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Mechanical Compression and Crushing Properties of a Straw-Lime Material

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Abstract. The aim of this study was to determine the compressive mechanical properties and the energy absorption characteristics of a bio-composite material based on lime, wheat straw, and additives (protein and entraining agent). The selected samples with fiber to binder ratio of 30% were subjected to compression tests at different strain rates (1 mm/min, 10 mm/min, and 100 mm/min), in the perpendicular and parallel directions to fiber orientation. Image analysis supported with Digital Image Correlation (DIC) method is performed to follow longitudinal and lateral deformations, thus making it possible to evaluate elastic properties.

The results show that the highest density and compressive strength in the parallel direction are $\sim 349 \text{ kg/m}^3$ and $\sim 0.101 \text{ MPa}$, respectively. The perpendicular specimens at 100 mm/min of speed test showed the highest values of densification strain, stress plateau, energy efficiency, and absorbed energy of 47.27%, 0.32 MPa, 16.98 %, and 13.84 kJ/m², respectively. The values of Young's modulus identified with DIC are significantly different from those determined by the slope of the linear part of the stress-strain curve. A slight influence of strain rate on mechanical properties is observed.

1 Introduction

The environmental issues related to climate change and energy consumption are receiving special consideration from many researchers around the world. The use of sustainable materials with improved energy efficiency is a major action to reduce the environmental impact of the building sector. The alternative to classical building materials using granular raw materials is the development of bio-composite based on plant and vegetal aggregates (Oskouei et al., 2017). These materials have shown interesting properties for building as reinforcing mortars, coating, and insulators. Furthermore, due to an important porosity, they may have interesting energy absorption capabilities.

This work focuses on the determination of compressive mechanical and energy absorption properties of bio-based lime-straw material, at different strain rates, in perpendicular and parallel directions. The accuracy of the results gained by DIC has been the main reason for some researchers to determine the behavior of shear concrete beams (Tahenni et al., 2021) and the mechanical properties of bicomponent liquid adhesive (Bertelsen et al., 2019). In this work, the DIC is used to follow longitudinal and lateral deformations. If the mechanical behavior of bio-based composite is studied in the literature (Belayachi et al., 2013; Bourdot et al., 2017), the identification of elastic properties from Digital Image Correlation (DIC) is not so often performed (Le et al., 2014).

2 Materials and Methods

2.1 Materials

The bio-composites considered for this study, based on lime, wheat straw, and additives were developed as a part of the PEPITE project funded by the “Region Centre Val de Loire” (Ismail et al., 2020). The ingredients used for preparing samples are Tradical PF70 (contained 75% of aerial lime, 15% of hydraulic binder, and 10% of pozzolan), wheat straw, additives (protein and entraining agent), and water. Wheat straw as bio-aggregates was harvested from Region Centre Val de Loire and obtained from the agricultural by-product of wheat crops. The preparation steps used are the same as those described in the previous work (Ismail et al., 2020). The cubical samples of about 100 mm x 100 mm x 100 mm (Fig. 1) have a fiber/binder (F/B) ratio of 30%.



Fig. 1: Cubical samples

2.2 Compressive test set-up

The compressive tests were performed on an MTS universal testing machine equipped with a 100 KN load cell. Two aluminum compression platens of 150 mm x 150 mm x 20 mm were used to correctly load the samples in compression. The tests were conducted at three different speeds: 1 mm/min (specimen referred as C1), 10 mm/min, (specimen referred as C10), and 100 mm/min (specimen referred as C100). Each test followed a two-stage loading system. First loading was operated until 95% of the load cell capacity and then unloading. Two directions of fiber specimen orientation were conducted in this study to evaluate the anisotropic behavior of the specimens (in perpendicular and parallel directions). For each configuration, at least three replications were performed.

