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Jacqueline SALIBA, Nathalie KOUTA, Nadia SAIYOURI - Effect of wetting/drying cycles on the durability of flax fibers reinforced earth concrete - Construction and Building Materials - Vol. 445, p.137924 - 2024

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# Effect of wetting/drying cycles on the durability of flax fibers reinforced earth concrete

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## ABSTRACT

### Keywords:

Earth concrete  
Flax fibers  
Wetting/drying cycle  
Acoustic emission  
Ultrasound

Earth concrete is composed of fine particles which make them very sensitive to humidity and affects their long-term durability. In this study, the effect of wetting/drying cycles on earth concrete according to ASTM D559 was studied by measuring the weight loss, pH, and Electrical Conductivity (EC). The effect of different percentages of flax fibers was investigated. The residual properties of reference specimens and earth concrete specimens subjected to wetting/drying cycles were evaluated by conducting compressive tests at the end of the 25 cycles. Ultrasound, Acoustic Emission (AE), and Digital Image Correlation (DIC) techniques were applied to estimate the concrete progressive deterioration during and at the end of the 25 wetting/drying cycles. The results showed that earth concrete degradation begins during the first cycle with visible cracks on the surface of the specimens. The mechanical tests showed a considerable loss of earth concrete mechanical properties after 25 cycles. The ultrasonic test showed that the degradation rate was more important for specimens without flax fibers. The cumulative acoustic activity was effectively used to assess the different damage progression phases and crack propagation. The signal parameters (energy, amplitude, etc.) evolution indicates premature damage for earth concrete specimens subjected to wetting drying cycles.

## 1. Introduction

The construction sector is responsible for 50 % of the global annual carbon dioxide emissions [1]. Hence, the need for an environmentally friendly and sustainable alternative material such as earth concrete [2] is important. Earth concrete gained interest recently as a viable alternative to conventional concrete due to its low environmental impact, its low cost, and its high availability. Earth concrete is recognized as a sustainable and environmentally friendly building material due to its utilization of local, natural, and renewable materials. Existing research has highlighted the potential environmental benefits of earth concrete, such as its reduced carbon emissions compared to traditional Portland cement-based concrete [3–5]. The application techniques used in the production and deployment of earth concrete can have a significant influence on its environmental footprint [6–8]. Factors such as energy consumption, waste generation, and water usage during the construction process must be carefully examined to gain a holistic understanding of earth concrete's environmental profile [3,9,10]. These considerations are further complicated by the fact that the environmental impacts of concrete are highly contingent on local conditions, such as the

availability of raw materials, energy sources, and waste management. The lifetime of a concrete structure is also a crucial factor in determining its overall environmental impact, as the environmental cost of construction is normalized over the structure's lifespan. Consequently, the durability and service life of earth concrete must be thoroughly evaluated to accurately assess its sustainability [11]. Accurately determining the CO<sub>2</sub> emissions associated with this material requires conducting a carbon footprint analysis and a life cycle assessment (LCA) [12–15], considering different standards such as the ISO 14040 series of LCA standards [16], and the French NF P 01–010 standard that addresses the environmental impacts of building materials [17]. Earth concrete is a composite material made up of a combination of soil, water, and often additional binding agents like straw or fibrous materials [18–20]. The specific soil composition, including particle size, organic matter content, and salt levels, plays a crucial role in determining the suitability and performance of earth concrete for construction purposes [21]. The application of earth concrete involves a labor-intensive process of mixing the soil-based material to create sturdy and durable walls or other structural elements. While earth-based construction methods like rammed earth, adobe, and BTC have been utilized for centuries, earth concrete offers distinct advantages and characteristics that set it apart.

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## Nomenclatures

AE	Acoustic Emission
DIC	Digital Image Correlation
EC	Electrical Conductivity
AC	With Cycles
SC	Without Cycles
LCA	Life Cycle Assessment
NDE	Non-Destructive Evaluation

Rammed earth, for example, relies on the compaction of soil layers, while adobe bricks are sun-dried and BTC are mechanically compressed. In contrast, earth concrete is typically cast in place, enabling the creation of more organic and free-flowing shapes that can be sculpted to meet specific design requirements. The use of natural fibers in earth concrete also represents a sustainable approach with considerable environmental advantages. They are environmentally friendly, renewable, abundant, have a lower carbon footprint, and are economically viable compared to synthetic alternatives [22]. The inclusion of fiber reinforcement has been shown to improve the mechanical properties of cemented and uncemented soils, leading to increased unconfined compressive strength, shear strength, and ductility [23]. Flexural capacity and the effects of fiber reinforcement have been also studied with researchers examining the relationship between fiber volume fraction, concrete strength, and mechanical properties [24]. The incorporation of fibers reduces the weight of the construction elements. Natural fibers have shown promising results in enhancing the hygrothermal and acoustic properties of sustainable building materials [25,26]. In fact, the fiber distribution influences the materials' ability to manage moisture and sound absorption and insulation through increased porosity and the damping of sound vibrations [27]. The usage of fibers prevents the formation of early-age plastic shrinkage cracking by constraining crack propagation through stress redistribution [28]. However, the durability of earth concrete with fibers represents a major problem in their use in construction [29–40]. Indeed, the presence of a large quantity of fine particles in earth concretes makes them very sensitive to the presence of water and to the variation of relative humidity. The composition and structure of clay particles play a crucial role in their water absorption capacity as this later is influenced not only by their size but also by their shape and charge. For example, Kaolinite, a 1:1 layered aluminosilicate clay mineral, is known for its low cation exchange capacity and relatively inert nature [41]. While smectite clays have a high cation exchange capacity and a swelling behavior due to their 2:1 layered structure [41]. The deterioration of earth concrete with natural fibers could be also caused by several mechanisms such as shrinkage-induced cracking; the loss of adhesion between the fibers and the matrix due to strain gradient at the interfaces during drying as water absorption leads to volume changes; and the weakening of the fibers in a high alkaline environment which dissolves the lignin and hemicellulose phases [42].

The effect of wetting/drying cycles has been studied in the literature to evaluate the durability of stabilized soils [43–45]. The wetting/drying cycles, performed on gypsum soil stabilized with 3 % lime, have shown a reduction in pH and Electrical Conductivity (EC) over the cycles [44]. This was attributed to the decrease in calcium ions and hydroxyls due to the pozzolanic reaction and ettringite formation. A decrease in ultrasonic velocity and strength was also detected over the cycles due to the degradation of the specimens. A cumulative mass loss of about 20 % was measured on lignin-stabilized silt due to the high suction produced by the drying process, which negatively influences the binding of soil particles resulting in surface crumbling and specimen failure [46]. Soils containing large amounts of fines exhibited greater mass loss during cycling [28]. The mass loss increases with increasing the percentage of clay and decreasing the percentage of hydraulic binder [47]. The liquid

limit and plasticity index of expansive soil specimens treated with sand and calcium carbide increased till the 7th cycle and then decreased. That was caused by the absorbed water in the electron double layers on the surface of the soil particles (mainly affected by the size and specific surface area of the particles). Indeed, the destruction of the microstructure during the cycles leads to the increase of the fine particles [48]. Akcanca and Aytakin [49] studied the variation of the hydraulic conductivity in function of the proportion of stabilized and non-stabilized bentonite during the wetting-drying cycles. As a result, the hydraulic conductivity decreased with the increase of the percentage of bentonite and the addition of lime in both wetting and drying cycles. It is estimated that the wetting-drying cycles, after 48 h in the oven at  $35 \pm 5$  °C, influence the curing of the specimens with lime.

Understanding the complex behavior of earth concrete under various loading conditions and exposure environments is crucial for its widespread adoption in the construction industry as it can compromise the structural integrity and durability [50]. To address these challenges, researchers have explored the use of various non-destructive evaluation (NDE) techniques for the assessment and monitoring of earth concrete structures over time [51,52]. These techniques, such as ultrasonic pulse velocity [29,53,54], AE [55], sclerometers that are designed for softer materials [56], and ground-penetrating radar, allow for the detection and quantification of damage without the need for destructive testing, which can be particularly beneficial for in-situ evaluations. Damage assessment and monitoring has been also conducted using (NDE) ultrasonic pulse velocity and AE. These complementary techniques can offer a comprehensive understanding of the complex failure mechanisms in earth concrete, enabling engineers to design more resilient and sustainable concrete structures.

