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Mechanical behavior of cement composites reinforced by aligned Enset fibers

Markos Tsegaye Beyene [*,a,b], Michael El Kadi [a], Tamene Adugna Demissie [b], Danny Van Hemelrijck [a], Tine Tysmans [a]

[a] Vrije Universiteit Brussel (VUB), Department of Mechanics of Materials and Constructions (MeMC), Pleinlaan 2, 1050 Brussels, Belgium
[b] Jimma University, Jimma Institute of Technology, Faculty of Civil and Environmental Engineering, Jimma, Ethiopia

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ABSTRACT

Driven by the search towards new materials with reduced ecological impact, several investigations on plant-based natural fibers for composite reinforcement have been undertaken by researchers in the past decades. However, Ensete Ventricosum (Ev) fiber as reinforcement in a cementitious matrix has not yet been studied. This research aims to assess the mechanical performance of aligned Ev fiber reinforced cementitious composites and particularly the influence of the fiber volume fraction on the flexural performance of the composite. Four different fiber content ratios (from 3 % up to 6 %) were compared to plain mortar specimens. Not only the flexural load–displacement but also the cracking behavior was studied in depth utilizing the optical Digital Image Correlation (DIC) technique. The developed material presented multiple cracking behavior under bending. The post-cracking stiffness, toughness and flexural strength of Ev fiber reinforced specimens were increased with higher fiber content: 3 %, 4 % and 5 % fiber content resulted in a strength increase of 260 %, 274 % and 396 %, respectively, compared to that of the reference mortar specimen. These results are promising for the development of a Ev fiber-based green composite.

1. Introduction

A shift to a bio-based economy is a high political priority on both the national and the international level [1]. Bio-based economy and sustainable developments after the Kyoto protocols on greenhouse gas (GHG) reduction and CO2 neutral production offers high prospects for natural fiber markets [2,3]. Bio-based economies use renewable bio-resources, like natural fibers, which are an eco-efficient product that contributes to reductions in GHG emission [4]. Non-biobased resources like man-made fibers release carbon dioxides into the atmosphere, some of which take thousands of years to be processed naturally [5]. Natural fiber reinforced products have shown recycling capability and generated biodegradability under controlled conditions after a defined lifetime, which makes them a sustainable option for composite productions. The biodegradability of natural fibers is due to organisms that have specific enzyme systems to hydrolyze carbohydrate from the cell wall into digestible units [6].

There are three types of natural fibers available for concrete reinforcement: animal-based, mineral-derived and plant-based. Animal fibers, which comprise specific proteins, include silk, wool and hair fiber. Mineral-derived fibers include asbestos, wollastonite and palygorskite. Finally, plant-based fibers include cotton, hemp, jute, flax, ramie, sisal, bagasse, specialty fibers processed from wood, etc. [7]. Natural fibers exhibit a set of essential advantages, such as wide availability at relatively low cost, bio-renewability, a wide variety of morphologies, ability to be recycled, biodegradability, non-hazardous nature and interesting physical and mechanical properties (low density and well-balanced stiffness, toughness and strength) [8,9]. Although brittle building materials have been reinforced with vegetable fibers since ancient times, the concept of natural fiber reinforcement in cement-based materials was developed in the 1940 s when these fibers were evaluated as potential substitutes for asbestos fibers [10]. Since then, significant efforts have been made towards the application of natural fibers as a reinforcing material to produce building components at a low cost.

Among natural fibers, the Ensete ventricosum (false banana) fiber is one of the most used in East Africa, Asia and North America. Ethiopia is one of the biggest producers [11]. The Ensete plant does not bear edible

* Corresponding author. Tel.: +251911853002.
E-mail addresses: Markos.Tsegaye.Beyene@vub.be, markos.beyene@ju.edu.et (M. Tsegaye Beyene).

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fruits and is not categorized as customary banana plant (genera Musa) [12,13]. Some studies on the mechanical properties of Ensete fibers have been published [14–17]. Also, several investigations on plant-based natural fiber reinforced cement composites have been undertaken by researchers in the past decades, using e.g. flax, cellulose, jute, hemp, kenaf, sisal, coir and bamboo [18–25]. However, there is no literature on the mechanical performance of aligned Ensete fiber reinforced cementitious composites.

Nadzri et al. [26] investigated the use of coconut fiber as reinforcement in cement composites production; 9 wt% coconut fiber composites gave better mechanical properties compared to 3 wt%, 6 wt%, 12 wt% and 15 wt%. Hakamy et al. [27] reported that the addition of a two-layer hemp fabric containing about 2.5 wt% fibers to plain cement paste increased the flexural strength from 5.18 to 6.87 MPa and the fracture toughness from 0.356 to 0.656 MPa.m$^{1/2}$. Sedan et al. [28] also examined the behavior of hemp fibers in a cement matrix. They concluded that for a composite containing 16 vol% of fibers, the flexural strength was maximal and about 40 % higher than that of the cement paste.

Several authors also focused on the beneficial properties of plant-based fiber reinforced mortars for impact loading. Ramakrishna and Sundararajan [29] concluded that plant-based fiber reinforced mortar slabs' impact resistance was 3–18 times higher than that of the unreinforced slabs. The impact resistance of all the slabs increased as the volume fraction and length of the reinforcing fibers increased. Fujiyama et al. [30] studied the mechanical behavior of sisal fiber reinforced cement mortar and concluded that the presence of sisal fibers in cement mortar considerably improved the fracture resistance and impact energy.

Most works on cellulose cement composites are based on short fibers; however, Toledo Filho and coworkers have analyzed composites' mechanical properties reinforced with long natural fibers [31]. De Andrade Silva et al. [32,33] studied the flexural static and impact strength of long, aligned unidirectional sisal fiber reinforced cement composites. This composite system presented improved strength and ductility that was primarily governed by the composite action when fibers bridge the cracks to transfer the loads, allowing a disseminated microcrack system to develop. A comparison with AR glass fabric-reinforced composites indicated that sisal fiber reinforced cement composites present a more ductile behavior under impact loads [32]. The authors also found that the corrugation of the flat sheets increased their ultimate bending load by about 260 % and the developed material presented multiple cracking behavior under bending, even after being subjected to 6 months of hot-water immersion at 60 °C [33]. These continuous fiber reinforced cement-based composites are a new class of sustainable construction materials with superior tensile strength and ductility [33], sufficient to be used as load-bearing structural members in applications such as impact-resisting panels, repair and retrofit, earthquake remediation, strengthening of unreinforced masonry walls and beam-column connections [34,35].

