive, shrinkage and tensile test at 28 days, it also compared two processes of wet/dry cycles subjecting samples to the same mechanical properties. MFTHS increased its mechanical properties for an average of 25% compared to MSF. The same pattern occurs after applying WD-1 and WD-2, MFTHS showed better bonding between the matrix and the treated abaca fiber.

1. Introduction

Concrete is one of the most used materials by man [1] and its main component, cement, is responsible for over 8% global CO_2 emissions [2,3]. The search for alternative materials to reduce the carbon footprint has led to the study of alternatives such as geopolymers [4–6], fly ash [7–9], metakaolin [10–12], slag [13–16], silica fume [17], calcined clay [18–20], construction/mine waste [21–23], carbon capture [24–26] and bio composites [27–31]. The use of vegetable fibers constitutes a very interesting alternative as raw materials for cement-based composites in terms of environmental conservation, energy, and resources having a low cost and obtained from renewable sources [32–37]. Natural fibers have been commonly used through years; in Ancient Greece, wood and straw fibers were particularly used in order to increase volume stability in mortars [38], they are generally used to avoid shrinkage cracking phenomena, increase brittle materials fracture toughness and develop strain-hardening behavior [39]. Studies demonstrate that natural fibers have higher toughness, improved impact and higher deformation capacity [40–44]. A variety of natural fibers are available in the nature such as: flex, hemp, jute, sisal, isora, ferula, bamboo, okra, guaruman, abaca, coir which are used as

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reinforcement in different matrices polymeric or cementitious [45–54]. As it is well known, the use of natural fibers, as an alternative to synthetic ones, as reinforcement of composite materials have received growing attention according to their specific properties, price, because of those reasons, natural fibers began to be used as reinforcement of composite materials in engineering [47]. The development of this type of materials may introduce new chances for improving the farming business where good quality cellulosic fibers species could be achieved; these vegetable fibers can be obtained from agricultural by products which may generate an additional value to agro-industrial products [55].

Between all available natural fibers around the world, there is abaca, also known as Manila hemp, this fiber has called researchers attention not only because of its flexibility and high tensile strength, but also because its cultivation reduces soil erosion levels and rehabilitates biodiversity in tropical areas. Abaca fiber is important to Ecuador's economy because it represents the 0.2% of the primary exports. Since 2010 this number has increased constituting more than $150 million in its economics [56], representing the 15% of the worldwide consumption [57,58]. According to Lomerio & Oloteo [59], there are more than 200 different varieties of abaca, Ecuador has two varieties: Bungalanon and Tangongon that differ from the ones in Philippines because of its farming and cultivation process [60]. Abaca has been widely used in ropes, bags, paper, including the automobile industry because of its mechanical properties [61,62].

As other natural fibers, abaca fiber could be used as composites reinforcement [63]. It is known that fibers as reinforcement for concrete are used to provide ductility so that they support the action of tensile loads [64], but its use may be affected in terms of adhesion and durability; therefore, in order to improve the necessary adhesion between fibers and matrix, several chemical treatments can be used [65], this is also helpful concerning to durability in which the natural fiber suffers a chemical or physical modification for increasing its stability in cementitious matrices [66,67].

Studies from Fidelis et al. [68] summarizes different treatments and their advantages, particularly focusing on controlled alkaline treatment. Among various treatments, alkali treatment stands out as one of the most popular due to its costs efficiency and favorable outcomes in enhancing adhesion. Studies have utilized different percentages of sodium hydroxide, including 3%, 5%, 10% and 15% [67,69], showing promising results in terms of increased crystallinity, tensile strength and Young's modulus when compared to untreated fibers.

Despite all these advantages, many challenges arise concerning the use of natural fibers in cementitious applications, perhaps the most critical is the low durability of fibers in cementitious matrix, knowing that natural fiber durability depends on the durability of constituents exposed to stress. In the case of natural weathering, most stress factors are a combination of temperature and humidity variations [70], the considerably lower resistance to the high alkaline environment of the cementitious matrix can reduce the reinforced effect of these fibers and lead to premature failure of the composites [71–74].

As a result the deterioration of natural fibers in a cement matrix has emerged as the major problem to be solved in order to produce durable natural fiber reinforced cement composites [75].

One of the methods that has been used for modifying the surface of the fiber is hornification, but the process of hornification cycles of wet/dry (w/d) could be used as well for estimating the degradation of the material, the main reason for analyzing the degradation is the lack of data on the behavior of the bio composite within its service life, years and years should be waited in order to analyze whether the fiber is still contributing to the mechanical properties of the mortar. For this reason, applying cycles of w/d are a good opportunity to estimate the degradation of the material. As Poletanovic et al. [76] described in her hemp study subjected to alkali treatment where 10 cycles of w/d alternatively used showed an increase of approximately 20% of compressive and flexural strength compared to reference mortar. Leng et al. [77] analyzed the performance of bamboo subjected to accelerated aging process through w/d cycles, applying 8 cycles alternatively, achieving size changes of samples after subjected to w/d, mortars reinforced with bamboo had better results in terms of flexural and compressive strength.

Therefore, durability is an important topic that must be analyzed. It is important to remark according to the literature available to date, accelerated cycles of w/d to treated alkali fiber has only been done before for hemp by Poletanovic et al [76]; not procedure of accelerated w/d cycle to treated abaca fiber or another natural fiber has been performed. In terms of bio composites, it is important to contribute by increasing the catalogue of available natural fibers and its behavior as bio composites since the availability of natural fibers vary according to the region.

For this reason, the aim of this research is to (1) compare the mechanical behavior of a mortar with no fiber (MSF) vs. an alkali treated fiber reinforced mortar (MFTHS) applied to masonry in construction industry and (2) to compare the mechanical properties of these mortars when subjected to accelerated aging process of w/d.

2. Material and methods

2.1. Materials

2.1.1. Natural fiber and alkali treatment

Abaca fiber is derived from the pseudo-stem of *Musa textile*, commonly referred as manila hemp. This plant produces small, inedible fruits with seeds, and its pseudo-stem can reach a height up to 6.5 m. The fiber was obtained at a national plantation located in Santo Domingo, Ecuador. The dosage was determined after evaluating various quantities in a preceding study conducted by same authors [78], ranging from 0.2% to 0.4%, along with differing fiber lengths 20 mm, 25 mm, 30 mm. The optimal outcome in terms of flexural strength, measured at 8.2 MPa, was obtained with a 0.2% concentration and a fiber length of 30 mm treated with 3%NaOH solution. This selection was influenced by findings from Lee et al., 2022 [79] where chopped abaca fiber of comparable lengths and concentrations was employed.

Fig. 1.a shows scanning electron microscope (SEM) results of no treatment and, Fig. 1.b shows NaOH treatment abaca fiber at 5μm of backscattered electrons, its surface has been modified and according to Alcivar-Bastidas et al. [78] better bonding and results were achieved. Fibers were dipped into this solution for 4 h and then in water for 10 h. Impregnated abaca fibers were rinsed with water until extruded brown washing became transparent, as described by Jiang et al. [67].