2.3 Digital Image Correlation set-up

A high-resolution low-speed camera (Prosilica GX 29 Mpixels) was used to take pictures of the specimen during experiments in order to get full-field measurements from DIC [Fig. 2 (a)]. Even if straw-lime specimens are naturally highly textured, random black and white speckle are sprayed for better pattern tracking [Fig. 2 (b)]. The image sequences were recorded at three different frame rates: 1 frame per second for C1 samples, 2 frame/s for C10 samples, and 4.5 frame/s for C100 samples. The focus of the camera was on the specimens, but to avoid edge effects it recorded a larger area than the surface size of the specimens. In these experiments, DIC is processed using a classical local subset-based DIC software classical local DIC (Touchal et al., 1996) where the displacements are computed by tracking the spatial correspondence between small sub-images from the region of interest (ROI) in the reference configuration and in the deformed configuration.

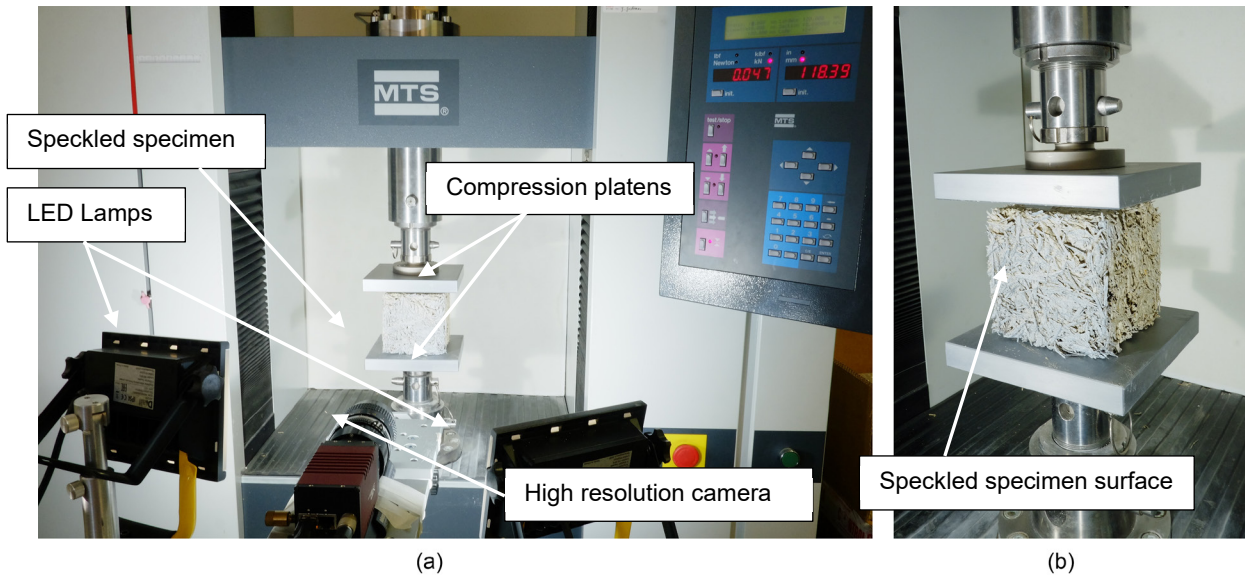


Fig. 2: (a) Set up of specimen compression test and DIC equipment, and (b) black and white speckled specimen

3 Results and Discussion

3.1 Mechanical behavior and compressive strength

For each direction and each speed, the mean values of the density in dry condition (ρ_{dry}), the compressive yield strength (σ_y), the ultimate strain [$\epsilon(\sigma_y)$] and the experimental Young's modulus deduced from the global measurements (E_{Global}) are reported in Tab. 1.