The study reported in this paper intended to investigate the mechanical behavior of aligned Enset ventricosum (Ev) fibers in a cement matrix. To the best of the author's knowledge, research on Ensete fibers in terms of aligned fibers as a reinforcement in a cementitious matrix is inexistent. Previously published scientific work explicitly focused on short Ensete fibers dealing with chemical and physical properties [11,36]. One of the most essential considerations using aligned natural fibers in loadbearing applications is the effect of their content on the mechanical performance of the composite. To characterize the newly developed material, Ev fiber reinforced specimens having 0 %, 3 %, 4 %, 5 % and 6 % fiber volume content were investigated. For each alternative, six specimens were produced and tested under a four-point bending configuration. To measure strains and displacements and to visualize cracks, Digital Image Correlation (DIC) was used [37]. This full-field optical measurement technique allowed us to have a complete view of the strain field on the surface of the specimens.

The mechanical properties of natural fiber cementitious composites are largely dependent on the bond between the cement matrix and the fiber which in turn depends on factors like fiber type, surface characteristics, chemical composition, orientation, treatment, content of fibers and also the additives in the cement mixture. Poor interfacial bonding between natural fibers and cementitious matrix is often due to swelling of the fibers due to water absorption from the wet mix and following shrinkage upon drying [38]. The interfacial bonding between natural fibers and cement matrix can be improved by reducing the voids that could be left between the fiber and the matrix during composite manufacturing. This could be attained by using methods like a vibrating table to compact cement mortars during specimen manufacturing and pre-treatment of natural fiber with tap water. Soaking of fibers with tap water could cleanse soluble substances from natural fibers. Certain water-soluble substances can affect the hydration reactions of cements, impairing adhesion [39,40]. The pre-soaking of the fibers is therefore an additional parameter studied in this paper, for all tested fiber volume fractions up to 5 %.

2. Material and methods

2.1. Material characteristics

The investigation was performed on 30 specimens: samples were considered with increasing fiber volume fraction (0 %, 3 %, 4 %, 5 % and 6 %) and for each fiber content, six specimens were tested. The material properties of both the mortar and the natural fibers are described below.

2.1.1. Ensete ventricosum (Ev) fibers

The Ensete ventricosum (Ev) fibers (Fig. 1 (a)) used in this research were obtained from the Jimma Zone in Ethiopia. The Ev fibers were manually decorticated and sun-dried without any prior treatment. The Ev fibers had a rough surface, white color and an irregular cross-section (Fig. 1 (d)). Typically, the fiber's diameter distribution data is used to estimate its cross-sectional area, assuming a circularly shaped cross-section [41]. As previous research has shown, however, direct diameter measurement on sisal/flax fiber results in an erroneous calculation of the fiber cross-sectional area, which translates into a questionable estimation of the fiber's mechanical properties [42]. Therefore, considering a non-circular fiber's cross-section, the cross-sectional area of the fibers was determined using a Leica DMi8 Fully customizable microscope and epoxy cold setting resin with SIC FOIL #4000 paper (Fig. 1 (b) and (c)); the cross-sectional area and thickness are averages from ImageJ software. The determined cross-sectional area and the Ev fibers' diameter were 0.014 ± 0.004 mm^2 and 0.14 ± 0.003 mm, respectively. To determine the single Ev fiber tensile strength, an electromechanical loading bench Instron 5885 equipped with a load cell of 50 N was used. Ev fibers were tied precisely on the edge of the upper and lower fiber grips, the gauge length was $L_0 = 300$ mm. The fibers were tested up to fiber breakage with a tension speed of 2 mm/min. The experiment was repeated fifty-two times with randomly selected fibers. The test was done using ASTM D3822-01 [43]. The average tensile strength and tensile Young's modulus obtained was of 587 ± 85 MPa and 27 ± 3 GPa, respectively, which were found to be in line with previous literature studies [12,16,36,44].

According to [12,36,45], the chemical composition of the Enset fibers ranges from, 56.5–64.5 % cellulose, 14.3–24.4 % hemicellulose, 2.2–10.5 % acid-insoluble lignin, 1.0–4.6 % ash and 0.5–4.4 % solvent extractives.

2.1.2. Matrix

For the matrix, an Ordinary Portland Cement-based, fine-grained and self-compacting mortar was selected [46]. The main requirement for the choice of the cementitious matrix was its pourability to impregnate the fibers easily. The chosen matrix is the commercially available SIKAGROUT 217, which contains Ordinary Portland Cement, siliceous sand and admixtures. The water to mortar ratio was 0.15 L per kilogram, the