2.1.2. Matrix

All samples, mortar with no fiber (MSF) and alkali treated fiber reinforced mortar (MFTHS) were designed according to UNE-EN 196–1 [80] and its composition is listed in Table 1. The cement used in this research is a general use (GU), its specification is indicated at ASTM C1157 [81], its bulk oxide composition and other properties are shown in Table 2. Natural sand was used and its granulometric curve was set as the average between ASTM C144 [82] maximum and minimum ranges; matrix ratio relation cement: sand 1:3 by weight, with 110±5 mm of the flow rate, following the procedure for workability test of flow table according to UNE-EN 1015–3 [83].

The flow rate range 110±5 mm was maintained for both types of mortars, MSF and MFTHS. However, due to the presence of fiber, additional water was necessary to achieve the same workability. In this study, the fixed flow rate enabled the control of mixture workability.

2.2. Methods

2.2.1. Accelerated aging processes

With the pass of the time there are factors that may improve or decrease certain mechanical properties. Previous researchers [71, 84–86] have analyzed different processes for simulating the degradation of cement composites. Therefore, in this research samples were subjected to two types of w/d cycles as accelerated aging processes, simulating severe and medium condition of affectation, the main reason for analyzing w/d cycles is because Ecuador is a country with only two seasons: dry and rainy, hence this process results in the most severe exposition for mortars. Two w/d cycle methodologies are proposed within the context of these conditions, and they follow the procedure as shown in Fig. 2.

The first w/d cycle (WD-1) is the one proposed by Neves et al. [87], with 6 cycles of w/d where samples were subjected to an accelerated aging test after 28 days of age. The aging cycles started with the specimens completely saturated in water at 30±1℃. The cycle had a duration of 3 days (1 day submerged in water for complete saturation followed by 2 days of drying inside the forced ventilated chamber). The chamber was set for a temperature of 36±1℃ and wind speed of 0.5 m/s. Considering that after 48 h of drying the specimens presented a mass loss of about 70% of the mass gained during its saturation.

Fig. 3 summarizes the process of WD-1.

The second w/d cycle (WD-2) is the one proposed by Wei et al. [88], but applying also 6 cycles of w/d. For this process, specimens were submerged in sealed tap water at 70℃ and then oven dried in a circulating air environment at 70℃ alternately. In order to determine the duration of each cycle, mass change was determined as a function of the immersing or drying time. Increase and decrease of specimen mass subjected to wetting and drying cycles were measured every 10 min for the first 2 h, every 1 h subsequently and every 3 (for wetting) or 4 (for drying) hours after 12 h. Samples were considered at equilibrium when the mass change was less than 2% over 3 consecutive measurements, resulting in 6 cycles. Samples within this research were subjected to both cycles analyzed through dry bulk density, shrinkage, compressive, flexural and tensile strength. Fig. 4 summarizes the process of WD-2.

2.2.2. Tests samples

2.2.2.1. Microstructural analysis to accelerated aging w/d alkali treated fiber.

SEM and FT-IR were performed to the alkali treated fiber (RF) subjected to accelerated aging cycles of w/d, named as: FWD-1 and FWD-2, according to the w/d process applied. FWD-1 and FWD-2 refer to the abaca fiber samples that underwent an accelerated aging process of w/d. This process was employed to observe the

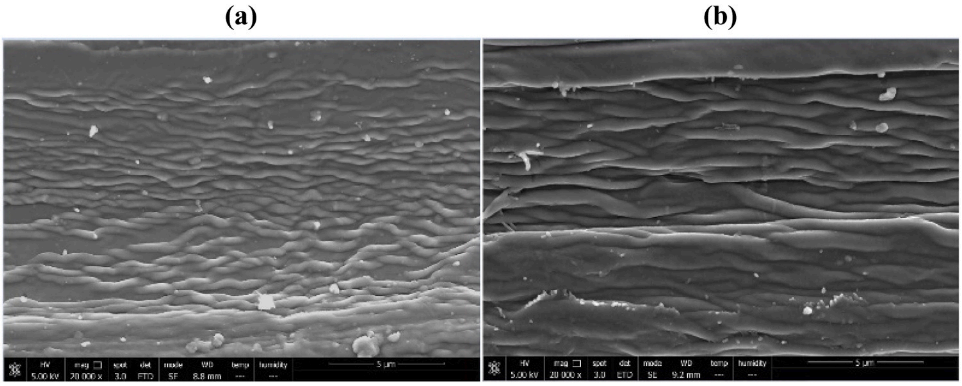

Fig. 1. Abaca fibers (a) no treatment, and (b) NaOH treatment, corresponding to 5μm of backscattered electrons.

Table 1
Mortar mix composition for 1 m^3.

Materials	Sand	Cement	Water Flow rate 110±5 mm	NaOH Abaca Fiber 0.2% total solid weight
MSF	1458 kg	486 kg	274 kg	–
MFTHS	1458 kg	486 kg	301 kg	4.37 kg

Table 2
Bulk oxide composition and other properties of GU cement.

Materials	Amount
SiO_2 [%]	16.9
Al_2O_3 [%]	3.05
Fe_2O_3 [%]	1.72
CaO [%]	58.6
MgO [%]	0.71
SO_3 [%]	2.41
K_2O [%]	0.13
Na_2O [%]	0.08
TiO_2 [%]	0.17
P_2O_5 [%]	0.25
LOI [%]	15.9
Specific gravity [g/ml]	2.85
Blaine [m^2/kg]	526
Compressive strength [MPa]	
1 day	7.7
3 days	17.1
7 days	22.4
28 days	28.3

direct effects of aging, specifically WD-1 and WD-2, on the fibers.

This technique (FT-IR) is sensible to internal structures since it reflects the characteristics vibrations of atomic groups and SEM analyze the superficial changes as a consequence of the accelerated aging w/d cycles applied.

2.2.2.2. Macro properties of the bio composite. Mortar with no fiber (MSF) and alkali treated fiber reinforced mortar (MFTHS) were analyzed at 28 days through: dry bulk density, flexural, compressive, tensile strength and shrinkage as follows:

Dry bulk density was determined after curing samples, firstly the weight of each water saturated specimen is recorded. Then, the specimen is maintained at 105°C in oven until one weight variation is further recorded. Finally, density is computed as UNE-EN 1015–10 recommendations [89] and the density mean values.

For flexural and compressive strength, prisms 40×40×160 mm^3 for each type were subjected to three-point bending under load control with loading rate equal to 44 N/s following the UNE-EN 1015–11 and 196–1 recommendations [80,90]. Drying shrinkage of mortars measured according to the method described in ASTM C157 [91], the length change of the specimen was measured using a vertical comparator for each type. The length was measured at 3, 7, 20, 28, 31, 33, 36, 40, 43, 46 days to later calculate the shrinkage. And tensile strength Fig. 5, was performed following the Japan Society of Civil Engineers (JSCE) recommendations [92] using the Shimadzu Autograph AGS-X with 50 KN capacity, allowing obtaining maximum load results and displacements

2.2.2.3. Macro properties of the bio composite after subjecting samples to accelerated process of w/d WD-1 and WD-2. Samples at 28 days of mortar with no fiber (MSF) and alkali treated fiber reinforced mortar (MFTHS), subjected to cycles of w/d according to Neves et al. [87] and Wei et al. [88] WD-1 and WD-2 respectively, were also tested through tests described in Table 3.