Tab. 1: Mechanical properties of the specimens

	Perpendicular direction			Parallel direction		
	C1-Pp	C10-Pp	C100-Pp	C1-Pl	C10-Pl	C100-Pl
ρ_{dry} (Kg/m ³)	342	339	340	337	330	349
σ_y (MPa)	0.054	0.064	0.074	0.059	0.070	0.101
ϵ_y (%)	4.00	4.00	4.00	1.92	1.92	1.92
ϵ_d (%)	37.16	45.56	47.27	32.70	34.89	35.92
$\eta(\epsilon_d)$ -(%)	16.74	16.91	16.98	23.06	23.37	24.17
σ_{pl} (MPa)	0.16	0.30	0.32	0.07	0.09	0.10
W (kJ/m ²)	5.54	12.55	13.84	2.39	2.95	3.67
E_{Global} (MPa)	1.50	1.62	1.95	7.50	7.50	7.50
E_{DIC} (MPa)	15	60	-	75	>17	-

As expected, the mechanical properties of the specimen depend on the fiber orientation (Page et al., 2017; Zemam et al., 2019). As shown in Fig. 3b and 3d, the initial responses in compression are very different with a smooth transition from linear to non-linear response in the perpendicular direction while in the parallel direction the transition is sharp. These differences are associated with two different initial failure modes: very progressive damage in the perpendicular direction and sudden delamination in the parallel direction. These observations can be related to the high differences in the wheat straw fibers stiffnesses in the longitudinal and diametrical direction which also explain the high difference in global Young's modulus. A strain rate sensitivity is observed on yield and plateau stresses in both directions. A strain rate effect on the global Young's modulus is seen only in the perpendicular direction. Again, the difference is supposed to be due to the different contributions of binder and fibers in longitudinal and perpendicular directions.