The AE technique allows to evaluate damage localization and to establish a correlation between the energy released at a micro-scale as a result of the conversion of strain energy to kinetic energy through crack formation and the fracture energy that can be determined based on the stress deflection curves at the macroscopic scale [57,58]. Monitoring fracture processes in concrete has shown a correlation between acoustic emission characteristics [59,60]. Advanced moment tensor analysis has also been used to explore mixed mode fracture, microfracture mode-fracture toughness relationships, and fracture properties of reinforced concrete structures [61,62]. Several studies have investigated the relationship between AE signals and the fracture behavior of concrete under various loading conditions. The AE signals, such as the magnitude and energy, are closely related to the crack propagation and stress-strain behavior of concrete specimens [63]. The incorporation of fibers within earth concrete matrix can significantly influence the crack propagation and final strength of the material, making it crucial to examine the bonding effect between the matrix and the fibers. Non-destructive techniques, such as ultrasound and acoustic emission, offer a promising approach to elucidate the mechanisms underlying crack formation and propagation [64]. The random distribution and orientation of fibers within the matrix relative to loading direction further complicates the analysis, as it can lead to variable crack paths and diverse fracture surfaces [65–67]. The increase of fiber volume fraction and fiber length increases toughness and ductility and exhibits multi-cracking [68,69]. The interface transition zone properties between fiber and matrix is also of great importance. In fact, the strain compatibility can be modified under loading or due to aggressive environment related to strain gradient generated by swelling. Microcracks are thus generated at the interface due to stress concentration which reduces the mechanical properties. The study on the pullout behavior of fibers [65], and the analysis of the toughening effects of fibers, can provide a comprehensive foundation for the investigation [65,66]. The study of AE feature allows to distinguish between the tensile and shear fracture mechanisms [70, 71].

In this paper, the influence of the percentage of flax fibers on the behavior of earthen concrete during drying/humidification cycles was studied. Three mixtures were designed with varying percentages of flax

**Table 1**  
Mixtures components and composition.

Components (kg/m <sup>3</sup> )	Sand	Bentonite	Cement	Lime	Total water	Super-plasticizer	Flax fibers
SA0F	931	405	152	34.2	367	1.6	0
SA03F	929	401	152	34.2	370	1.6	5.7
SA06F	925	399	152	34.2	375	1.6	11.4

fibers (0 %, 0.3 %, and 0.6 %) to assess the extent to which the inclusion of these natural fibers can enhance the overall performance and properties of earth concrete. Flax fibers are known to be a sustainable and environmentally friendly reinforcement [72-74]. By testing earth concrete with different flax fiber percentages, the optimal fiber content that provides the best balance of mechanical, thermal, and other relevant properties can be determined. Specimen degradation during the wetting/drying cycles was monitored by the ultrasound technique and the measurement of weight loss, pH, and EC. This degradation has been evaluated by the evolution of the mechanical properties of earth concrete and by the appearance of imperfections such as cracks or voids on the surface of the material. Capillary absorption has also been measured for specimens with and without fibers at the age of 28 days. In addition, the AE and DIC techniques have been applied to compare the fracture behavior of earth concrete specimens subjected to wetting/drying cycles to that of reference specimens. Those techniques allow for monitoring the accumulation of damage under loading and thus, a better understanding of the cracking process in earth concrete [28,75-79].

## 2. Experimental program

### 2.1. Materials and mixtures

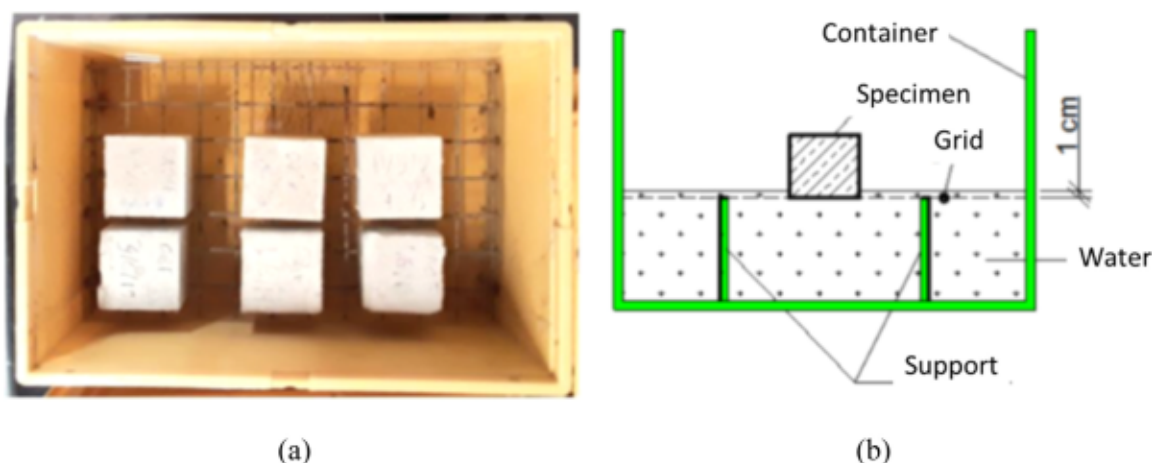
Earth concrete mixture is constituted of artificial soil to avoid the variability of a natural one. It is composed of 30 % bentonite clay (75 % Smectite, 10 % Kaolinite, and 15 % Illite) and 70 % sand. This soil has been stabilized with 3 % of natural hydraulic lime (NHL5/ EN 459-1 [80]) and 8 % of cement (CEM 1, 52.5 N PM-CP2 / EN197-1 [81]) of the overall quantity of clay-sand mixture.

The length of natural flax fibers is constant and equal to 12 mm with a diameter of  $14.66 \mu\text{m} \pm 2.95$  [82]. Flax plants are pulled up and left flat in the fields. The straws are then harvested and put into bales. The objective of scutching is to separate the different constituents of the flax stems. The linen is then prepared to be spun; the fibers will be divided to homogenize them. The combers are equipped with increasingly fine needles, so the linen fibers will be separated more and more finely. A clamp grabs these fibers to place them so that they overlap on a spreader. This is how a combed linen ribbon of infinite length is formed

to be cut later with fixed lengths. A life cycle inventory study of flax-based technical textiles found that the production and transformation of flax fibers can be a relatively environmentally friendly process, particularly when accounting for the valorization of co-products [83]. The use of natural fibers in earthen concrete has gained increasing attention due to their potential to improve the durability and sustainability of these materials [84]. Flax fibers have been found to have high specific strength and stiffness, making them a promising reinforcement material for construction applications. The addition of flax fibers can improve the strength, ductility, and impact resistance of the material [64] and slow down the degradation of earthen concrete during cycles of exposure to various environmental conditions [84]. Different types of treatment for natural fibers have been tested in the literature (Alkaline treatment, acetylation, hydrothermal treatment, water repellent coating, ect...) with the aim to improve their properties and the adhesion with earth concrete matrix [85]. The fibers used in this study were not treated to keep these materials natural and easy to use. The absorption coefficient is equal to  $105 \pm 5 \%$  [28]. Additional details about the choice of the materials and their properties can be found in [28].