3. Results and discussion

Results have been divided in three parts, the first part corresponds to the microstructural analysis to accelerated aging w/d alkali treated fiber; the second part, corresponds to the comparison of MSF vs MFTHS mechanical properties of the bio composite. And finally, the mechanical properties of the bio composite after subjecting samples to accelerated process of w/d WD-1 and WD-2.

3.1. Microstructural analysis to accelerated aging w/d alkali treated fiber

3.1.1. Scanning electron microscopy (SEM)

FR, FWD-1 and FWD-2 are shown in Fig. 6. SEM analysis of 100μm backscattered electrons show the behavior of all three samples; in these images FR and FWD-1 exhibit similarities, but are not identical, there appears to be fiber bonding, and a flatter surface is

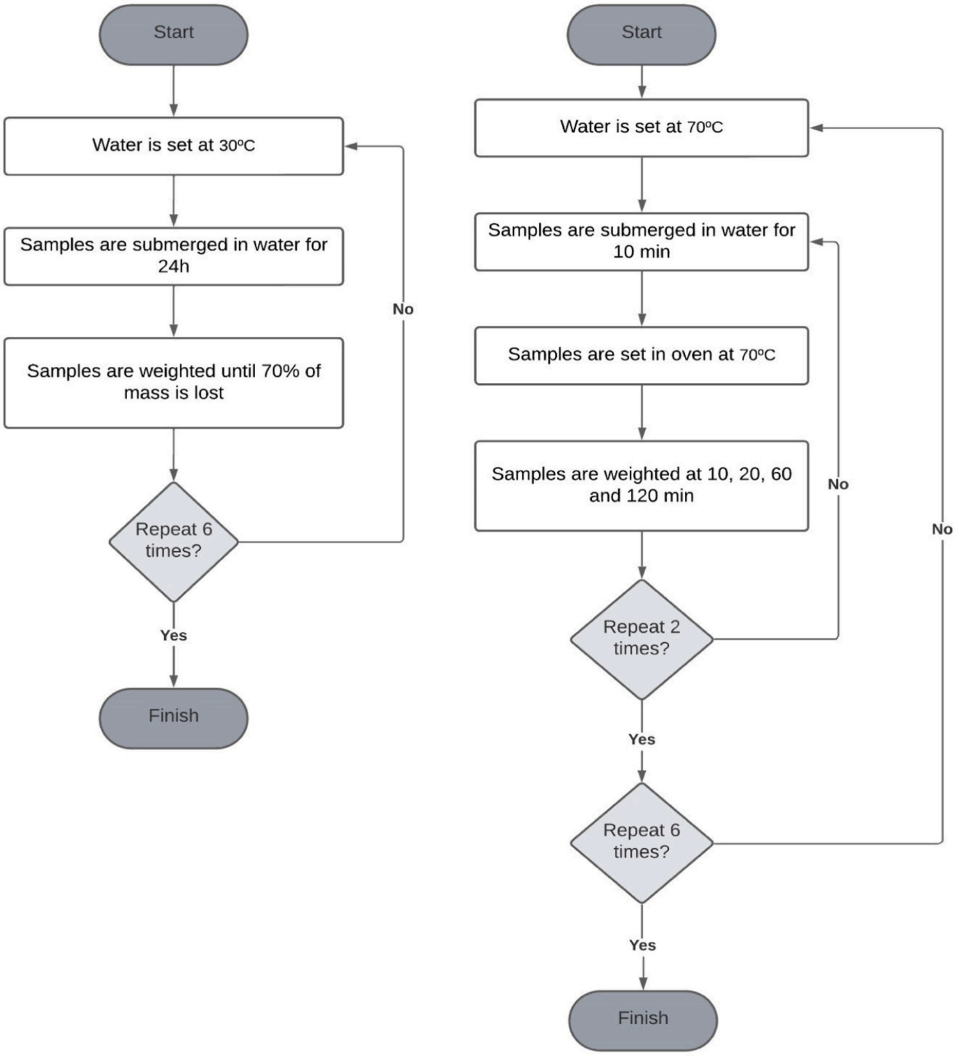

Fig. 2. (a) Aging process of wet and dry 1 (WD-1), according to Neves et al. [87]. and (b) aging process of wet and dry 2 (WD-2) according to Wei et al. [88].

observed in FR. Similarly, FWD-1 shows some flattening, although not as pronounced as in FR. However, in FWD-2 a rougher surface is evident, and the bonding pattern seems to change. This may occur since WD-2 is more severe if compared to WD-1.

3.1.2. Fourier-transform infrared spectroscopy (FT-IR)

The chemical composition of all samples is listed in Table 4. Fig. 7 shows the comparison between three samples. At first view it can be seen that the chemical composition does not vary significantly between samples, reference abaca alkali treated fiber (FR) in red show a peak between 3450 cm^{-1} corresponding to stretching bands of intermolecular and intramolecular hydrogen bonds, between FWD-1 and FWD-2 the peaks occur at 3433 and 3437 cm^{-1} respectively presenting the same composition. At 2920 cm^{-1} a peak of FR, FWD-1and FWD-2 is visible representing the stretching vibration bands of the C-H group in cellulose. Another important peak occurs at 1640 cm^{-1} producing the stretching vibration band of the free hydrogen-bound hydroxyl, demonstrating the hydrophilic nature of the natural fiber.

There is no great difference between FR, FWD-1 and FWD-2 in chemical terms, hence aging process of w/d does not vary the effect of abaca alkali treated fiber even if different procedures applied to the fiber.

3.2. Mechanical properties of the bio composite

Samples were subjected to different mechanical properties as showed in Table 3, results are summarized in Table 5. Determining the mechanical properties of the bio composite is important in order to measure the influence of the alkali treated fiber with the cement matrix.

