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STUDY OF THE MECHANICAL BEHAVIOR OF HEMP CONCRETE WITH TWO DIFFERENT MINERAL BINDERS THROUGH DIGITAL IMAGE CORRELATION IN VARIED AGGREGATE ORIENTATIONS.

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Abstract

The construction sector is increasingly turning to eco-materials derived from agricultural products due to their low embodied energy and carbon sequestration. Plant-based concrete, composed of particles from lignocellulosic plants and mineral binders, presents environmental advantages. However, predicting its mechanical behavior remains challenging. This study focuses on hemp concrete, employing two mineral binders: sulfoaluminate cement (CSA) and pozzolanic cement (CEM IV). Digital Image Correlation (DIC) evaluates mechanical properties in different aggregate orientations. Cyclic compression tests reveal differences in mechanical behavior. Maximum stiffness and ultimate strength are determined, with maximum stiffness corresponding to the floating modulus during reloading. DIC is used to quantify macroscopic properties and create kinematic plots. Hemp concrete in perpendicular orientation exhibits increased stiffness, and sustaining strength, while parallel orientation specimens experience stress reduction.

Notably, stress continues to increase for perpendicular aggregates, while parallel specimens show early stress reduction. This discrepancy is attributed to loading orientation, affecting contact areas between machine plates and specimens. Perpendicular specimens resist strength loss, while parallel ones are more susceptible to stiffness reduction at low strain rates.

Hemp CEMIV specimens outperform CSA counterparts, emphasizing the adverse chemical impact of hemp on sulfoaluminate binders. For instance, CEMIV-based specimens demonstrate significantly higher maximum stiffness and ultimate strength.

DIC kinematic plots indicate that hemp concrete in parallel orientation tends to split horizontally due to stress concentration. This is proven by Poisson's coefficient, twice as high for parallel specimens, indicating significant horizontal displacement. Vertical deformation plots for perpendicular specimens reveal stress concentration lines from the manufacturing process, while parallel ones show split parts with a stress concentration interface.

Hence, the loading orientation significantly influences the mechanical properties of hemp concrete. This study highlights the importance of binder selection, aggregate orientations, and fabrication processes in optimizing the mechanical properties of plant-based concrete in sustainable construction practices.

1 INTRODUCTION

Buildings are considered among the largest consumers of energy worldwide, where the building sector is currently estimated at 45 % of total energy consumption[1], [2]. In this regard, a significant growth of so-called bio-based building materials has been remarked due to their advantageous properties such as low carbon footprint, hygrothermal, and acoustic properties where they provide thermal insulation and humidity control as infill materials in walls[3], [4], [5]. In the literature, LCA (life cycle assessment) of bio-based materials proved that on an overall scale, bio-based materials exhibit lower embodied greenhouse emissions than conventional solutions, ie: brick or concrete-based elements[6]. However, the mechanical properties of plant-based concrete are notably influenced by various factors, with the nature of the binder content playing a particularly significant role[7], [8]. This is due to the substantial contribution of the hydrates of the binder to the overall mechanical properties of these materials. In this regard, Murphy et al, have obtained a compressive strength of hemp concretes having the same formulations after 28 days of 16 MPa and 2.7 MPa between commercial lime (hydraulic & pozzolanic additions) and hydrated lime, respectively[9]. As a matter of fact, the addition of pozzolans to lime-based binders improved their compressive strength due to shrinkage reduction, resulting in the elimination of cracking around aggregates in mortars[10]. In a parallel study, Walker et al, have shown that water retainers enhanced the hydration mechanism in binders containing lime and pozzolans, thereby contributing to an increase in the compressive strength[11].

Another factor that can cause a wide variability in the mechanical properties of the same plant-based concrete is the orientation of the particles. In this context, the orthogonal or perpendicular orientation of aggregates to the casting direction results in completely different mechanical properties than parallel-oriented particles at the composite scale of the materials [12], [13].

On the other hand, digital image correlation (DIC) was successfully proven to be an efficient method in evaluating inter and intra-granular deformation, as it is independent of the precise physical length of the materials[14]. Indeed, Bardouh et al. have investigated the mechanical response of hemp concrete using digital image correlation [15]. The authors have outlined a heterogeneous approach regarding the mechanical behavior of hemp concrete thanks to the deformation fields.

The purpose of the current study is to couple digital image correlation observations with the mechanical properties of hemp concrete, using two different mineral binders: CEMIV and CSA, and considering two aggregate orientations: orthogonal and parallel to casting direction.