Three mixtures have been tested by varying the percentage of flax fibers: 0, 0.3, and 0.6 %. The percentage of flax fibers added to the mixture was calculated by weight. First, clay and sand were mixed to ensure a certain homogeneity of the artificial soil. Lime and cement were added later to the dry mixture followed by water and superplasticizer. The small quantity of cement has been added to facilitate early formwork removal and enhance durability. The superplasticizer (Tempo 10) was used due to its efficiency as a water reducing admixture [28] and thus for reduction of shrinkage in earth concrete. Flax fibers were finally progressively added to the mixture. The mixture components and composition are presented in Table 1. To keep an equivalent solid mass, the quantity of fibers was subtracted from the artificial soil mass. The effective water to binder ratio was constant with a value of 0.45. Additional water has been added to consider the water absorbed by flax fibers. Mixtures have been named by presenting the % of fibers with a length of 12 mm. Based on that, SA0F, SA03F, and SA06F represent the mixtures containing 0 %, 0.3 %, and 0.6 % of flax fibers respectively.

The capillary rise test, the wetting/drying test, and the compressive



**Fig. 1.** (a) Specimens and (b) experimental setup of capillary rise test.



Fig. 2. Ultrasonic pulse velocity measurement (calibration and measurement) [87].

test have been performed on cubic specimens of  $10 \times 10 \times 10 \text{ cm}^3$  for the three mixtures 'SA0F, SA03F, and SA06F'. At least, 2 specimens have been tested each time for durability and mechanical tests.

## 2.2. Methods

### 2.2.1. Capillary rise test

The capillary rise coefficient was determined for the three mixtures at the age of 28 days. Specimens were first dried in a ventilated oven at  $60^\circ\text{C}$  until weight stabilization. Then, specimens were immersed in a thin layer of water with a depth of 10 mm (Fig. 1). The weight variation was continuously measured manually using a balance with a precision of 0.01 g. The mass was measured many times during the first day and then the time interval was increased with age. The evolution of the water absorption coefficient was determined according to the following equation:

$$C_b = \frac{100 (m(t) - m_0)}{(S\sqrt{t})}$$

where  $C_b$  is the absorption coefficient ( $\text{g} / \text{cm}^2 \cdot \text{min}^{-1/2}$ );  $m(t)$  the weight of the specimen after an immersion time  $t$  (g);  $m_0$  the specimen weight after drying and before immersion in water (g);  $S$  the surface of the specimen in contact with water ( $\text{cm}^2$ ) and  $t$  the immersion time in water (min)

### 2.2.2. Wetting / drying cycles

The accelerated durability of earth concrete has been studied to present internal and external damage related the various natural climatic phenomena (humidity, temperature, wind, rain, etc.) [43]. In this study, the durability test of the wetting/drying cycles according to ASTM D559 [86] was presented. This test provides a better understanding of the behavior of these materials against humidity variation. Specimens were stored in their molds under endogenous conditions for

24 hours after casting. They were then cured in a climatic chamber with a relative humidity of 80–95 % and a temperature of  $20^\circ\text{C}$ . After 28 days, two specimens were subjected to wetting/drying cycles, and two others were used as reference specimens and kept under the same curing conditions.

25 wetting and drying cycles were applied according to ASTM D559 while modifying the drying temperature to  $60^\circ\text{C}$  to prevent the dehydration of the cement present in the mixture. A wetting/drying cycle is divided into two phases: the first phase (wetting) consists of placing specimens in water for 5 hours while the second phase (drying) consists of placing specimens in an oven for 42 hours. Specimens were placed on a thin grid to ensure that all the sides are exposed to the same environmental stress during the wetting and drying cycles. This ensures uniform exposure and accurate assessment of the degradation process.

Specimens tested under wetting/drying cycles have been designated as AC for example SA0F-AC and the reference specimens as SC.

### 2.2.3. Ultrasound tests

The ultrasound test is a non-destructive technique that aims to identify the velocity of ultrasound waves in concrete. The ultrasound velocity can be related to the mechanical properties of the concrete, its quality (defects, cracks, voids, etc.), and its dynamic elastic modulus. The ultrasound system used in this study is composed of two transducers and a PUNDIT pulse generator (Portable Ultrasonic Nondestructive Digital Indicating Tester) (Fig. 2). The transmitter coupled to the surface with gel converts the electrical pulse into a longitudinal pressure wave with a frequency of 200 kHz. The wave passes through concrete and is received by the receiver transducer located on the opposite surface. The system thus displays the time difference between sending and receiving the signal with an accuracy of  $0.1 \mu\text{s}$ . The propagation speed is calculated using the formula ( $V = L / t$ ) where ( $t$ ) represents the propagation time and ( $L$ ) the distance between the 2 sensors. The device was calibrated before each measurement. Several factors can influence this

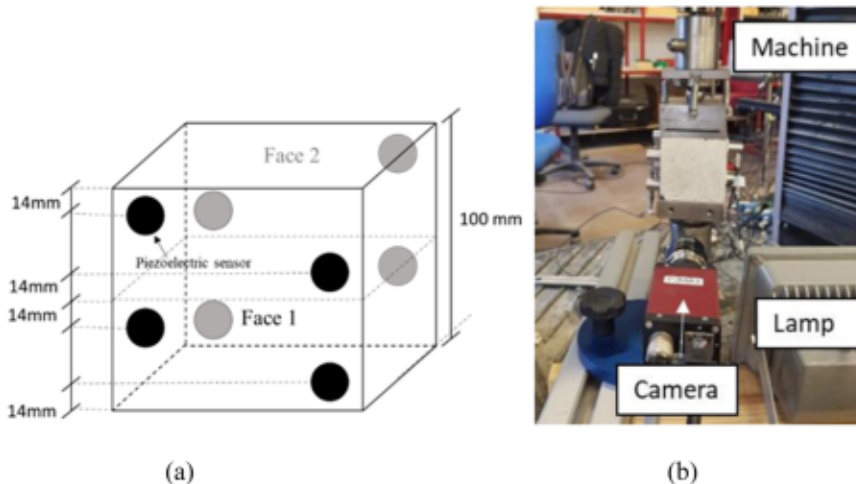


Fig. 3. a) Cubic specimen geometry and position of AE transducers b) DIC measurements.



Fig. 4. PH and EC measuring portable device.

measurement such as the coupling, the sensor type, the measurement conditions, and the water content of the tested material [29]. The velocity was measured at different positions on the cubic specimens: at the center and near the 4 corners as the surface might be more affected by the degradation. The average value has been considered.

#### 2.2.4. Compressive tests

ASTM C39/C39M standard [88] was followed for testing the compressive strength of concrete specimens. An electromechanical machine with a capacity of 100 kN was used to conduct unconfined compressive tests on earth concrete specimens without wetting/drying cycles and at the end of the 25 cycles (at an age of around 100 days). The loading displacement rate is constant and equal to 0.6 mm/min. This test has been carried out on the same cubic specimens subjected to wetting/drying cycles and reference specimens. Compressive tests were conducted in parallel with the AE and DIC techniques.

#### 2.2.5. Acoustic emission technique

The AE system consists of an eight-channel AEWIN system with a general-purpose interface bus and a system for data storage analysis. Calibrated R15 $\alpha$  AE sensors were placed on the surface as receiver of the generated AE signal. The piezoelectric transducers, with a frequency range between 50 and 200 kHz and a resonance frequency of 150 kHz, were placed on two opposite sides of the specimen using a thin layer of silicone grease expelled from air (Fig. 3). A 40 dB gain differential amplifier was used to amplify the detected signals. The detection threshold is set at 35 dB to avoid the background noise. A high pass filter with a cut-off frequency of 20 kHz, and a low-pass filter with a cut-off frequency of 400 kHz were used to eliminate mechanical and electromagnetic disturbances. The acquisition system was calibrated before each test using a pencil lead break procedure, HSU-NIELSEN source, according to standard NF EN 1330 [89]. Peak Definition Time (PDT), Hit Definition Time (HDT) and Hit Lockout Time (HLT) parameters are similar to those used in [90]. A 3D localization algorithm has been used.