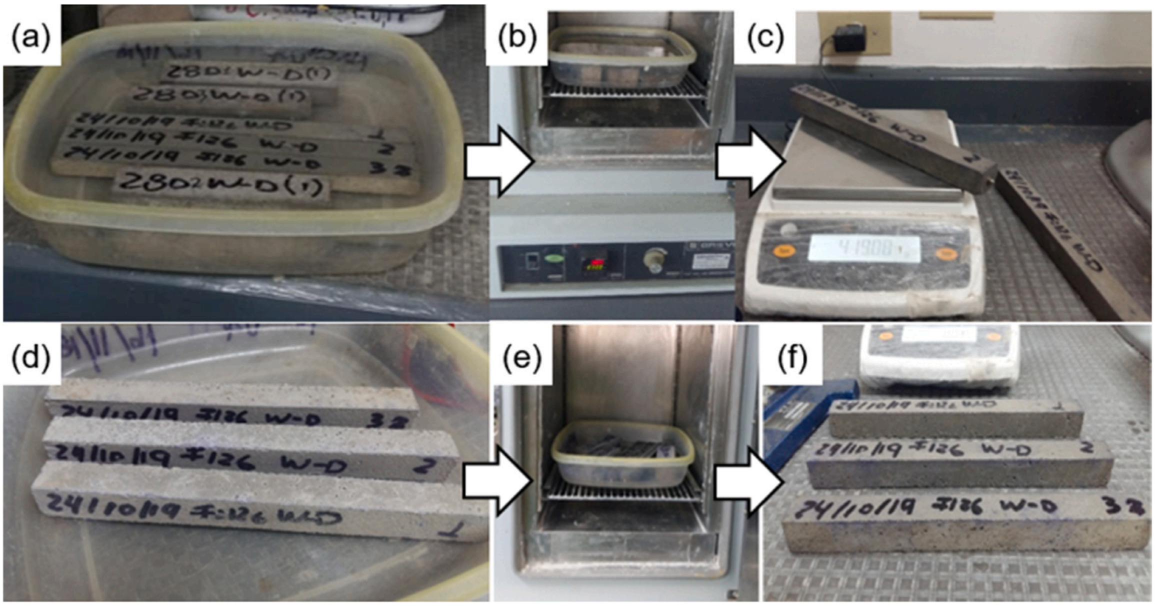

Fig. 3. Aging process of Wet and Dry 1, according to Neves et al. [87]. (a) 24 h in water, (b) oven at 30°C, (c) weight test, (d) 48 h dried. (e) oven at 30°C, (f) weight test.

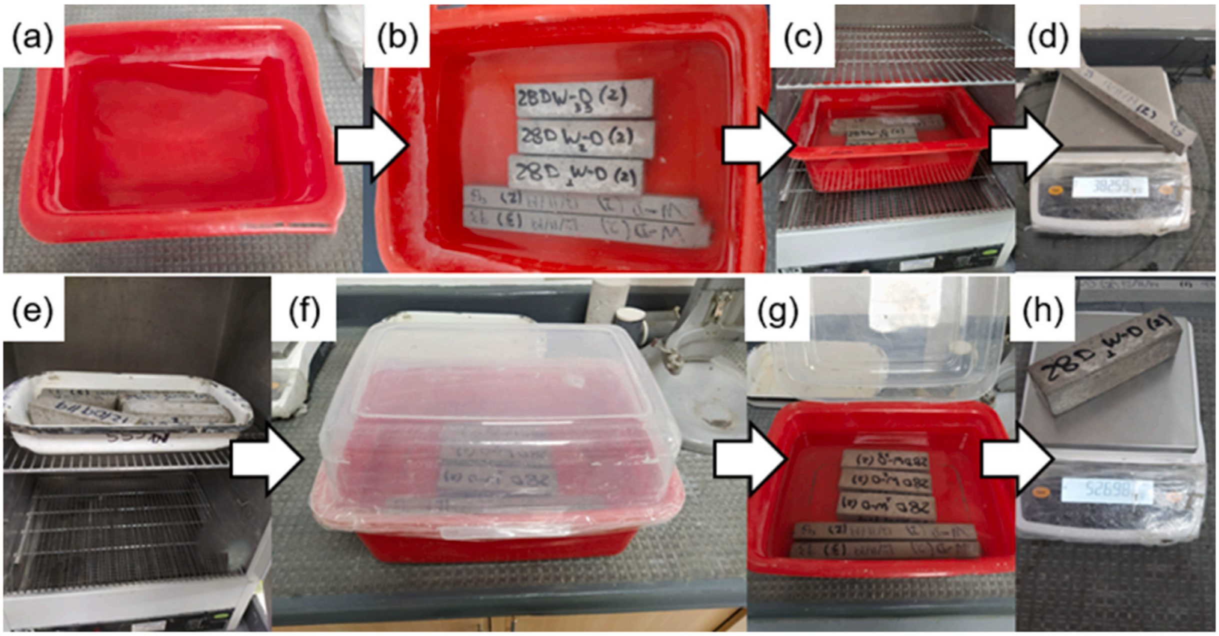

Fig. 4. Aging process of Wet and Dry according to Wei et al. [88]. (a) water at 70°C, (b) submerged in water for 10 min (c) oven at 70°C, (d) weight test. (e) oven at 70°C, (f) submerged in sealed 70℃ water (g) measured after 10,20,60,120 min, (h) weight test.

In terms of dry bulk density, mortars using the same water content and design composition achieved similar dry bulk density values as mortar Reference Mortar (RM). Samples were measured every 15 min until the mass difference was ≤0.2%. MFTHS results were slightly higher (between 3% and 4%), this could be due to the fact that it contains an additional 0.2% of the total solid weight of abaca fiber resulting in a more compact mortar.

In terms of flexural strength, the MSF mortar reached a 6.54 MPa, but after the addition of treated abaca fiber, MFTHS increased 22% of its original strength resulting in 8.2 MPa, augmenting its early age of flexural strength (Fig. 8.a). These results are comparable to other natural fibers behavior where flexural strength has been improved as summarized by Sood et al. [48].

It is important to analyze that during the flexural test, RM experienced compression on the top and tension on the bottom surfaces,

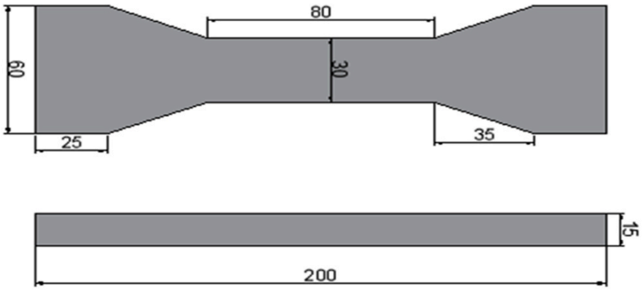

Fig. 5. Tensile strength measurement for samples according to JSCE recommendations (in mm).

Table 3
Tests and standards used.