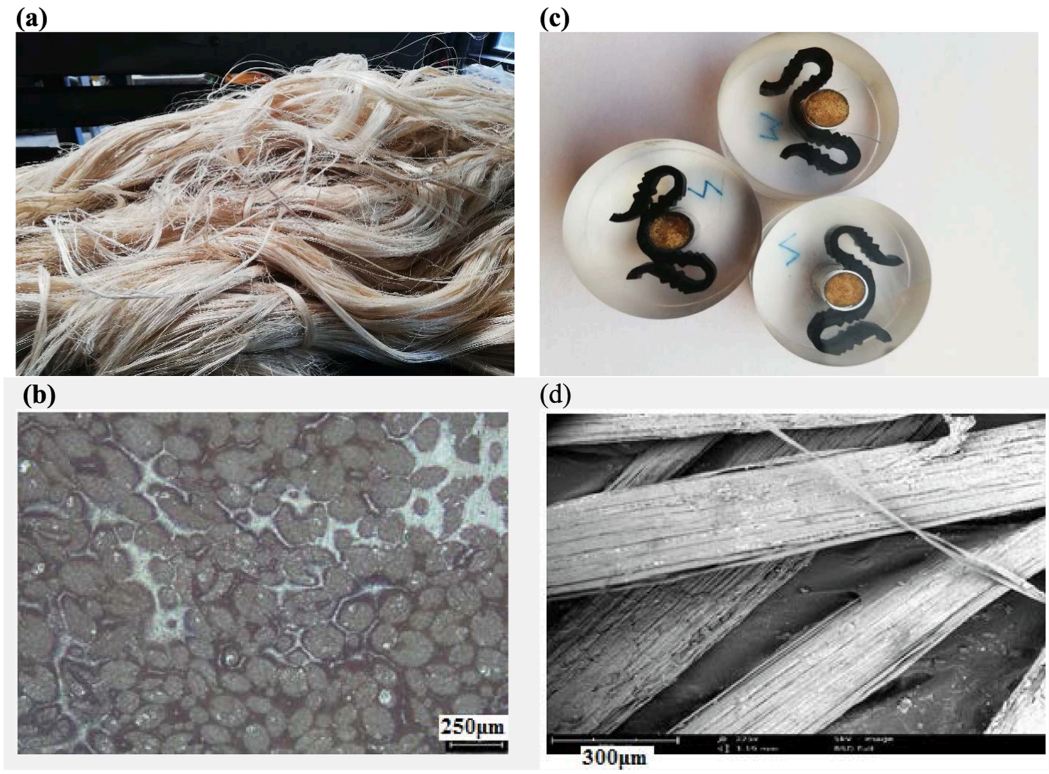

Fig. 1. (a) Enset (Ev) fiber bundles, (b) An optical microscope cross-sectional observation (scale bar 250 μm), (c) Ev fibers imbedded in Epoxy and (d) SEM Surface observation (scale bar 300 μm).

properties are summarized in Table 1.

2.1.3. *Specimen manufacturing*

The specimen dimensions were 450 mm × 60 mm × 22 mm. The Ev fiber reinforced composites were manufactured by integrating one layer of Ev fibers aligned longitudinally, resulting in a fiber volume fraction of 0 %, 3 %, 4 %, 5 % and 6 %, depending on the amount of added fibers. The centerline of the fiber layer was 5 mm from the bottom of the sample. However, the specimens with more fiber content had a thicker fiber layer and therefore, the cover thickness was slightly different from 5 mm. The Ev fiber reinforcement for half of the specimens of 3 %, 4 % and 5 % was therefore soaked for 48 h in tap water, after which the fibers were dried for 4 h at room temperature before application in the cementitious matrix, however, 6% were not soaked before introducing the fiber in the matrix. The reason was, as the fiber content increased, the fiber thickness that would be introduced in the composite also increased which affected the workability and the impregnation of the fibers. The water absorption of Ev fibers was measured after treatment by weighing the dry fiber and then after 48hr, soaked fiber was measured after wiping away water from the surface, a precise 4-digit balance was used to find out the content of water absorbed. The water absorption of the Ev fiber samples was 164 ± 16 %. The condition under which non-presoaked Ev fibers were introduced in the cement matrix was dry under the standard laboratory environment.

Fig. 2 shows the manufacturing process of the composite specimens. Before the matrix preparation, oil was applied carefully to the mold surface, the fibers were cut at 490 mm length, weighed and separated (Fig. 2 (a)). The matrix was produced using a bench-mounted mechanical mixer with a capacity of 20 L. The 5 mm thickness mortar cover layer was poured at the bottom of the mold (Fig. 2 (c)). Then, a layer of aligned fibers was placed on top of this mortar layer (Fig. 2 (d)). During fiber layup, the position of the centerline of the fibers was kept constant with respect to the specimen's cross-sectional height. The exact location and alignment of the fibers were controlled by first straightening the fibers (by manual tension) and then fixing the fibers at the edges of the mold by screws. Finally, the rest of the mold was filled with mortar (Fig. 2 (e)). A vibrating table was used to allow the mortar to penetrate the fiber layer fully. Once the mold was filled, the excess of mortar was removed using a flattening ruler and the mold was covered with a stiff plastic foil and sealed off. The composites were left to harden for 28 days at room temperature. Afterward, a speckle pattern was painted on the beam's side surface (Fig. 2 (f)) and used for DIC monitoring.

Table 1
Properties of the cementitious matrix [46].

Property	Unit	Value
Aggregate size	mm	0 – 1.6
Compressive strength (After 28 days)	[MPa]	70
Flexural strength (After 28 days)	[MPa]	12
Density after mixing	[kg/m^3]	2010.49 [47]

2.2. *Experimental test setup*

Four-point bending tests on the specimens were conducted using an Instron 5885 test bench under a controlled crosshead speed of 2 mm/min. The distance between the supports and loading pins was 350 mm and 100 mm, respectively (see Fig. 3 (a)).

A speckle pattern was applied on the specimen's side surface over the full measuring length (see Fig. 2 (f)). DIC was used to monitor the specimens' side view and to obtain vertical displacements and crack opening (see section 2.3). The reaction force was directly obtained from the loading bench, while the vertical displacement and strains were obtained from the DIC monitoring technique.

2.3. *Digital Image Correlation (DIC)*

DIC is a full field, a non-contact optical technique to measure contour, deformation, vibration and strain on almost any material or