#### 2.2.6. Digital image correlation

The monitoring of crack damage in concrete structures using DIC has been a topic of significant interest. Recent advancements have also demonstrated the potential for efficient damage detection in engineering structures through the capture and analysis of static deformation profiles. The DIC technique was applied to better understanding of the cracking process in earth concrete and compare the fracture behavior of earth concrete specimens subjected to wetting/ drying cycles to that of reference specimens. Displacement values were captured in 2D by tracking the changes in markers' length, and strain values were later derived from these measurements. The current focus on 2D digital image correlation analysis has provided valuable insights into crack damage in concrete, the exploration of 3D deformation analysis could unlock new possibilities for a more comprehensive understanding and further enhance the effectiveness of crack monitoring [91]. The commercial VIC

2D software was used for the image treatment processing with a resolution of 0.06 mm per pixel. Before testing, a white speckle followed by a black one was sprayed onto the surface. DIC tracks distinct points on the specimen's surface, each unique from the others by monitoring groups of neighboring pixels known as subsets. The used cameras had a resolution of 2452 $\times$ 2056 pixels. To enhance image contrast, two lamps positioned at each side were employed.

#### 2.2.7. Measurement of pH and electrical conductivity

The measurement of pH and EC allows macroscopic monitoring of the physicochemical reactions in earth concrete during wetting/drying cycles. The device for measuring pH and EC is shown in Fig. 4. Measuring the pH of a solution consists of measuring the concentration of H<sub>3</sub>O<sup>+</sup> ions. If the pH is less than 7, the solution is considered acidic, if the pH is greater than 7, the solution is considered basic and for a pH equal to 7 the solution is neutral. The EC expressed in Siemens per meter (S / m) shows the ability of a solution to conduct electric current. It depends on the nature of the ions present in the solution and increases with their concentration. To accurately measure the pH and EC of a concrete sample, it is essential to prepare a representative solution that accurately reflects the chemical composition of the concrete [92–94]. The preparation of a concrete solution involves several steps. First, a representative sample of the concrete should be collected. The collected sample should be crushed or ground into a fine powder to increase the surface area and facilitate the extraction of ions. Next, the concrete powder should be mixed with distilled or deionized water [92]. The mixture should be thoroughly agitated or stirred to ensure the dissolution of the various ions and minerals present in the concrete [95]. The pH and EC of the concrete solution can then be measured. The pH measurement is particularly important, as it can provide insights into carbonation for example that may be occurring [96]. The EC of the concrete solution can also be a valuable indicator of the dissolved ion content, which can be related to the durability and performance of the concrete [97]. The preparation of the concrete solution for pH and EC measurement should be carried out with care, following standard procedures and guidelines, to ensure accurate and reliable results [98]. The measurements for the same solution were made simultaneously for the pH and the EC with a measurement accuracy of  $\pm 0.01$ . The solution is prepared according to the method proposed by Eades and Grim [99] and presented below:

- Drying of earth concrete samples at 60°C until weight stabilization
- Crushing of dry earth concretes and passing them through the sieve # 40
- 20 g of sieved earth concrete is mixed with 100 ml of distilled water
- Regular stirring of the mixture for 30 s every 10 minutes for one hour
- Measurement of pH and EC of the mixture.

### 3. Results and discussions

#### 3.1. Capillary rise test

The use of fibers has been found to reduce permeability and infiltration rate while improving durability [84]. The interaction between the fiber surface and soil matrix plays a crucial role in these observed enhancements. However, the specific application of flax fibers in earth concrete and their impact on capillary rise behavior has not been extensively explored. Given the potential benefits of fiber reinforcement in construction materials, it is worthwhile to investigate the impact of the percentage of flax fibers on the capillary rise behavior and absorption coefficient of earth concrete to understand the optimal fiber content for improving the material's water resistance and durability. Such an investigation could provide valuable insights into the suitability of flax-reinforced earth concrete for applications where capillary rise resistance is a critical property, such as in building foundations or retaining walls [23,100–103]. The investigation by [101] on the use of

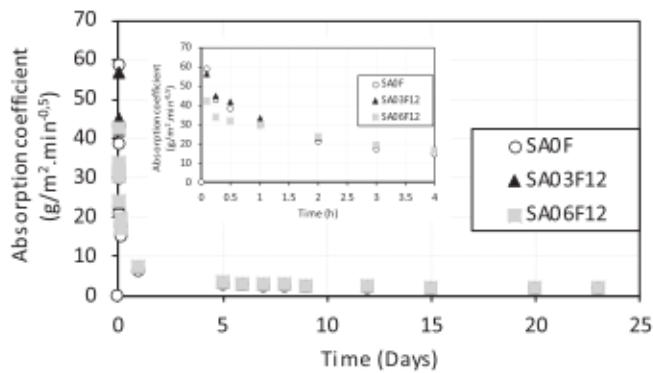


Fig. 5. Evolution of the water absorption coefficient for SA0F, SA03F, and SA06F versus time.

coconut fibers in mud concrete revealed that the addition of fibers can improve the compressive strength of the material. The study concluded that there is a negative correlation between compressive strength and water content. Additionally, the research by [104] on the use of coir fibers in concrete production demonstrated that the inclusion of coir fibers can increase the compression strength, split tensile, and split tensile, when compared to reference concrete. However, the study also found that the addition of coir fibers had a significant impact on the mix's water holding capacity, leading to increased water absorption values.

The capillary rise test was conducted on SA0F, SA03F, and SA06F mixtures. Fig. 5 shows the evolution of the water absorption coefficient of the specimens versus time. Two phases can be observed with a

transition after around 1 hour for all mixtures. During the first phase, absorption occurs quickly, and the weight gain reaches almost 22.5 % (after 5 h) for SA0F and 25 % for mixtures with fibers. During the second phase, the rate of absorption decreases with a small increase in weight over time. The capillary absorption coefficient is the inclination of the first segment of the absorption curve obtained when the amount of absorbed water is plotted against the square root of time [105]. The subsequent points were not considered as the inclination happens when the wet front reaches the top of the specimen. The capillary absorption of earth concrete is very high due to the presence of bentonite and increases with the addition of fibers. The mechanism behind the higher absorption coefficient in mixtures with more flax fibers can be explained by several factors related to the hydrophilic property of the fibers and their interaction with the earth concrete matrix. In fact, when added to earth concrete, these fibers create additional pathways for water to travel through the material. The distribution and orientation of the fibers within the concrete matrix can also influence water movement. Their presence increases the overall porosity of the mixture and can create micro-channels and interconnected voids which provides more surface area and more capillary channels leading to a higher absorption coefficient. The interaction between the bentonite, a highly absorbent clay present in the mixture, and the flax fibers further amplifies this effect.

### 3.2. Effect of wetting/drying cycles on earth concrete degradation

#### 3.2.1. Visual effect

Photos were taken before each wetting stage to visually follow the degradation of the specimens. The photos presented in Fig. 6 correspond to the beginning of cycles: 1, 8, and 25 for SA0F, SA03F, and SA06F