Tests	Standards	References
Dry bulk density	UNE-EN 1015–10	[89]
Flexural strength	UNE-EN 1015–11	[90]
Compressive strength	UNE-EN 196–1	[80]
Dry Shrinkage	ASTM C157	[91]
Tensile strength	Japan Society of Civil Engineers (JSCE)	[92]

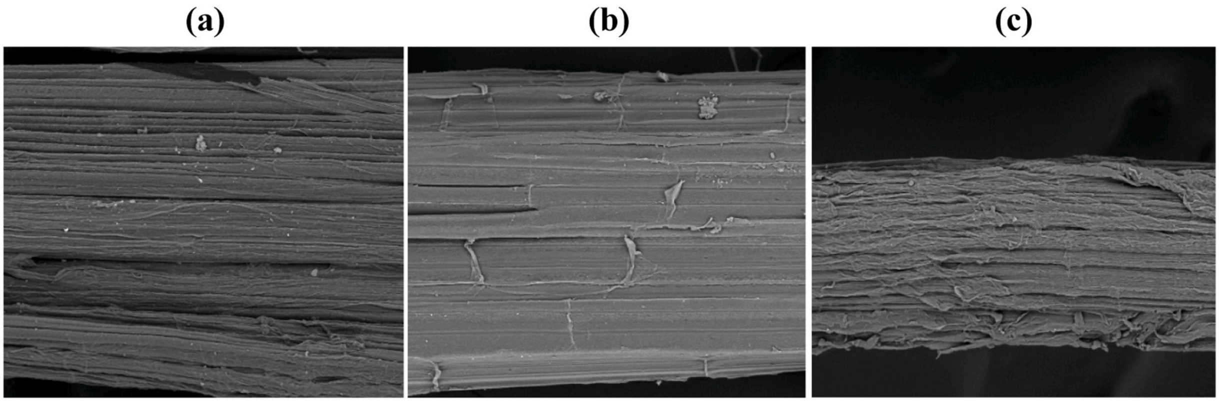

Fig. 6. FR (a), FWD-1 (b) and FWD-2 (c) subjected to SEM 100μm backscattered electrons.

Table 4
Absorption peaks of abaca alkali treated fiber subjected to processes of WD-1 and WD-2.

Wavenumber (cm^{-1})			Link (functional group)	Possible assignment
FR	FWD-1	FWD-2		
3449.05	3433.8	3437.41	-	Stretch bands of intermolecular and intramolecular hydrogen bonds.
2921.67	2916.36	2922.04	C-H	Stretching vibration bands of the C-H group in cellulose.
2852	2858.2	2851.06	$C\text{-}H_2$	Stretching vibration band of the $C\text{-}H_2$ group due to the presence of meicellulose.
1745	—	—	C=O	C=O stretching vibration of p-coumaric acids of lignin and/or hemicellulose (small shoulder pad).
1640.21	1636.1	1634.26	-	Band stretching vibration of free and hydrogen-bonded hydroxyl, demonstrating the hydrophilic nature of the natural fiber.
1462	1461.3	1467.1	C=C	Vibration caused by the deformations of the C=C bonds of the aromatic ring of lignin.
—	1319.9	1315.1	C-O	C-O bond vibrations.
1269.43	1233.5	1269.99	C-O	Stretching vibration of C-O bonds of acetyl group in lignin.
1044.26	1044.08	1042.57	C-O	Stretching of C-O bonds of hydroxyl and ether groups in cellulose.
784.66	771.7	771.42	C-H	C-H bond stretching vibration of lignin.

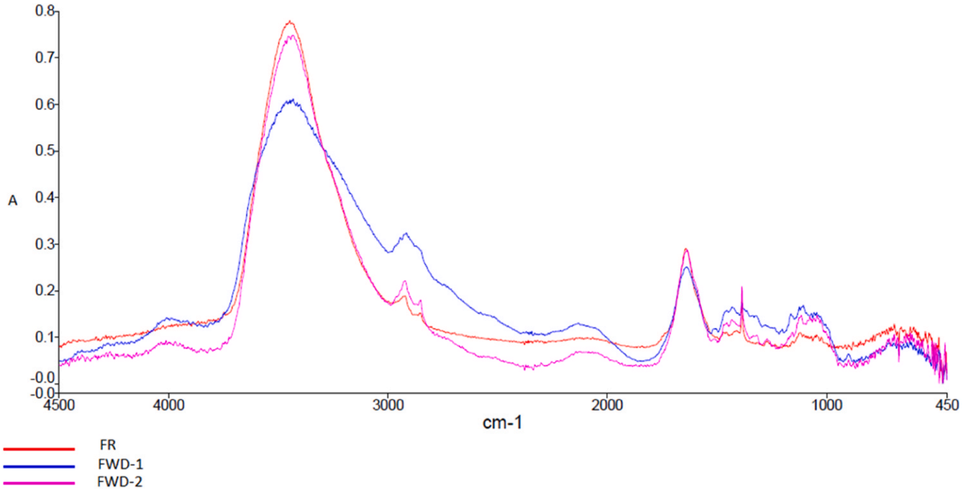

Fig. 7. FT-IR of abaca alkali treated fiber (FR), and w/d aging process WD-1 and WD-2 (FWD-1, FWD-2).

Table 5

Results of mortar samples with and without treated abaca fiber at 28 days.

Tests	MSF	MFTHS
Dry bulk density [Kg/m^3]	1854	1917
Flexural strength [MPa]	6.54	8.2
Compressive strength [MPa]	19.33	26.69
Shrinkage at 28 days [%]	-0.0627	-0.0542
Tensile strength [MPa]	2.87	3.89

leading to cracks at the bottom, and a visible crack located near the mid-spam of the sample, regarding to MFTHS, up to certain load the cement mortar mainly absorbed the stress before cracks appearance. Even at early ages, the MFTHS results were higher than RM (Fig. 8.a) Hence, it can be stated that treated abaca fiber slowed down the propagation of cracks due to the bridging effect on both sides of the flexural cracks

The same pattern occurs when analyzing through compressive strength, MSF reached a 19.3 MPa, and MFTHS increased its strength by a 30% (26.69 MPa). The addition of treated abaca fiber in the cementitious mortar improved its strength allowing a better bonding between the matrix and the fiber. Fig. 1.b shows alkali treated abaca surface, the adhesion of the fiber to the matrix depends on numerous factors such as: length, diameter, ratio and roughness. Abaca's roughness allows this bonding resulting in better mechanical strength. Also, MFTHS may have the ability to constrain the growth and widen the cracks in the mortar matrix by bridging micropores and cracks, requiring a greater applied load to propagate cracks when subjected to uniaxial compressive loading. This pattern occurs since early ages as showed in Fig. 8.b, where at 7 and 14 days, the compressive strength of MFTHS are higher than MSF.

Shrinkage is an important phenomenon that has a direct relation with the amount of free water and the porosity of the cementitious material. This response occurs after an evaporation of the free water stored in the capillary pores due to a low environmental relative humidity. Within this research, samples were cured by air simulating the most critical scenario (MSF/MFTHS AIR). Values of drying shrinkage were measured for calculation of drying shrinkage rate after 1 up to 45 days. Fig. 10 shows the results of MSF (RM) and MFTHS (RM) samples subjected to shrinkage, the shrinkage of mortar reinforced with treated abaca fiber illustrates the excellent efficiency in fostering shrinkage reductions. The shrinkage of MFTHS diminishes if compared to MSF, that could expand and generate more cracks. The presence of treated abaca fiber in the reinforced mortar may have inhibited the formation, growth and widening of cracks and micro-cracks due to the bridging mechanism between the pores and cracks. Also, the modified surface of treated abaca fiber could provide a better bonding between the fiber and the mortar matrix resulting in minimizing stress concentrations and minimizing local strains in the mortar matrix.