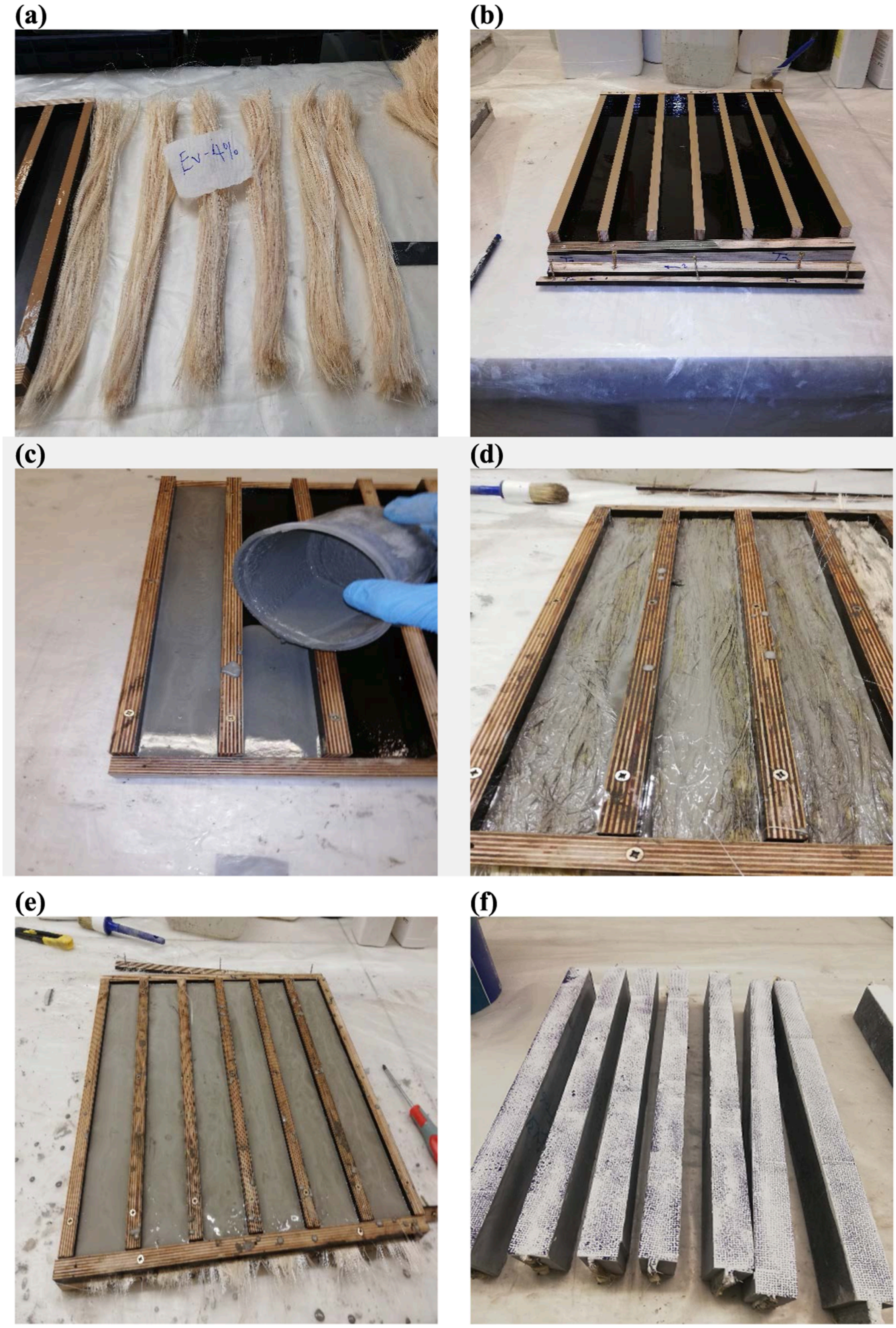

Fig. 2. Ev fiber cement composite manufacturing process : (a) weighed fraction of Ev fiber, (b) 450 mm × 60 mm × 22 mm mold, (c) placement of the first matrix layer (5 mm), (d) fibers were straightened and fixed at the edges of the mold, (e) covering the remaining layer with mortar until the full depth of the specimens, (f) hardened specimens with painted speckle pattern.

geometry. In this research, DIC was used to monitor the strain field of the specimen's side surface and to analyze crack formation (see Fig. 3 (b)).

The strains can be derived from an array of displacement measurements; the size of this array is called the filter size. The settings of the DIC analysis, done with the commercial software Vic 3D, are specified in Table 2. The features of the used cameras are listed in Table 3. A more extensive description of the working principle of DIC can be found in the literature [37].

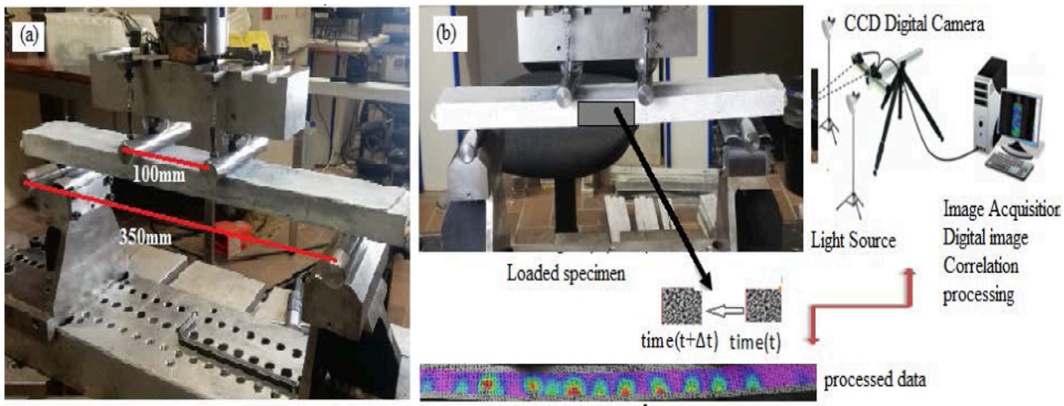

Fig. 3. (a) Four-point bending test setup, (b) DIC equipment ().
adapted from [48]

Table 2
Settings DIC analysis.

Subset (pxs)	21
Step (pxs)	7
Filter size (-)	11
Area of interest (mm X mm)	350 X 22

Table 3
Camera features [48].

Type of camera	CCD
Lens size (mm)	17
Resolution (pxs)	2546 X 2048
Sensitivity (mm/pxs)	0.15
Frame rate (fps)	5

3. Results and discussion

Fig. 4 presents the load versus deflection results of all specimens tested in four-point bending, grouped per fiber volume fraction. As these results indicate, the Ev fiber reinforced specimens prepared with increasing volumetric fiber ratios showed improved mechanical properties compared to the control specimens with no fibers. The following parameters were analyzed to assess the flexural performance of the composites: the ultimate failure load (section 3.1), the post-cracking stiffness (slope of the load–deflection curve in the post-cracking stage) and the post-cracking toughness (section 3.2) [49]. The cracking and failure pattern is discussed in section 3.3.

3.1. Effect of fiber content on flexural strength

During the four-point bending testing of the specimens, flexural load–deflection curves were recorded for all specimens. While brittle failure was observed for the control specimens (Fig. 4 (a)), Ev fiber reinforced specimens showed a clear strain hardening behavior in the post-cracking stage (Fig. 4 (b-f)). This is due to the fibers' bridging effect in the specimens, bridging cracks and ensuring an additional load can be applied after cracking.

As expected, the use of Ev fibers as a reinforcing component resulted in a significant increase in flexural strength, which increased when increasing the fiber content to 3 %, 4 %, 5 % and 6 %. All reinforced alternatives achieved a higher failure force than the unreinforced reference specimens (see Table 4). The maximum flexural strength increment was attained for the fiber content of $V_f = 5$ % (presoaked Ev fiber reinforced), which showed an increase in failure load of 396 % compared with that of the reference specimens (Table 4). This improvement of the composites' flexural strength is due to the increase of transferred load to the fibers and the effect of pretreatment of the fibers with tap water, which creates a strong fiber–matrix interface and results in a composite with improved flexural strength.