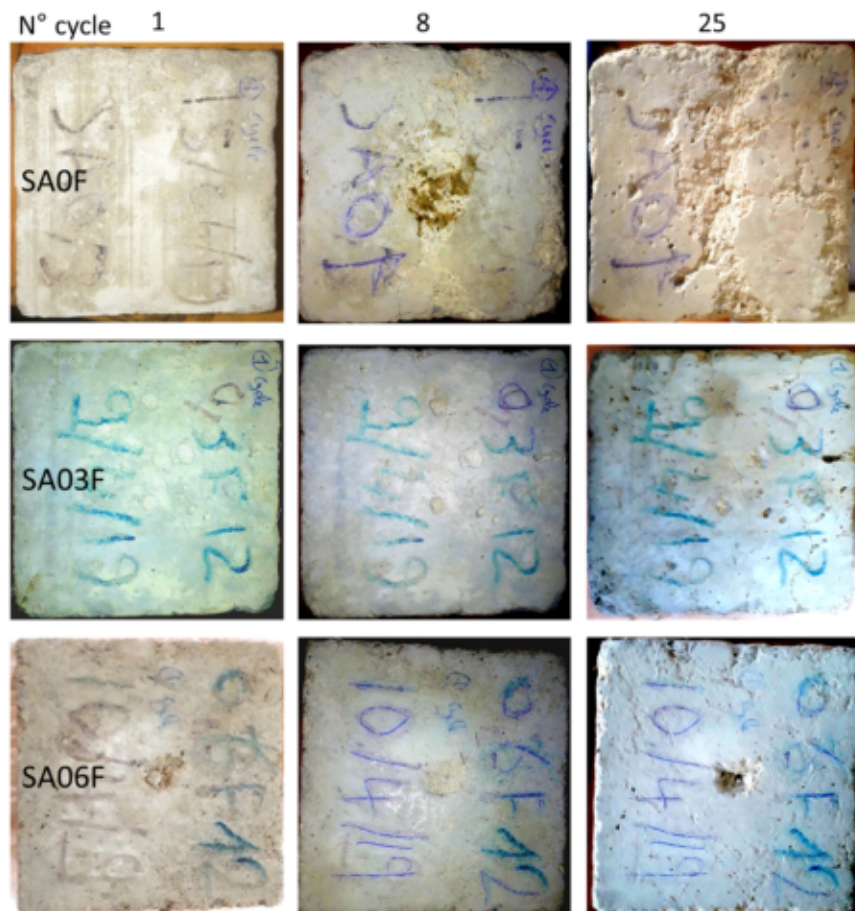


Fig. 6. Photos of the specimens before the start of each wetting cycle for SA0F, SA03F, and SA06F.

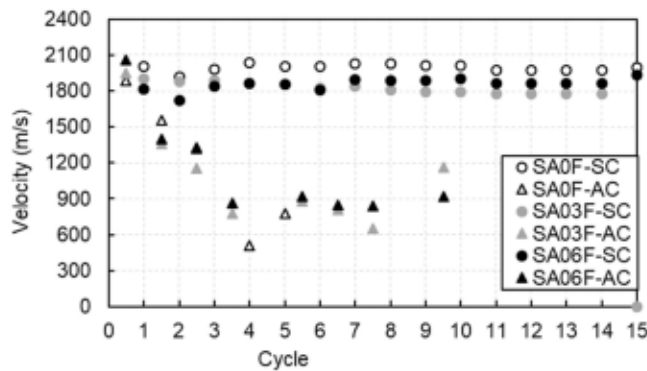


Fig. 7. Evolution of the propagation velocity of the ultrasonic waves during wetting/drying cycles compared to the velocity of reference specimens.

respectively. The degradation evolves with the number of cycles. Visible cracks are detected with surface flaking mainly for specimens without fibers. The cracks start to appear in the 2nd cycle for SA0F and propagate quickly over the entire surface of earth concrete, inducing a progressive loss of the concrete's surface layer and flaking from the 6th cycle. In fact, during drying, the water present in the pores evaporates, inducing suction forces. The negative pressure triggered in the pores causes the rearrangement and brings together the grains. When the tensile stress is equal to the cohesive attraction force between the particles, cracks will be formed [44,47–49,106]. After each cycle, the primary cracks increase in size and new cracks form until the cracks intersect. The external surfaces of earth concrete specimens are more affected because of the gradient deformation due to the faster loss of water at the surface than inside the sample considering the drying kinetics. Hence, flaking appeared on the surface. Note here that flaking might be also related to salt crystallization. Salt crystallization is due to potential chemical interaction between salt ions and hydrated cement [107,108]. During the wetting phase, small cracks can be healed but develop again during drying [44]. For mixtures with 0.3 % and 0.6 % of flax fibers, cracks begin to develop after the 8th cycle and the 20th cycle. However, no significant loss has been observed at the surface of earth concrete specimens. The slow degradation of fiber-reinforced earth concrete specimens can be associated with better-cracking resistance. The adhesion between the matrix and the fibers limits the propagation of cracks [106,109]. In fact, the fibers act as a reinforcement, providing additional tensile strength and resistance to cracking [64] which helps maintaining the structural integrity of the earthen concrete during cycles. Additionally, the fibers may interact with the soil in a way that enhances the overall durability of the material by improving the bonding and altering the microstructure of the material making it more resistant [22]. On the other hand, the fibers also degrade during the cycles. In fact, the degradability of natural fibers in certain environments has been a significant limitation [110]. The results of this investigation indicate that the wetting-drying cycles can lead to the degradation of flax fibers, which in turn affects the cohesion between the fibers and the earth concrete matrix [84]. In fact, during the wetting stage, flax fibers absorb water and swell but, during drying, the volume of the fiber's decreases, inducing voids and thus degrading the interface [85,111]. A comparative study examining the biodegradability of different natural fibers, such as flax, cotton, and ramie, found that flax fibers degrade most rapidly when buried in soil [112]. This suggests that flax fibers are highly susceptible to environmental stressors, such as wetting-drying cycles, which contribute to their accelerated degradation. Thus, understanding the long-term behavior of natural fibers is important to optimize the design and performance of earth concrete structures [113–115]. The findings from these studies suggest that the degradation of natural fibers can occur through two primary mechanisms: alkaline attack and fiber mineralization [116]. When natural fibers are in contact with an alkaline cementitious matrix, they can start to degrade, leading to a

reduction in the mechanical properties of the composite material [116]. To address this issue, researchers have explored various strategies to enhance the durability of natural fiber composites. Surface modifications of natural fibers, such as alkaline treatment, silane coupling, or acetylation, have been investigated to improve the interfacial adhesion between the fibers and the matrix [31,117,118].

### 3.2.2. Evolution of the propagation velocity

Fig. 7 presents the evolution of the propagation velocity of the ultrasonic waves after the wetting phase during the cycles in comparison with that of the reference specimens stored at 20 °C and 90 % relative humidity. The speed at the age of 28 days is equal to 2006 m/s and decreases with the addition of fibers to 1900 m/s for SA03F and 1800 m/s for SA06F which may be due to the low density of fibers and the higher porosity for specimens containing flax fibers [119,120]. This velocity remains almost stable for the reference specimens while it decreases during wetting/drying cycles indicating the degradation of earth concrete. The velocity decreases significantly during the first 4 cycles to almost half and continues to decrease slowly. The increase in ultrasonic velocity observed in the 10th cycle of wetting-drying cycles of earth concrete with 0.3 and 0.6 percent of flax fibers can be attributed to several factors. One possible explanation is the progressive densification of the concrete matrix due to the repeated cycles of wetting and drying. During the wetting phase, the fibers may absorb water, causing swelling and better integration with the surrounding concrete matrix. As the concrete dries, the matrix may become more compact, resulting in a higher ultrasonic velocity. The velocity measurement was not possible after the 5th cycle for SA0F and after the 9th cycle for SA03F and SA06F. Indeed, the propagation of large discontinuities or cracks in the material more particularly for SA0F prevents the propagation of ultrasonic waves from one sensor to another, severely hampering the measurements. This indicates that SA0F specimens are more affected by the drying-wetting cycles and thus damaged earlier. These results are consistent with the degradation observed on the different faces of earth concrete specimens (Fig. 6) and indicate the presence of through cracks and not only on the surface of the material.