Samples were subjected to tensile strength, acceptable samples for MSF and MFTHS at 28 days reached 2.87 MPa and 3.89 MPa respectively (Fig. 8.c); MFTHS samples showed an increase of 26% in its strength compared to MSF (Fig. 8.b), this behavior could be given by the addition of abaca alkali treated fiber where a better bonding and cohesion is displayed, delaying the tensile cracks and restrict the crack propagation that typically occurs in the middle portion of mortar specimens under uniaxial tensile force. Hence, a higher load after forming a major crack due to the development of a bridge between the treated abaca fiber and the mortar matrix throughout the rupture zone is more resisted. Pattern than repeats since early ages as shown in Fig. 7.c.

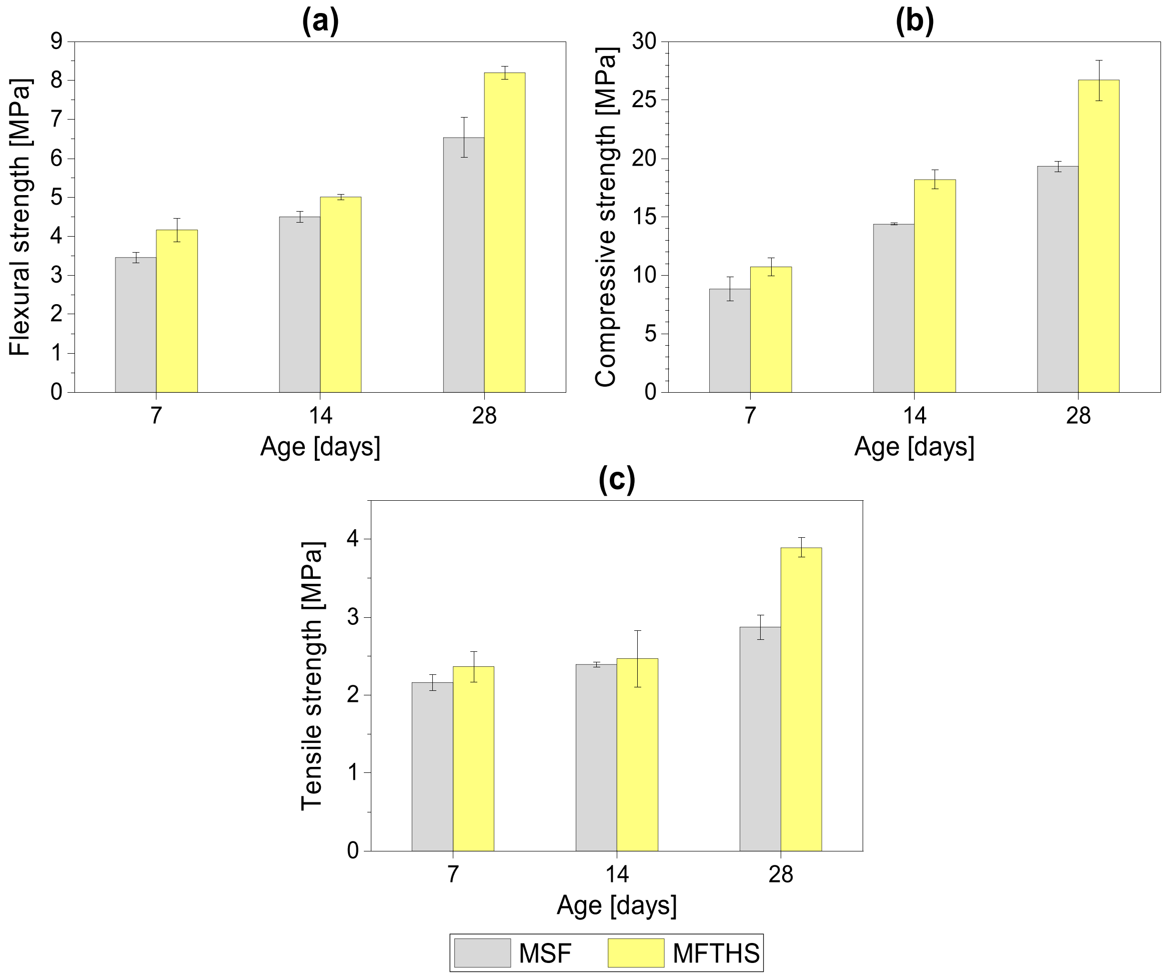

Fig. 8. Results of mechanical properties (a) flexural strength, (b) compressive strength, (c) tensile strength. MSF: mortar with no fiber. MFTHS: alkali treated fiber reinforced mortar.

Table 6
The effect of different cycles of wet/dry in natural fibers mechanical properties.

Reference	Bio product	MSF	MFTHS
[46]	Sisal fiber	Dry/wet 16+5 h/3 h T:80℃/22℃ Cycles: 10	Better tensile strength and stiffness compared to RM.
[93]	Sisal fiber	Dry/wet 15 h/3 h T:80℃/22℃ Cycles: 5	Better tensile strength compared to RM.
[94]	Pine fiber and unbleached eucalyptus	Dry/wet 7 h/15 h T:60℃/22℃ Cycles: 4	Better results in terms of water absorption, bulk density, modulus of rupture, modulus of elasticity compared to RM.
[95]	Sisal, jute and curauá fiber	Dry/wet 16+5 h/3 h T: 80℃/22℃ Cycles: 10	Better results in terms of tensile strength compared to RM.
[96]	Bamboo	Dry/wet 48 h/24 h T:50℃/22℃ Cycles: 10	Better results in terms of modulus of elasticity compared to RM.

3.3. Mechanical properties of the bio composite after subjecting samples to accelerated process of w/d WD-1 and WD-2

As described in Section 2.2.1 samples were subjected to two different processes of w/d cycles, applying 6 cycles, the main reason for performing maximum 6 cycles is that only a 2% variation mass is allowed in order for the samples to be considered at equilibrium. The comparison of w/d cycles is important since this procedure could modify the mechanical behavior of the bio composite.

Table 6 summarizes the results obtained from subjecting various types of fibers such as: sisal, pine, eucalyptus, jute and bamboo to different w/d cycles. Results show that mechanical properties decline due to the severity of the process after undergoing these cycles; however, if RM and MFTHS are compared following the application of these cycles on the samples, better results are achieved with treated natural fiber.

As Table 6 shows, it is important to analyze the effect of applying these cycles to the samples, comparing the mechanical behavior of RM and MFTHS.

3.3.1. Dry bulk density

The dry bulk density values for all studied mortars are shown in Fig. 9.a. These results show that after applying both processes WD-1 and WD-2 to MSF and MFTHS, alkali treated fiber reinforced mortar have higher density, resulting in a more compact and dense material. Even if both samples were treated with the same procedure of w/d, alkali treated fiber reinforced mortar that were subjected to WD-2 have higher density (2013 Kg/m^3) compared to WD-1 (1997 Kg/m^3).

Apparently, the effect of submerging and drying samples at high temperature (70℃) result in a more compact and dense mortar when referring to MFTHS.

In both w/d processes it can be seen that MFTHS samples show higher density, hence previous treatment applied to the fiber might have contributed to improve the particle packing and enhanced interfacial bonding.