These performance improvements are consistent with literature; F.A. Silva et al. [33] have found that the use of long-aligned sisal fibers as reinforcement in thin cement-based laminates increased the ultimate bending load by about 260 %. F.d.A. Silva et al. have investigated the mechanical properties of long natural fiber reinforced composites [50]. To characterize the materials, they used tensile tests and a four-point bending test. They concluded that the bridging effect of sisal fibers leads to a high mechanical performance and energy absorption capacity.

The flexural failure mode for both non-presoaked and presoaked samples occurred in the same way. In this study, the presoaked specimens had a flexural strength 6 % − 19 % higher than non-presoaked samples, however, the difference remained limited (see Fig. 5). An increase in fiber content increases the failure load and thus also the corresponding mid-span deflection. Adding Ev fiber with increasing volume fraction to the cement mortar, the mid-span displacements at the maximum applied load were about 14 to 32 times higher than that of the control specimen (see Table 4). The mid-span deflections for the presoaked Ev fiber reinforced specimens also show an increase as compared to non-presoaked specimens. In the soaked specimens, the deformation is 1.2–1.6 times higher than that of the non-soaked specimens.

As the comparison of the effect of soaking and non-soaking of the fibers shows, all parameters of first crack load, maximum failure load and deflection were generally better for the presoaked specimens compared to the non-soaked (see Table 4). A possible explanation is that in non-soaked fiber specimens the water was absorbed by the fibers from the mortar mix, leaving a void between fibers and matrix which resulted in poor impregnation. This negatively affected the water to cement ratio within the cement paste, which contributed to the reduction of composite strength. More investigations on the chemical analysis of the fiber–matrix interfacial transitions zone, pull out and fiber–matrix interactions in cement mortar composites behavior should be performed to systematically study the effect of fiber soaking in water.

Regarding Modulus of rupture (MOR) [51] (Table 5) values, it can be observed that, for composites reinforced with 450 mm Ev fiber length, there is an increase of 38 % and 48% when the volume fraction increases from 3 to 5 % and 3 to 6 % for presoaked and non-presoaked specimens respectively. A similar behavior was observed for cement composites reinforced with unidirectional aligned sisal fibers [52] and long vegetable fibers [50].

3.2. Post-cracking toughness and stiffness

The reinforcing efficiency of the fibers can be investigated not only

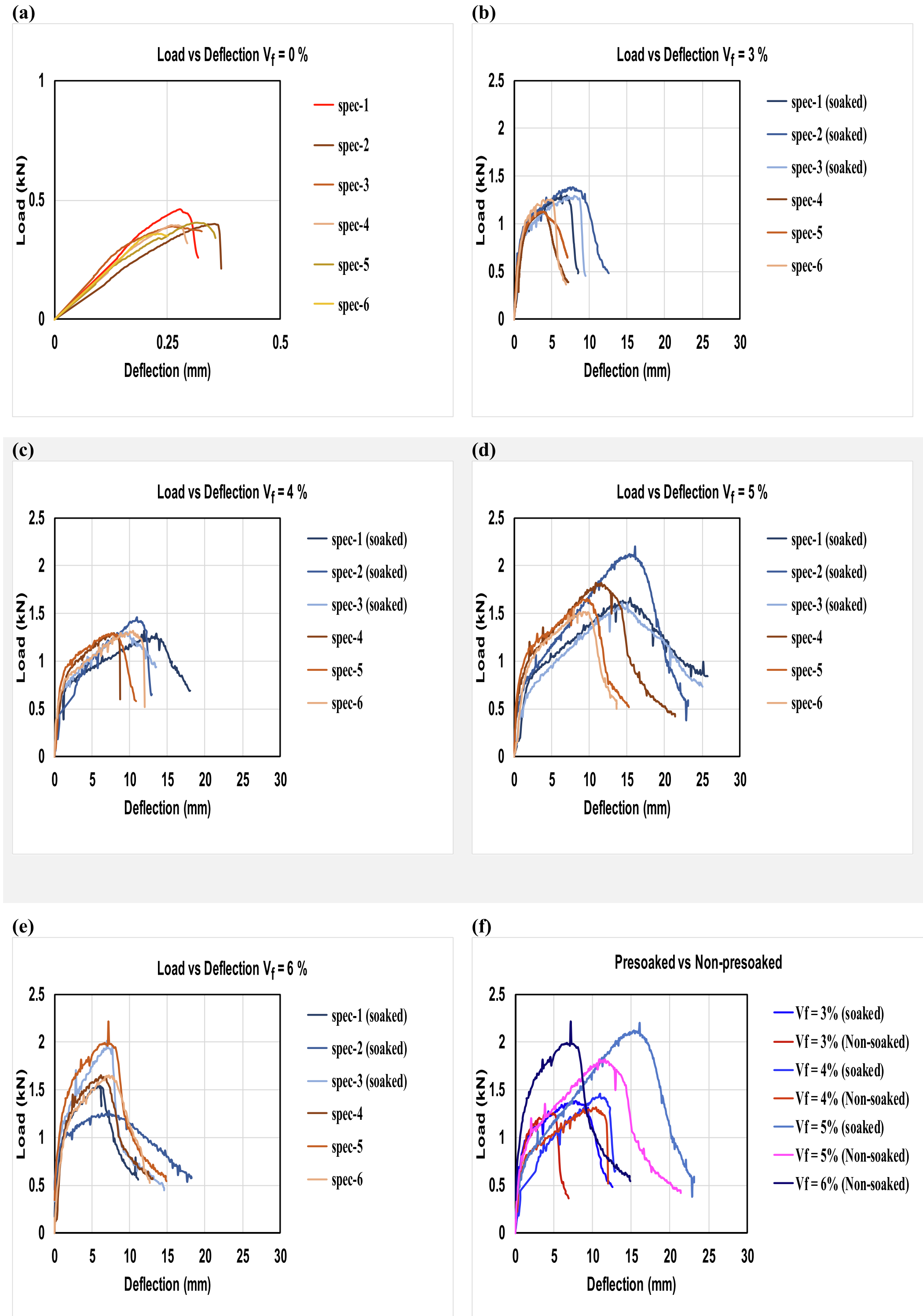

Fig. 4. Load vs deflection curve of aligned Ev fiber reinforced cement composites (a) Vf = 0 %, (b) Vf = 3 %, (c) Vf = 4 %, (d) Vf = 5 %, (e) Vf = 6 %, (f) comparison presoaked vs. non-presoaked Ev fibers.

by looking at the composite's strength but also by analyzing the post-cracking behavior, as this stage is dominated by the fibers. The post-cracking stiffness (PCS) was calculated from the slope of the load–deflection curve in the post-cracking stage and the post-cracking toughness (PCT) was calculated as the area under the load–deflection curve beyond the first cracking for all Ev fiber reinforced specimens. The PCS and PCT values for the non-presoaked and presoaked Ev fiber reinforced cement composites are shown in Table 5.