Note that the ultrasonic pulse velocity can be correlated to the elastic properties and strength of concrete. This later can be affected and disturbed by obstacles that can be present in concrete, such as cracks and porosity [121]. The dynamic Young's modulus has not been calculated to uncertainties concerning the value of Poisson's ratio. The ultrasonic pulse velocity is also affected by the moisture content of concrete. It is higher in water-saturated concrete than in dry concrete [121,122]. Therefore, the ultrasonic pulse velocity depends on the change in proportion between solid, liquid, and gaseous phases, as well as the increase in elasticity modulus related to particle interaction bonds. The rate of degradation is a key factor in the durability and longevity of earth concrete structures [123]. The addition of flax fibers to earth concrete resulted in differing degradation rates compared to specimens without fibers. The observed differences in degradation rates between earth concrete specimens with and without flax fibers can be related to different mechanisms such as the different porosimetry that might affect the shrinkage rate during the wetting drying cycles. In fact, the material contracts with water movements with a surface water gradient. Micro-cracks are induced by the water imbalance between the core of the material and the environment, generating tensile stresses at the surface of the material and compression at the core. Additionally, there are micro-cracks due to fiber and matrix incompatibility that are influenced by the fiber fraction. Fibers will reduce the propagation of macrocracks due to different stress redistribution and improvement of tensile strength which enhances the overall durability of the material. In addition, the interaction between the natural fibers and the matrix is complex. The strength of the bond between the flax fibers and the earth concrete matrix can influence the fibers' ability to effectively transfer stress and mitigate crack propagation. Variations in the surface characteristics of the fibers, such as roughness or chemical modifications,

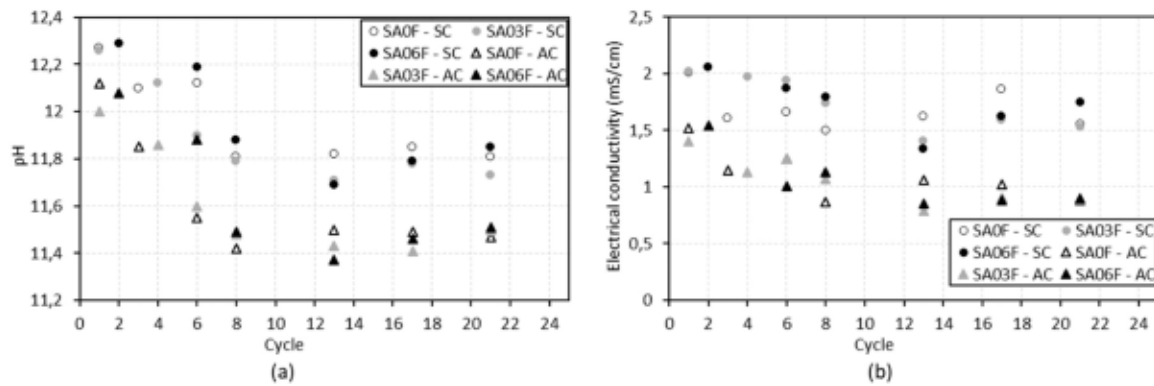


Fig. 8. Evolution of the pH and the EC during wetting/drying cycles and comparison with the values of reference specimens.

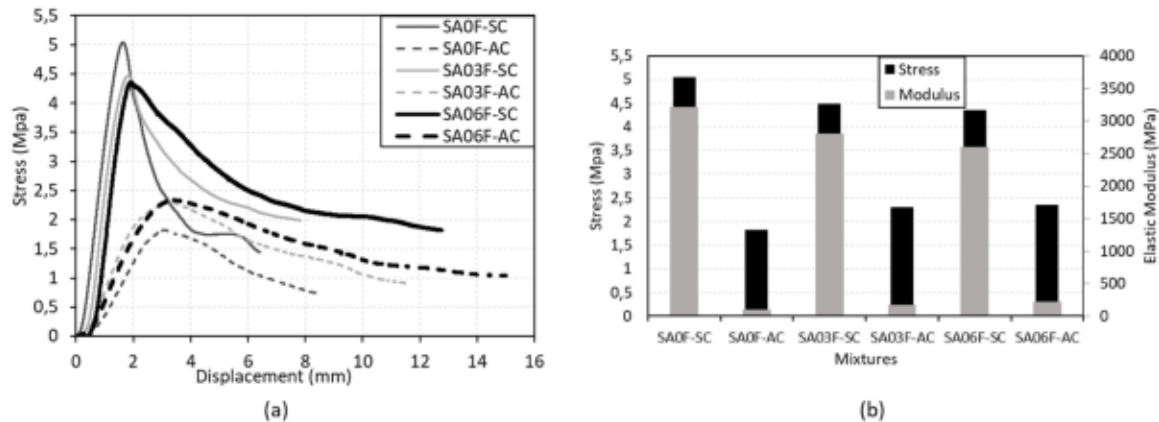


Fig. 9. Effect of wetting/drying cycles on stress/displacement curves (a) and on the maximal compressive strength and Young's modulus (b) for SA0F, SA03F, and SA06F.

may impact the adhesion and, consequently, the degradation resistance of the composite [22]. The inherent durability of the flax fibers themselves, which can be affected by environmental factors such as moisture, alkalinity, and UV exposure, may play a role in the long-term performance of the earth concrete composite [22]. The inclusion of flax fibers may alter the microstructure of the earth concrete, leading to changes in the pore structure, density, and overall homogeneity of the material. These microstructural changes can potentially influence the susceptibility to degradation processes. Studies on the effects of macrosynthetic fibers on pervious concrete have found that the fibers can reduce permeability and infiltration rate while improving freeze-thaw durability and surface abrasion resistance [84].

### 3.2.3. Evolution of pH and electrical conductivity

Fig. 8 presents the evolution of pH and EC during wetting/drying cycles and the comparison with the reference specimens. A decrease in the pH values was observed with the cycles. The pH allows us to monitor the chemical reactions between clay and hydraulic binders [124] as it is related to the measurement of the concentration of OH<sup>-</sup> hydroxyls in the solution. Thus, the decrease in pH is related to the decrease in the OH<sup>-</sup> concentration. The presence of cement and lime promotes the attack of clay layers and releases silicates and aluminates. Hydroxyls and calcium Ca<sup>2+</sup> are consumed to form new binding bridges or calcium hydrates CSH and/or CASH [44,125]. The consumption of the ions present in the solution by the pozzolanic reactions results in the decrease of the EC values over time [124]. It should be noted that the wetting/drying cycles were performed at the age of 28 days during which the hydration of cement and the cation exchange took place as well as the start of the phase of pozzolanic reactions [124]. The pH and EC values of the specimens exposed to wetting/drying cycles were lower than those of

the reference specimens from the first cycle. This decrease continues in function of the number of cycles, which can be attributed to the leaching of a certain quantity of alkaline substances from earth concrete or/and the evolution of pozzolanic reactions which require the consumption of OH<sup>-</sup> ions [126,127].

### 3.3. Effect of wetting/drying cycles on fracture behavior

Fig. 9 presents (a) the stress/displacement curves and (b) the maximum compressive strength of specimens subjected to 25 wetting/drying cycles and reference specimens at the same age. The compressive strength decreased sharply after 25 cycles with a rate of 63 % for SA0F, 48 % for SA03F, and 46 % for SA06F. A notable decrease in the elastic modulus was also observed due to the degradation of earth concrete subjected to cycles as observed by the velocity of the ultrasonic waves.

#### 3.3.1. Digital image correlation analysis

Fig. 10 shows the evolution of the 2D deformation field along x for SA0F, SA03F, and SA06F specimens subjected to wetting/drying cycles and reference specimens at different loading levels. For specimens subjected to cycles, cracks started to propagate at low loading levels in comparison with reference specimens. For SA0F-AC, a large macro crack was observed on the surface of the specimen around 50 % of the maximum load. Specimens containing flax fibers exposed to cycles also exhibited a well-developed macro-crack around 90 % of the maximum load. This confirms the degradation of specimens during the cycles. For the same loading level, the deformation is greater for specimens exposed to wetting/drying cycles indicating a greater fragility. For instance, the crack area has been found to reflect the stress drop of a concrete specimen under compressive loading. Note that for specimens containing