3.3.2. Flexural strength

Fig. 9.b shows the results of flexural strength after applying WD-1 and WD-2 to both samples. It can be seen that both procedures diminish flexural strength if it is compared to 28 days' samples, it is certain that aging processes are very aggressive to the samples (temperatures of 70℃, immersion of samples for 24 h, drying of 48 h), hence this decrease of strength is suitable.

Regarding Fig. 9.b it can be seen that MFTHS, samples subjected to both processes WD-1 and WD-2 have higher results in terms of flexural strength, 12% and 17% respectively if compared to MSF, it can be stated that the addition of abaca alkali treated fiber improves internal bonding and the matrix enhances load transfer and prevents fiber-matrix debonding or pullout during loading [97]. However, results show that WD-2 has lower strength compared to WD-1, apparently the 6 cycles applied at 70℃ of immersion and oven dried affects more than keeping samples to lower temperatures (30℃).

3.3.3. Compressive strength

Analyzing compressive strength in Fig. 9.c, it shows the same tendency as in flexural strength, where MSF and MFTHS samples subjected to WD-1 and WD-2 are lower in terms of strength when compared to 28 days, this is logical due to the great impact of aging processes where the water absorption by the matrix could lead to swelling and dimensional changes that could weaken the bond between the matrix and the fiber. On the other hand, MFTHS samples show higher strength in terms of compressive strength by both processes than MSF, 19.5% and 21% respectively. Poletanovic et al. [76] findings indicate that subjecting alkali treated hemp to w/d cycles led to an enhancement in compressive strength compared to MSF, although it decreased in comparison to the 28-day mark [76]. Incorporating alkali-treated abaca fiber enhances internal bonding, leading to a denser and more compact matrix structure, thereby reducing void presence and enhancing material density, as previously investigated [98].

3.3.4. Tensile strength

In terms of tensile strength, the same behavior occurs, as shown in Fig. 9.d. It can be seen that MSF and MFTHS when subjected to WD-1 and WD-2 decrease its strength when compared to samples at 28 days without aging processes. In both aging processes mortars reinforced with treated abaca fiber show higher strength in terms of tensile strength approximately 30% in both processes, as Wei et al. [88] results after the addition of fiber in different percentages. It can be said that the presence of treated abaca fiber contributes to better performance of these mortars, the addition of fiber could if not treated properly affect this bonding or not being able to stand the heat of treatment. In both cases, it can be seen that tensile strength is higher when fibers were involved.

3.3.5. Shrinkage

The behavior of MSF and MFTHS after applying both aging process of WD-1 and WD-2 is as Fig. 10 shows. At first sight, it is important to remark that within 28 days the main problem is to counteract the shrinkage that is natural because of the water loss, which is improved with the used of abaca alkali treated fiber. After 28 days, aging processes affect directly to the sample since they are subjected to aggressive cycles of w/d and different temperatures in short term. Within this research samples reached 28 days, at this day mark process of w/d WD-1and WD-2 were applied to those samples. Shrinkage was measured up to 28 days and after finishing the cycles of w/d, during the process of WD-1 and WD-2 the percentage of mass loss was measured at each cycle.

MFTHS show better behavior to these processes whether WD-1 or WD-2; in both scenarios the expansion of these mortars as a result of aging process is more controlled and reduced if compared to MSF. The average expansion of MSF subjected to WD-1 is around 0.0316% while MFTHS-WD-1 is 0.011%, between ranges of 0.0215%-0.0503% and 0.0026%-0.00246% respectively.

The same pattern occurs with WD-2, the average expansion of MSF is 0.0691% and 0.0466% for MFTHS within a range of 0.0607%-

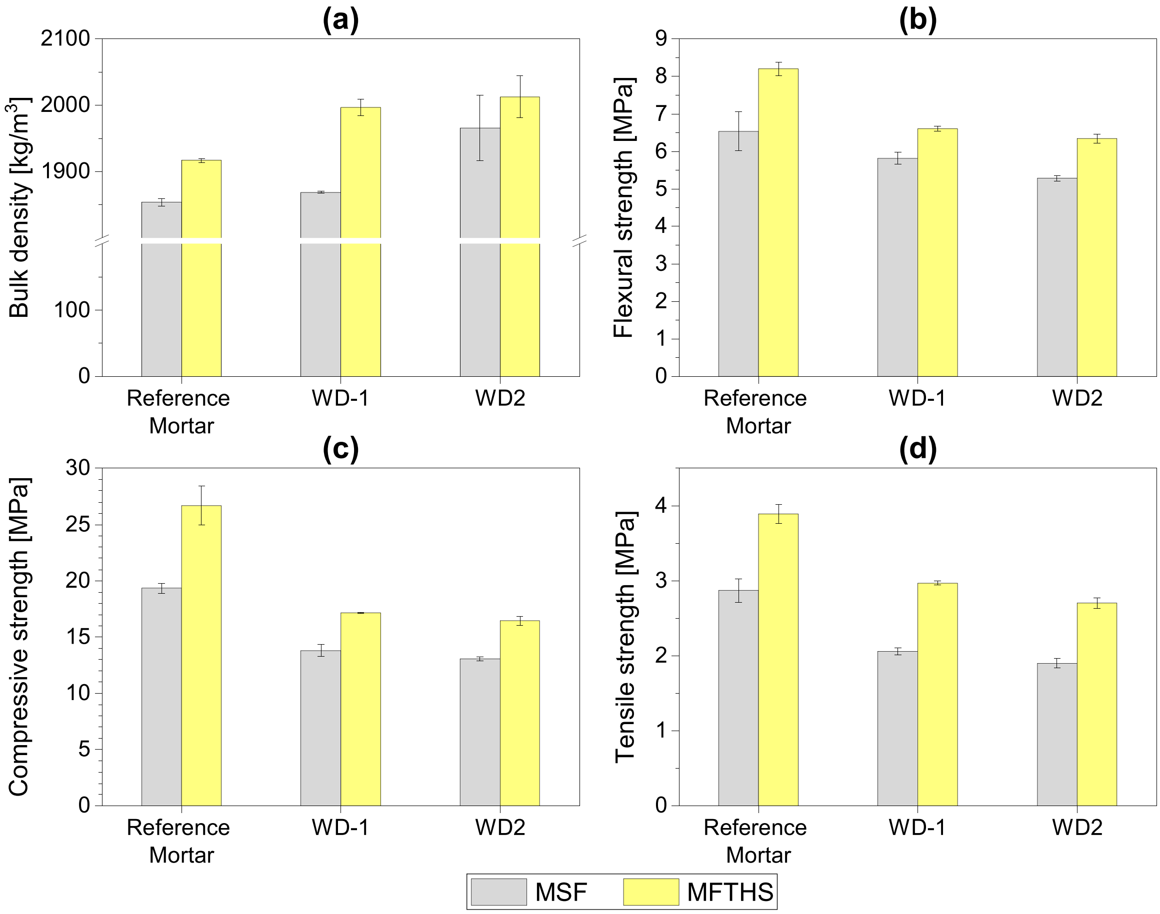

Fig. 9. Results of mechanical properties at 28 days for (a) dry bulk density, (b) flexural strength, (c) compressive strength, (d) tensile strength. MSF: mortar with no fiber. MFTHS: alkali treated fiber reinforced mortar. WD-1: wet/dry cycle method 1 [87]. WD-2: wet/dry cycle method 2 [88].