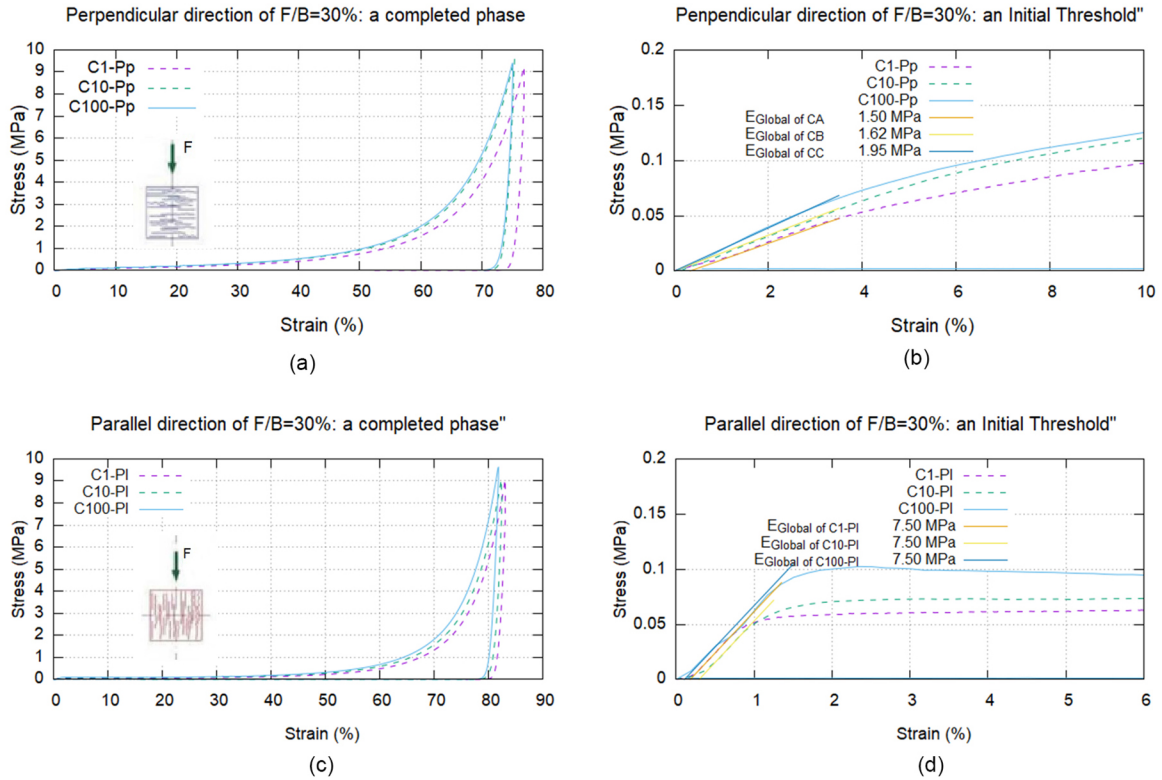


Fig. 3: Stress-strain curves of the tested specimens in the perpendicular direction (a) a completed phase, (b) an initial threshold and in the parallel direction (c) a completed phase, and (d) an initial threshold

3.2 Energy absorption-efficiency

According to the approaches established for cellular materials, three main phases are distinguished in the strain-stress curves: (i) an elastic stage with reversible deformations, (ii) a plateau stage where the material is crushed, and, (iii) a densification stage in which the material compaction capacity is exceeded and for which a strong stiffening is observed. To evaluate the energy absorption capabilities of the wheat straw-lime composite we define several parameters (Li et al., 2006):

The energy absorption efficiency is expressed by:

$$\eta(\varepsilon) = \frac{\int_{\varepsilon_y}^{\varepsilon} \sigma(\varepsilon) d\varepsilon}{\sigma(\varepsilon)} \quad (1)$$

The densification strain (ε_d) is defined as the critical strain value where the energy absorption efficiency is at the maximum peak position on the energy efficiency-strain curve:

$$\varepsilon_d = \operatorname{argmax}(\eta(\varepsilon)) \quad (2)$$

The plateau stress (σ_{pl}) is defined as the mean stress during the plateau regime, which is determined by:

$$\sigma_{pl} = \frac{\int_{\varepsilon_y}^{\varepsilon_d} \sigma(\varepsilon) d\varepsilon}{\varepsilon_d - \varepsilon_y} \quad (3)$$

The absorbed energy per unit volume (W) obtained by plotting the function of the stress is defined as the strain at the onset of densification, which formulated by:

$$W = \int_0^{\varepsilon_d} \sigma(\varepsilon) d\varepsilon \quad (4)$$

Based on compressive stress-strain curves of specimens with different speeds and directions, the mechanical parameters are summarized in Tab. 1. The energy efficiencies are superimposed on the engineering stress-strain curves for the experiments in the two directions (perpendicular and parallel) and three test speeds (Fig. 4). Energy efficiencies for the specimens tested in the parallel direction are a little bit higher than for the specimens tested in the perpendicular direction. These values do not seem to be rate sensitive.

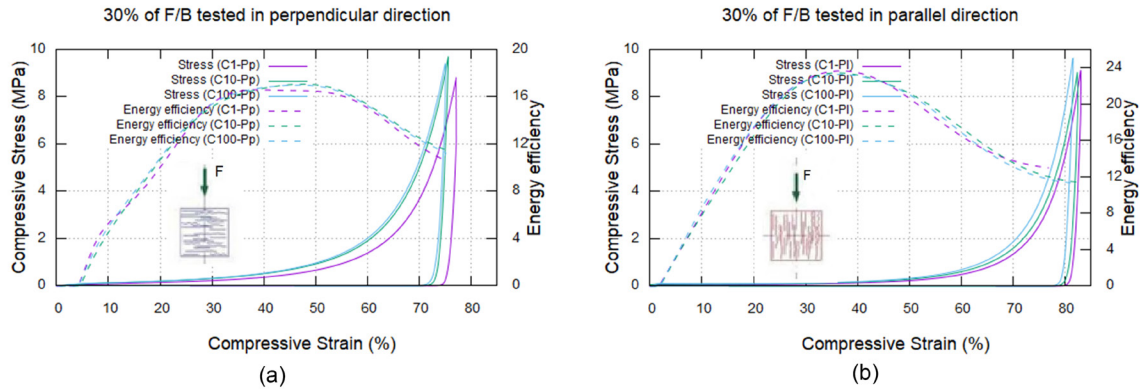


Fig. 4: Stress-strain and energy efficiency relationships recorded (a) in the perpendicular direction, and (b) in the parallel direction