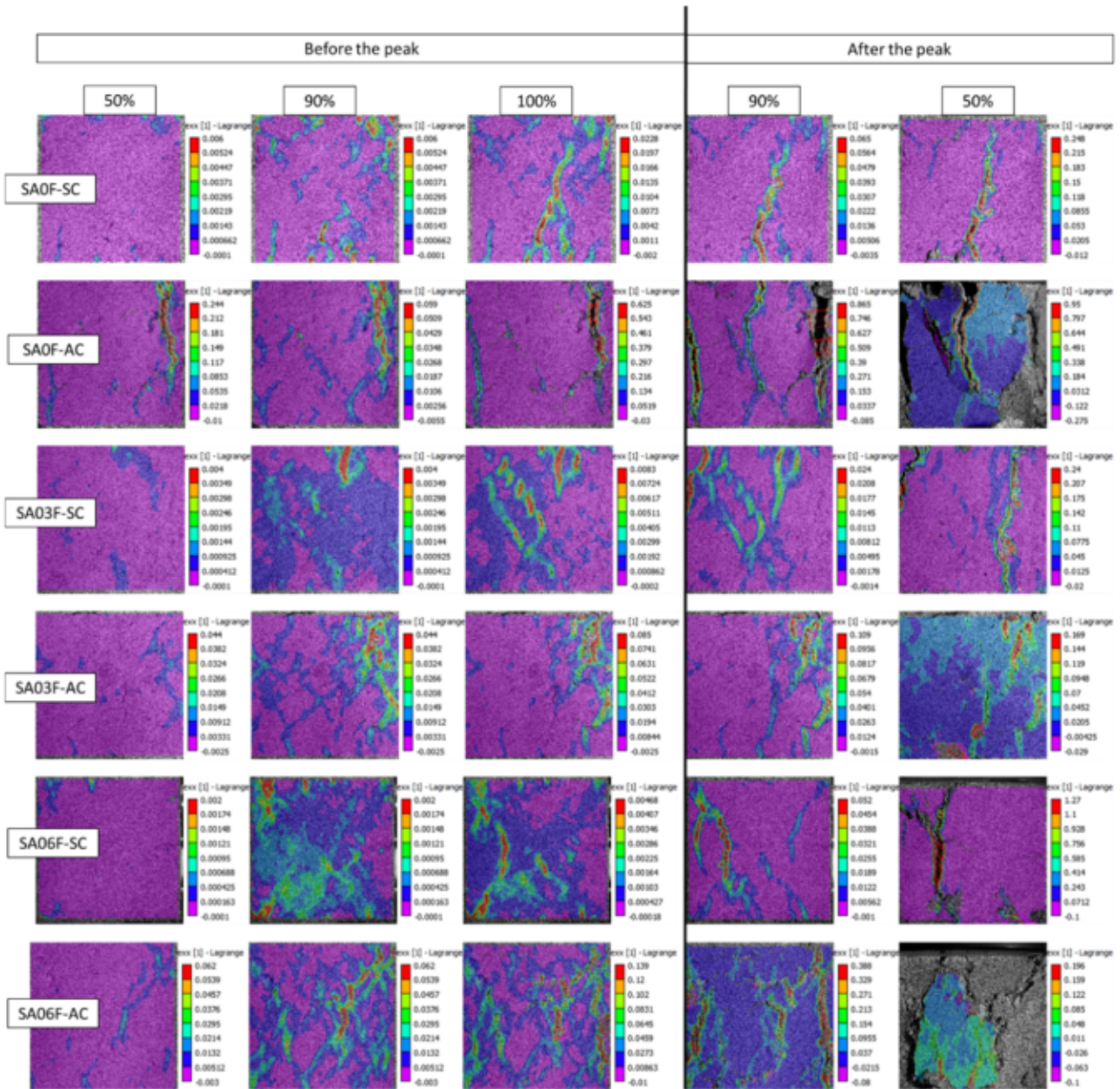


Fig. 10. Strain fields along X of SA0F, SA03F, and SA06F for reference specimens (SC) and specimens subjected to 25 wetting/drying cycles (AC).

fibers, the cohesion between the fibers and the matrix decreases due to the strain gradient during the shrinkage and swelling of the fibers during the cycles as well as the degradation of the fibers [128,129]. The spaces between the fibers and the matrix reduce the area of contact and decrease the adhesion resulting in a reduction of the frictional pull-out force and bridging. In addition, the tensile strength of the fibers decreases significantly following wetting/ drying cycles. Filho et al. [42] found that the degradation process of sisal fibers occurs very quickly when immersed in alkaline solutions and calcium hydroxide solutions. The original strength was completely lost after 300 days of immersion in a calcium hydroxide solution. The cell walls of fibers are damaged by mineralization, i.e. the migration of hydration products mainly ( $\text{Ca}(\text{OH})_2$ ) to the structure of the fibers and crystallization of lime in the fibers pores. A sharp decrease in the flexural strength was thus observed after 10 wetting/drying cycles.

### 3.3.2. Acoustic emission activity analysis

Fig. 11 presents the correlation between stress and the cumulative

number of acoustic emission signals during compression tests for SA0F, SA03F, and SA06F exposed or not to wetting/drying cycles. For reference specimens, the acoustic activity is very low in the elastic phase and increases very slowly in the non-linear phase (before the peak) with low amplitude signals indicating the start of the development of microcracks. The rate of acoustic activity increases after the peak indicating the propagation of cracks in the specimens. It is important to note here that the acoustic activity increases with the percentage of fibers indicating additional and different damage mechanisms such as microcracks at the matrix/fiber interfaces, bridging, and friction ...

The evolution of the acoustic activity during loading is different for specimens exposed to cycles (Figure 12). The acoustic activity increases at a significant rate from the start of the test for the three mixtures with the release of energetic signals indicating the absence of the elastic phase and the evolution of the damage even for low loading levels. Unlike reference specimens, the rate of acoustic activity decreases as they approach the peak and stabilizes after, indicating that the specimens have ruptured before the peak. The cumulative number of AE

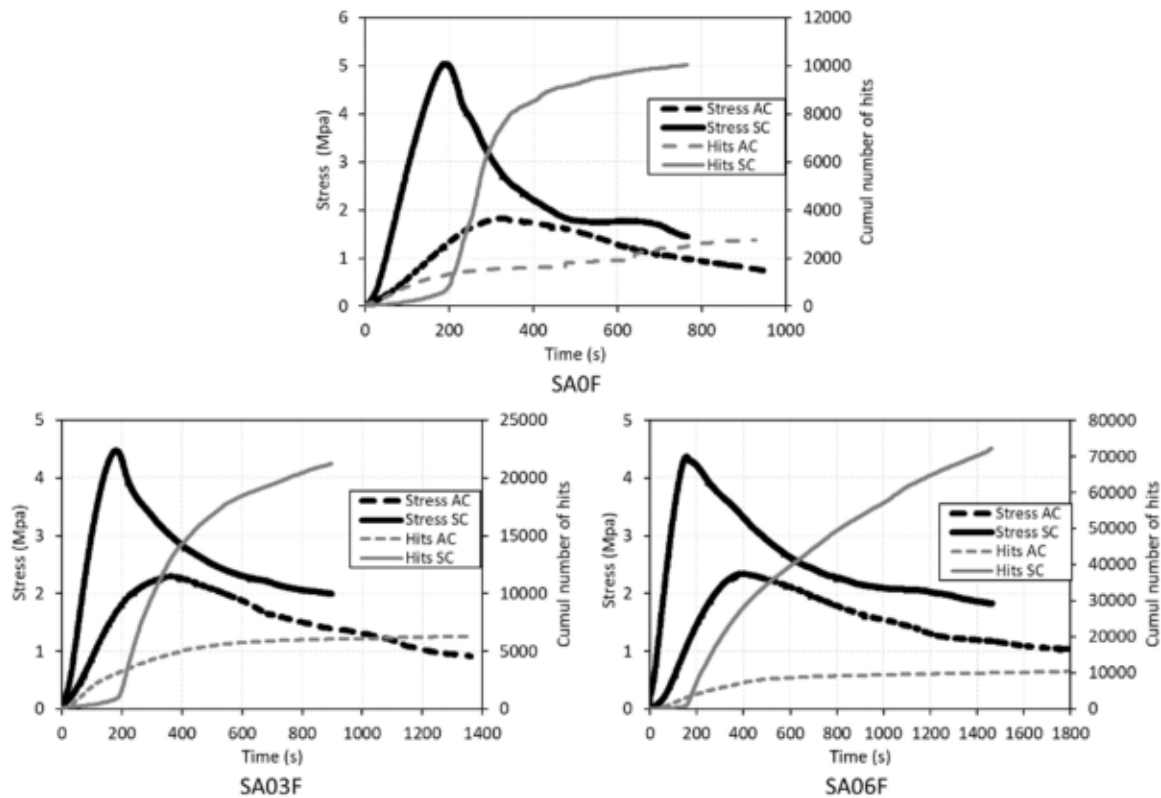


Fig. 11. Correlation between the stress and the cumulative number of AE hits for SAOF, SA03F, and SA06F reference specimens (SC) and specimens subjected to 25 wetting/drying cycles (AC).