As can be observed in Table 5, both the stiffness and toughness increased with increasing amounts of Ev fiber. By adding 3 % Ev fibers, the PCS amounts to 72.9 ± 7.5 and 86.7 ± 3.8 N/mm for non-presoaked and presoaked fiber specimens respectively, while adding 6 % of aligned Ev fibers leads to the highest PCS value of 112 ± 30 N/mm (non-presoaked). The highest flexural toughness was observed by reinforcing with presoaked Ev fibers at a volume fraction of 5 %, which also showed the highest failure load.

Table 4
First cracking load, flexural failure load, Modulus of rupture (MOR), and mid-span displacement at maximum load of (non–)presoaked aligned Ev fiber reinforced cement composites.

V_f (%)	1st crack load (kN)		Ultimate Load (kN)		Modulus of rupture (MOR)(MPa)		Deflection (mm)	
	presoaked	Non-presoaked	presoaked	Non-presoaked	presoaked	Non-presoaked	presoaked	Non-presoaked
0	0.279 ± 0.089		0.369 ± 0.046		–	4.76 ± 0.59	0.30 ± 0.18	
3	0.641 ± 0.096	0.533 ± 0.025	1.327 ± 0.040	1.167 ± 0.061	17.14 ± 0.52	15.07 ± 0.79	7.22 ± 0.75	4.16 ± 0.54
4	0.583 ± 0.077	0.494 ± 0.053	1.362 ± 0.067	1.300 ± 0.011	17.59 ± 0.87	16.79 ± 0.14	10.85 ± 0.96	8.6 ± 1.3
5	0.68 ± 0.15	0.856 ± 0.038	1.83 ± 0.27	1.68 ± 0.11	23.6 ± 3.4	21.7 ± 1.5	15.29 ± 0.71	9.5 ± 1.2
6	–	0.677 ± 0.080	–	1.73 ± 0.31	–	22.3 ± 4.0	–	7.13 ± 0.54

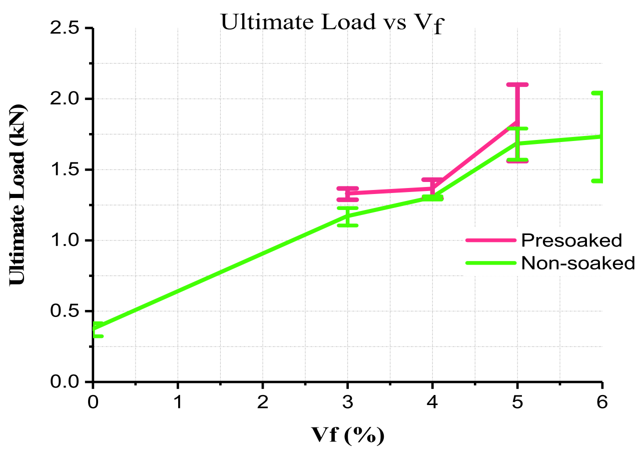

Fig. 5. Ultimate flexural load versus volume fraction for presoaked and non-presoaked aligned Ev fiber reinforced cement composites.

Table 5
Post-cracking stiffness (PCS) and post-cracking toughness (PCT) for presoaked and non-presoaked aligned Ev fiber reinforced cement composites.

V_f (%)	Post cracking stiffness (N/mm)		Post cracking toughness (kN.mm)	
	presoaked	Non-presoaked	presoaked	Non-presoaked
0	–		–	
3	86.7 ± 3.8	72.9 ± 7.5	9.6 ± 2.2	5.85 ± 0.44
4	87 ± 13	82.0 ± 7.0	16.0 ± 3.4	10.3 ± 1.6
5	101.4 ± 5.3	95 ± 12	29.8 ± 1.3	16.3 ± 3.5
6	–	112 ± 30	–	16.4 ± 1.5

For non-presoaked Ev fiber specimens, the post-cracking stiffness increases quasi linearly with increasing fiber volume fraction. This linear relationship can be explained by the ACK theory, according to which the post-cracking stiffness is proportional to the stiffness of the fibers and the fiber volume fraction [53].

Compared with the non-presoaked specimens, presoaked specimens showed a slightly higher post-cracking stiffness (3 %, 4 % and 5 % fiber content exhibited 19 %, 6 % and 7 % greater PCS, respectively). Similarly, by presoaking the fibers the post-cracking toughness was approximately 1.5–1.8 times higher than for specimens reinforced with non-presoaked Ev fibers (presoaking increased the PCT by 65 %, 55 % and 83 % for 3 %, 4 %, and 5 % of fiber content, respectively). This demonstrates that the incorporation of soaked fibers promotes not only increased failure load but also post-cracking stiffness and toughness of the Ev fiber reinforced cement composites. As mentioned in section 3.1, dry fibers absorb water from the cement paste, which consequently affects the matrix strength and the bond between matrix and fibers.

3.3. Crack and failure patterns

In a flexural test, especially after cracking, the embedded long natural fibers are subjected to longitudinal tension. Therefore, the post-cracking flexural behavior of natural fiber–reinforced cement composites is mainly determined by the embedded fibers and ultimately, failure occurs by a combination of fiber fracture and fiber pullout [54]. In the present experimental campaign, the plain mortar/reference specimens showed a brittle failure, while fiber breakage and pullout failure were observed in all other specimens reinforced with Ev fibers.

Detailed information about the cracking process was derived from the analysis of displacement fields processed from the specimen's digital images captured at different load levels. The typical crack patterns for the specimens are shown in Fig. 6 (f). The first microcrack appeared at the extreme tension fiber of the specimen at the constant bending moment region and the first cracks were barely visible. With the increase of the applied load, new micro-cracks were developed between the existing cracks and most of them slightly expanded towards the top surface of the specimen. Meanwhile, the cracks expanded with minimal increments. This is attributed to the fact that the fibers, bridging the gap between the crack surfaces, are effectively restraining the width expansion of the flexural cracks [55]. The experiments thus indicated that the Ev fiber reinforced cement composites exhibit multiple-cracking behavior (see Fig. 6) and that cracks were formed with tight spacing. These investigations were found to be in line with previous studies; F.d. A. Silva et al. [50] have investigated the mechanical properties of composites reinforced with long sisal fibers. They observed multiple cracking behavior under both tensile and bending loads and concluded that sisal fibers were capable to bridge and arrest the cracks within the tensile region response, leading to improved mechanical performance and energy absorption capacity. F.A. Silva et al. [33] also studied the potential use of long-aligned sisal fibers as reinforcement in thin cement-based laminates for structural and semi-structural applications and observed multiple cracking with a strain hardening behavior both in tension and bending.