The plateau stress and densification strain values for the specimens tested in the perpendicular directions are higher than in the parallel direction, so that the absorbed energy per unit volume is more than twice the value in the parallel direction. For a fixed test direction, these characteristics also clearly appeared to depend on the test speeds. The highest values are observed from specimens at the higher speed tests. It can be seen in Tab. 1, that for specimens tested in perpendicular direction specimens with 160 kPa, 300 kPa, and 320 kPa of plateau stress values provided 5.54 kJ/m², 12.55 kJ/m², and 13.84 kJ/m² of the absorbed-energy, respectively. The same trends were also gained in the parallel direction specimens, the plateau stress values of 70 kPa, 90 kPa, and 100 kPa lead to 2.39 kJ/m², 2.95 kJ/m², and 3.67 kJ/m² for the absorbed-energy, respectively.

3.3 DIC complementary results

The nominal strain, deduced from the change in height of the specimen, reflects only the mean global deformation of the specimen but cannot give information about the strain field heterogeneity. Furthermore, due to the manufacturing process and to the low mechanical resistance of the bio-composites, a proper flatness of the upper surface of the molded specimen cannot be guaranteed. The DIC method was applied to further investigate the initial deformation modes of the composite materials and to evaluate an initial Young's modulus at low strain (E_{DIC}) and an apparent Poisson ratio (ν). These values are reported in Tab. 1. Fig. 5 shows a comparison of stress-strain curves based on global or DIC measurements during a compression test at 1 mm/min in the perpendicular direction at low strains. In the initial stages of the stress-strain curves, the DIC response shows an almost tri-linear response with an initial slope 10 times larger than the one deduced from the global measurement, then an intermediate slope and a third slope equal to the one identified with a global measurement. For these three stages, the apparent Poisson's ratio is equal to 0.5. The same differences between initial and DIC stress-strain curves are observed at a speed of 10 mm/min (Fig. 6). For the DIC stress-strain curves, the apparent Poisson's ratio is equal to 0.11. The camera frame rate was insufficient to allow a successful DIC analysis for tests at 100 mm/min. For specimen tested in the parallel direction, the DIC analysis reveals higher Young's modulus values and emphasized the sudden change in mechanical response with delamination.