signals is also greater for specimens with a higher percentage of fibers. On the other hand, the cumulative number of AE signals is much less important for specimens exposed to cycles, which may be related to the reduction in resistance as well as to the degradation of the fibers and the fibers/matrix interface. In addition, the amplitudes of the AE signals are significant at the beginning of the test and decrease after the peak, unlike the reference specimens. This may be due to the degradation of flax fibers during cycles. The presence of fibers in an alkaline environment causes their mineralization due to the migration of hydration products, in particular calcium hydroxide, towards the cell walls specifically the lumen, the walls, and voids in the fibers [130,131,132]. This is responsible for the breakdown of lignin. In addition, internal hemicelluloses easily undergo alkaline hydrolysis, which leads to the elimination of cellulose microfibrils [131]. Hence, for reference specimens, the fibers provided the connection in the post-peak part with a stretched rupture of the fibers, thus increasing the ductility; while for the specimens subjected to cycles, the fibers were easily broken at the rupture with a brittle behavior.

#### 4. Conclusions

The durability of earth concrete with and without flax fibers considering wetting/drying cycles has been studied. The conducted tests such as the visual, ultrasonic and mechanical tests results showed that the addition of flax fibers slows down the degradation of earthen concrete during cycles. In fact, fibers act as a reinforcement and can inhibit the initiation and propagation of cracks by providing additional tensile strength, which is particularly important for maintaining the structural integrity of the earthen concrete during cycles. In addition, the fibers may interact with the soil in a way that enhances the overall durability of the material by improving the bonding and altering the microstructure of the material making it more resistant. The findings from the study are as follows:

- The capillary absorption of earth concrete is very high due to the presence of bentonite and increases with the addition of fibers due to their hydrophilic property
- The pH and EC values of the specimens exposed to wetting/drying cycles decreased due to the leaching of alkaline substances or/and the evolution of pozzolanic reactions.
- The velocity of the ultrasonic waves decreases during the cycles with a visual degradation of the concrete.
- The addition of flax fibers slows down the degradation of earthen concrete during cycles.
- The compressive strength and Young's modulus decreased sharply after 25 wetting/drying cycles.
- The study demonstrated the ability of the AE technique to estimate the amount of energy released during the fracture process and to obtain information on the criticality of ongoing processes within these structures. Significant acoustic activity was detected before the peak for the specimens subjected to cycles.
- The crack area obtained by DIC, AE magnitude, and AE energy release occur nearly simultaneously, suggesting a strong correlation between these parameters.

Comprehensive studies examining the fiber-matrix interactions, fiber durability, and the resulting microstructural changes within the earth concrete composites would provide valuable insights to optimize the performance and long-term stability of these sustainable construction materials. Additional tests at the microscopic level as SEM observations will be carried out in the future for a better understanding of the degradation mechanisms and hydration parameters. In addition, different surface treatment techniques such as alkaline treatments will be tested to reduce the hydrophilicity and improve fiber/matrix compatibility. The classification of AE signals for specimens with and without wetting/drying cycles will also be realized to distinguish between the different damage mechanisms. A comprehensive evaluation

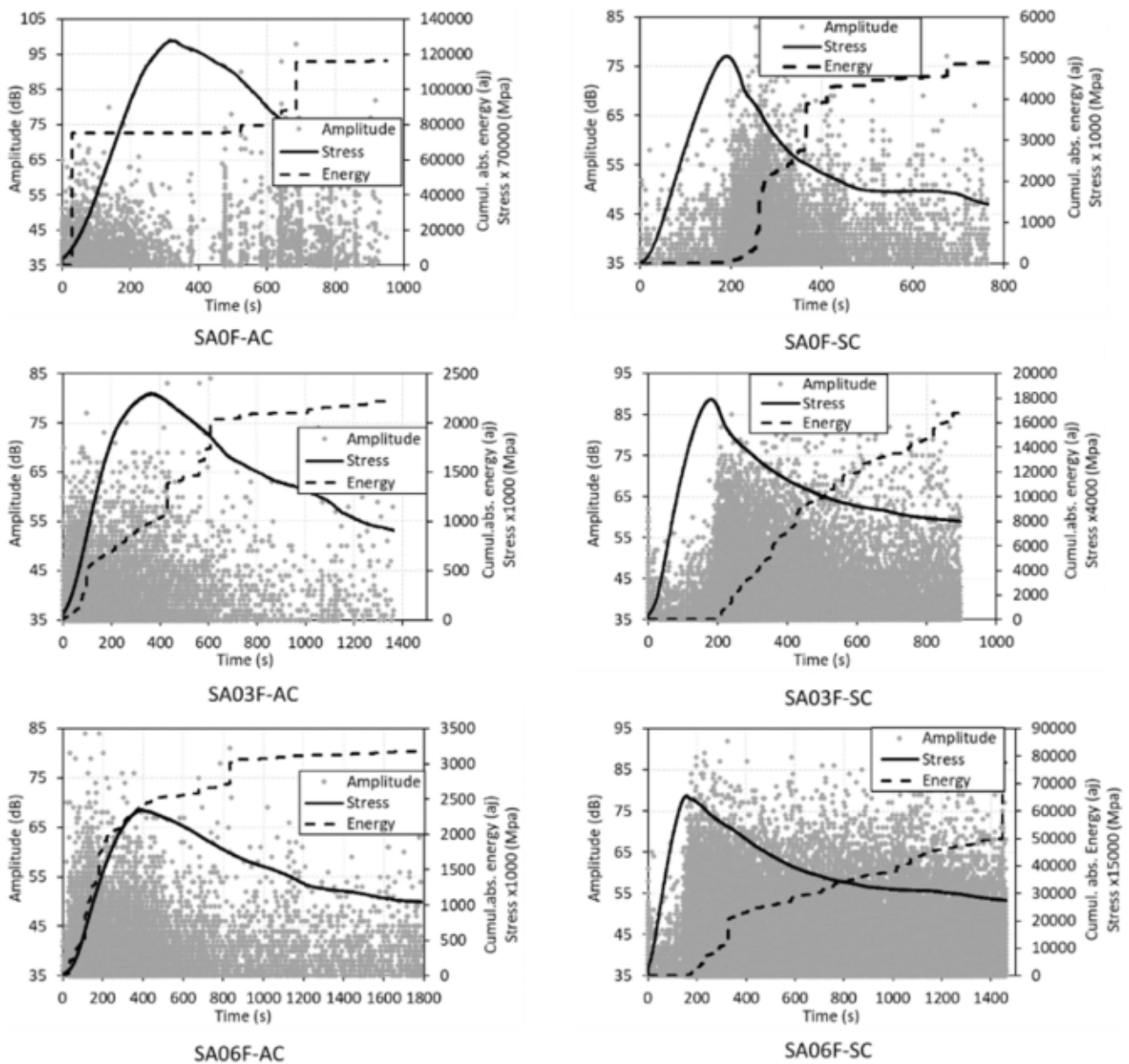


Fig. 12. Correlation between stress, cumulative absolute energy, and AE signal amplitude for SA0F, SA03F, and SA06F reference specimens (SC) and specimens subjected to 25 wetting/drying cycles (AC).

will be also realized to provide a clear understanding of earth concrete's true environmental impact.

#### CRediT authorship contribution statement

**Nathalie Kouta:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jacqueline Saliba:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Nadia Saiyouri:** Validation, Supervision, Resources, Project administration.

#### Declaration of Competing Interest

The authors declare no conflict of interest

#### Data availability

Data will be made available on request.

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