Table 6 indicates the average number of cracks, crack spacing and crack width of the specimens at the maximum applied flexural load. A substantial increase in the number of cracks and a lowered crack spacing was recorded as the fiber dosage was increased. The maximum crack widths of the specimens occurred for the non-presoaked specimens. The fiber bridging action for the Ev fiber reinforced specimens with a presoaked fiber condition was thus more significant.

3.4. Consideration of composite durability

In the design of cementitious-based composites, consideration of durability is very important since it has a significant impact on the long-term performance of the material. Studies have shown that natural fibers are susceptible to degradation in cement matrices due to the alkaline nature of cement attacking the lignin of these fibers [56]. Several durability improvement techniques such as matrix modification (replacing the Portland cement with supplementary cementitious materials like fly ash, silica fume, ground granulated blast-furnace slag, metakaolin etc.), fiber surface modification (beating, bleaching, hornification, treatment by alkali, chemicals, coupling agents and additives), combined fiber and matrix modification and CO_2 curing have been identified by different researchers [57,58,67–71,59–66].

Taking these references into account, a preliminary study on the durability of Ev fiber reinforced cementitious composites was performed. The primary goal was not to have a full quantitative analysis,

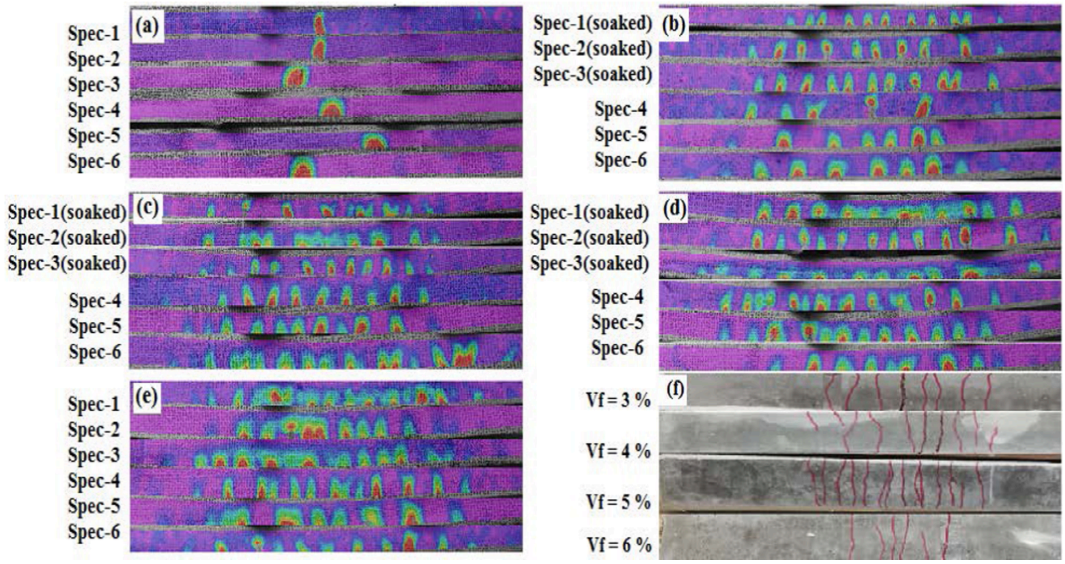

Fig. 6. Quantitative crack pattern observation from DIC at peak load (a) Vf = 0 %, (b) Vf = 3 % (c) Vf = 4 %, (d) Vf = 5 %, (e) Vf = 6 %, (f) typical crack patterns.

Table 6
Average number of cracks, crack spacing and crack width at maximum applied load.

V_f (%)	Number of cracks in the pure bending zone		Total number of cracks		Crack spacing (mm)		Crack width (mm)	
	Non-soaked	presoaked	Non-soaked	presoaked	Non-soaked	presoaked	Non-soaked	presoaked
0	1 ± 0		1 ± 0		–		–	–
3	4.67 ± 0.47	6.33 ± 0.47	6.33 ± 0.94	11.00 ± 0.82	2.5 ± 1.2	1.63 ± 0.15	0.290 ± 0.015	0.118 ± 0.021
4	7.33 ± 0.47	6 ± 0	10.00 ± 0.82	11.00 ± 0.82	1.29 ± 0.13	1.93 ± 0.52	0.242 ± 0.069	1.161 ± 0.087
5	6.67 ± 0.47	7 ± 0	12.3 ± 2.0	14.0 ± 1.4	1.32 ± 0.47	1.39 ± 0.22	0.13 ± 0.10	0.43 ± 0.10
6	7.50 ± 0.76	–	9.83 ± 0.69	–	1.44 ± 0.29	–	0.56 ± 0.22	–

but solely to assess the importance of the durability problems occurring when using the OPC-based matrix in this study. Ev fiber reinforced cementitious composite specimens with dimensions 450 mm × 60 mm × 15 mm were manufactured by integrating one layer of Ev fibers aligned with the loading direction, resulting in a fiber volume fraction of 3 %. Accelerated aging was performed by subjecting the samples to wetting/drying cycles. The wetting/drying cycle was defined as 23 h and 30 min drying in an oven at 60 ± 5 °C and 20 ± 5 % RH, followed by 30 min of air drying at 22 ± 5 °C and 60 ± 5 % RH, then 23 h and 30 min soaking in the water at 20 ± 2 °C and finally 30 min of air drying of samples between saturation and drying to avoid unrealistic thermal shocks and subsequent micro-cracking [57]. The mechanical performance of 12 similar specimens (six specimens for wetting/drying and six reference specimens) was tested under a four-point bending test. As the results indicated, the ultimate failure load of specimens undergoing 12 wetting/drying cycles was 347 ± 73 N (Fig. 7 (c)), while for the reference specimens (Fig. 7 (a)) the ultimate failure load was significantly higher (842 ± 89 N). The unaged specimens showed an average post cracking stiffness of 58 ± 5 N/mm and toughness of 7234 ± 522 N mm. The reference specimens presented a multiple cracking behavior (Fig. 7 (b)). Specimens undergoing 12 wetting/drying cycles present single cracking in the post cracking behavior, and the formation of only one crack (Fig. 7 (d)), highlighting the loss of composite action due to the wetting/drying cycles. There is a 58.8 % loss of peak strength after 12 wet/dry cycles. These results agree with those obtained by different authors using Portland cement materials [34,72].