0.0779% and 0.0398%-0.0574% respectively. After subjecting samples to process of WD-1 and WD-2, a different behavior occurred, expansion in samples. It is well known that cement paste shrinks due time, leading to shrinkage cracking in the cement mortar due to a volume change which could be caused by a variation in temperature, within both process of w/d, samples were subjected to aggressive changes of temperature in short periods of time; as it is seen in Fig. 10 samples that weren't subjected to these aggressive cycles of w/d keep a slope that tend to maintain, but all samples that were subjected to WD-1 and WD-2 vary and tend to expand, according to some literature review, shrinkage cracking of cement based materials can be improved by incorporating fibers [99] which augment the dimensional stability and control cracking. These results show that the adhesion of treated abaca fiber improves the shrinkage behavior allowing the formation of cracks, but in a more controlled way resulting in a better performance.

4. Conclusions

This study presented the analysis of a treated alkali abaca fiber when subjected to accelerated aging process of w/d. As well as the comparison on: mechanical properties between a reference mortar (RM) and an alkali treated fiber reinforced mortar (MFTHS) at 28 days, and after subjecting both type of samples to accelerated aging process of w/d WD-1 and WD-2. From this investigation, it can be concluded that:

- Despite the usage of accelerated aging process of w/d WD-1 and WD-2, the alkali treated fiber preserves the same chemical composition as FT-IR results show, resulting in minimum variation peaks. These results can be correlated with SEM analysis where no great variation was displayed between samples.
- From both aging processes of w/d, results show that WD-2 is more aggressive to samples, even if 6 cycles were applied to each one, the higher temperature and the dipping time of WD-2 diminished its properties if compared to WD-1 for MFS and MFTHS.
- When correlating results from flexural, compressive and tensile strength (Fig. 9) to results from Fig. 6, it's apparent that better outcomes are achieved with MFTHS. However, within WD-1 and WD-2 better results are attained with WD-1. This behavior may be attributed to surface modifications and fiber bonding, which appear to be enhanced when subjected to WD-1.

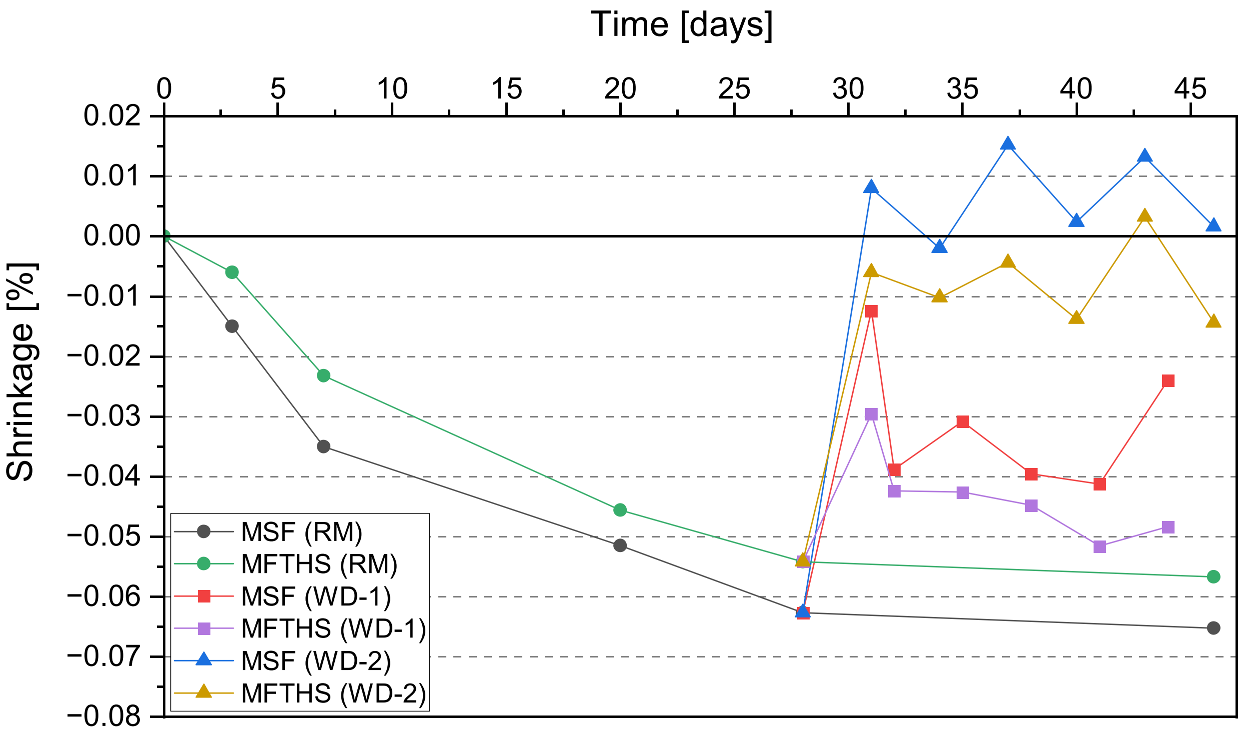

Fig. 10. Results of shrinkage in RM: reference mortar. MSF: mortar with no fiber. MFTHS: alkali treated fiber reinforced mortar. WD-1: wet/dry cycle method 1 [87]. WD-2: wet/dry cycle method 2 [88].

- The addition of alkali treated abaca fiber to the bio composite resulted in a 5% more compact sample, all mechanical properties increased compared to reference mortar, resulting in a 20% more resistant mortar in terms of flexural strength, 28% in terms of compressive strength and 26% in terms of tensile strength
- In terms of shrinkage, after subjecting both samples to most critical scenario (not curing), results show that the addition of alkali treated abaca fiber improved with the volume expansion and loss of water of the cementitious mortar resulting in a more controlled behavior.
- After applying accelerated aging process of w/d WD-1 and WD-2 results in terms of dry bulk density, flexural, compressive and tensile strength show that even after applying w/d cycles, MFTHS WD-1 increased their mechanical properties resulting in a 6% more compact mortar, 11% more resistant to flexural strength, 20% higher for compression and 30% higher for tensile strength, and MFTHS WD-2 resulted in a 2% more compact mortar, 17% more resistant to flexural strength, 21% higher for compression and 30% higher for tensile strength. In terms of shrinkage the tendency on this behavior is reflected.

CRediT authorship contribution statement

Daniel M. Petroche: Writing – review & editing, Visualization, Investigation. **María José Martínez-Echevarría:** Writing – review & editing, Supervision, Conceptualization. **Mauricio H. Cornejo:** Investigation, Visualization, Writing – original draft. **Stefany Alcivar-Bastidas:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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