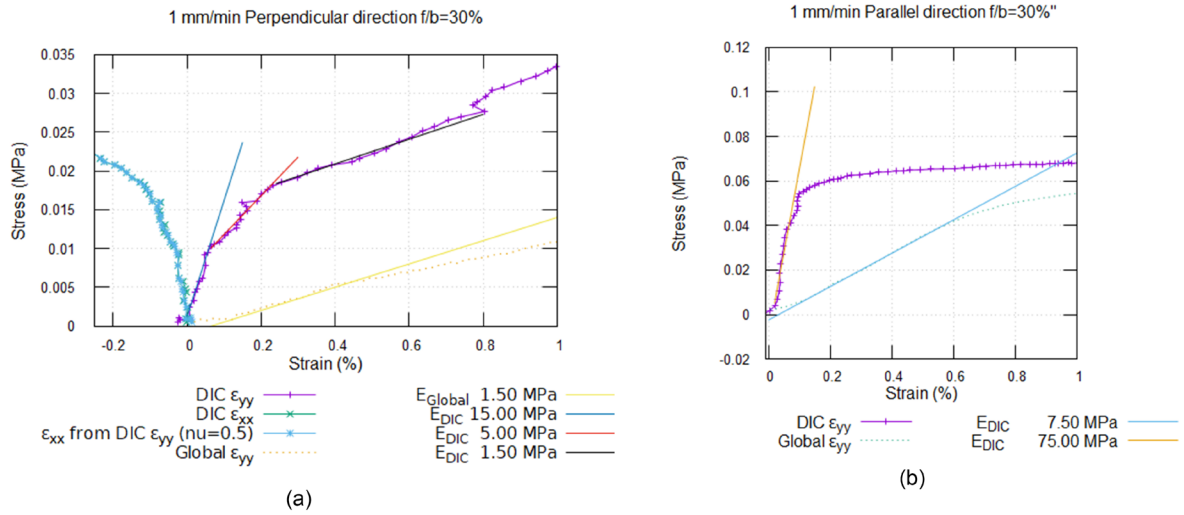


Fig. 5: Stress-strain curves obtained by DIC vs experimental results conducted the test at 1 mm/min of speed (a) in the perpendicular direction, and (b) in the parallel direction

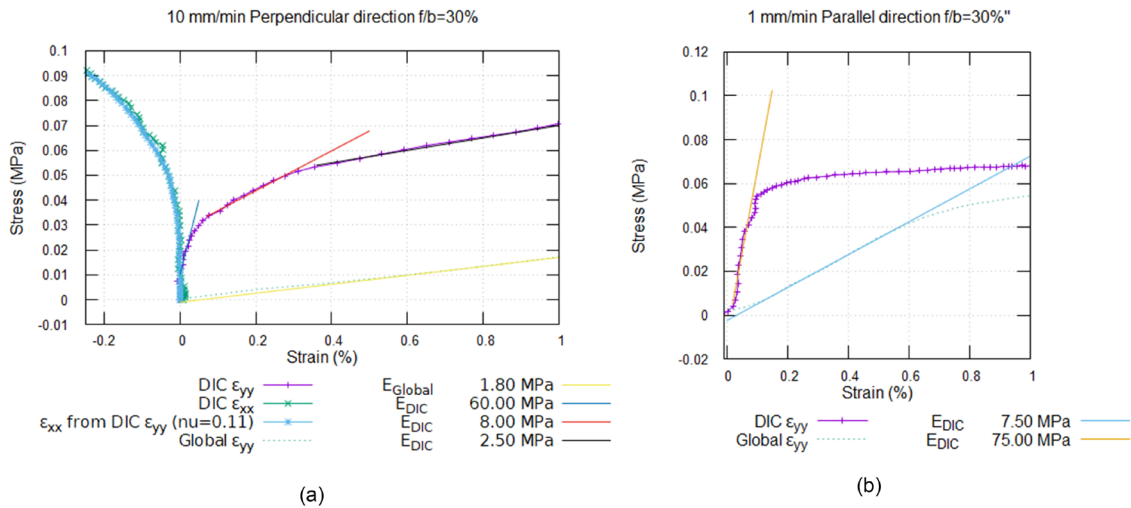


Fig. 6: Stress-strain curves obtained by DIC vs experimental results conducted the test at 10 mm/min of speed (a) in the perpendicular direction, and (b) in the parallel direction

4 Conclusion

An experimental investigation of the mechanical response of a bio-composite material based on lime, wheat straw, and additives, in the perpendicular and parallel directions at different speeds test, has been conducted. The energy absorption performance of the composite materials has also been reported. In the present work, a Digital Image Correlation method was applied to better analyze the mechanical response at low strains.

The results showed that the mechanical strength and the absorption energy capacity are strain-rate dependent. This increase is observed both in the directions parallel and perpendicular to the main orientation of the straw fibers. The higher capacity of the bio-composite material to absorb energy can be found from the perpendicular direction of specimens which the higher values of strain at the onset of densification, energy efficiency, and plateau stress are found. The DIC has been found to be a very interesting tool for a better evaluation of elasticity properties.

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