These preliminary tests showed that the fibers were severely damaged by the Portland cement matrix after the aging process and that further investigation of the effect of aging on the mechanical performance is required. Particularly the matrix composition will be subject to further study in order to enhance its compatibility with the Ev fibers and improve the durability of the cementitious composite.

4. Conclusions

This paper investigated the loadbearing performance of aligned Ev fiber reinforced cement composites. The main investigated parameters were the influence of the fiber volume fraction (0 %, 3 %, 4 %, 5 %, 6 %) and the effect of fiber pretreatment (soaking in water). Based on the results of the flexural experiments carried out in this study on specimens with and without Enset fiber reinforcement, the following conclusions can be drawn:

- As observed from the Digital Image Correlation measurements, the use of Ev fibers as continuous reinforcement in cementitious composites resulted in a material with multiple cracking behavior under flexural loading for all tested fiber volume fractions (range of 3 % up to 6 %). The multiple cracking process is extremely important, as it controls the toughness of cementitious composites. The flexural strength, post-cracking stiffness and post-cracking toughness of the Ev fiber reinforced cement composites increased with the fiber content. The post-cracking stiffness of the non-presoaked Ev fiber cement composites closely followed the linearly increasing tendency with increasing fiber volume fraction as described by the ACK theory.
- The pretreatment of the Ev fibers (soaking in water for 48hrs) before the application as a reinforcement in the cementitious matrix improved the mechanical performance of the Ev fiber reinforced composite, in particular the flexural strength and toughness characteristics.
- Cement composites reinforced with 5 % fiber volume fraction of presoaked Ev fibers gave globally the best mechanical capacity compared to the other tested series: These composites achieved the highest failure load (1.83 ± 0.27 kN), corresponding to a strength increase of 396 % compared to the unreinforced mortar specimens.

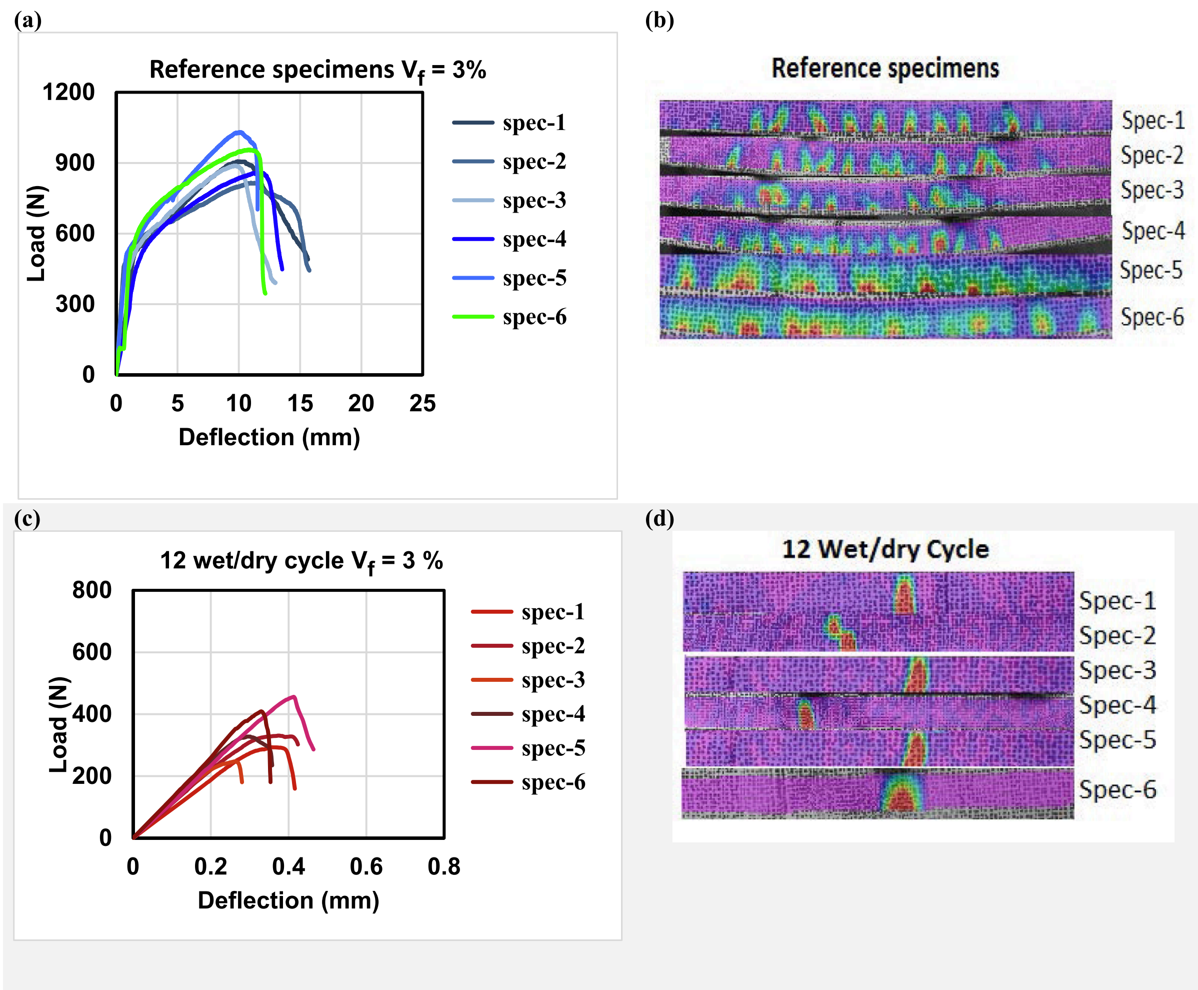

Fig. 7. Load vs deflection curve and crack pattern observation from DIC at peak load, (a) and (b) are reference (c) and (d) are 12 wet/dry cycles.

Based on the above results, the use of continuous, aligned Ev fibers in a cementitious composite system presents a new perspective for the use of natural fiber reinforced composites in the construction industry. However, the durability properties of the composite reinforced with Ev fiber need to be evaluated in the future due to the organic nature of the Enset fiber.

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.

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