2 MATERIALS AND METHODS

2.1 Materials

2.1.1 Mineral binders

Two mineral binders from VICAT were used in this study: a pozzolanic cement “CEMIV”, and a low-alkaline sulfoaluminate cement “CSA”. The CSA cement comprises 81% of clinker and 19% of anhydride[16]. Tables 1 and 2 present the differences in compressive strength and chemical composition of these binders. Compressive strength was tested on prismatic mortars of 4×4×16 cm³ according to the French Norme NF EN 196-1[17], while chemical composition, measured by XRF was provided by the manufacturer. CSA hydrates primarily form ettringite (C₆A₃S₃H₃₂) as reported in equation (1), unlike the hydrates of CEMIV/A which form conventional calcium silica hydrates (C-S-H). The main chemical elements that induced a difference between the two mineral binders used in this study are SiO₂ which is relatively rich in CEMIV, Al₂O₃, and SO₃ which are relatively higher in CSA.

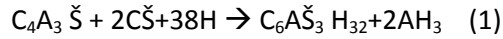


Table 1: Compressive strength of CEMIV and CSA used in this study.

Compressive strength (MPa)	1D	2D	7D	28 D
CEMIV	18.53±0.74	29.27±2.78	41.24±2.62	58.29±2.29
CSA	9.48±0.53	13.25±1.37	31.73±2.19	60.32±3.01

Table 2: chemical composition of CEMIV and CSA cement used in this study.

Chemical composition (Wt.%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	TiO ₂
CEMIV	27.3	6.7	5.6	51.3	2.2	2.9	0.9	0.6	-
CSA	9.6	18.9	8.4	43.7	0.9	14.8	0.38	0.14	1.07

2.1.2 Plant aggregates

Plant aggregates used in this study were industrial hemp shive under scientific name of “cannabis sativa” provided by La chanvière. The physical and hygothermal properties of the corresponding shive were given in a previous study[18].

2.2 Mix design and preparation

Cubic hemp concrete specimens of 15 cm each side were prepared under the same formulation of binder:aggregate:water ratio of 1:0.5:1 regardless the nature of the mineral binder. The casting process was elaborated in a previous study[18]. 2 specimens were fabricated per each configuration. After being demolded, the specimens were placed in a controlled environment under a temperature of 20°C and 50 % RH for 12 months prior to testing. The bulk density of the specimens after fabrication and demolding was 570 ± 30 kg/m³ and 552 ± 24 kg/m³ for CEMIV and CSA-based specimens, respectively. However, the dry density of the specimens was 356 ± 39 kg/m³ and 335 ± 28 kg/m³ for CEMIV and CSA-based specimens, respectively. The dry density corresponds to the density of the specimens after 12 months of age, which were placed in an oven under 60°C for 48 hrs, before the testing day.

2.3 Compression test setup

Bio-based specimens were tested using a Zwick Roell machine with an overall 250 kN loading capacity. However, only a 10 kN load attached to a force sensor was used in applying the mechanical load on the hemp concrete specimens. 19 cycles of charging and discharging were settled between 1% and 10% of deformation with an increment of 0.5% between each cycle. The charging and discharging velocities were 3mm/min and 10mm/min, respectively. Zwick software was programmed to stop the compression test at an 80% drop in maximum force at the end of the 19 charging-discharging cycles. The compression test setup is shown in Figure 1. Two wood plates were positioned above and under the specimen, in order to provide a suitable smooth contact surface with the machine jaws.

2.4 Digital image correlation

2D digital image correlation (DIC) was performed to compute the displacement and deformation fields of the corresponding bio-based specimens. To establish the (DIC) technique, a PCO 2000 digital camera featuring a 2048 × 2048 pixel2 CCD sensor was positioned in front of the hemp concrete specimen, operating on 14-bit encoding, and equipped with a 105 mm lens. The images captured by the camera were recorded using Camware64 software at a rate of 1 frame per second for data acquisition. Two main parameters were settled before the image correlation: the subset and step size. Step and subset size were set to 10 pixels which correspond to the size of the grid that divide

the image in a sequence of equivalent squares and the pattern size in which the correlation pattern is tracked, respectively. Furthermore, these two parameters as illustrated in Figure 1.b serve as the basis for computing the vertical displacement maps which are shown in section 3.3 of this study. The image sequences were analyzed using 7D software. The calculation method is based on the displacement fields between two images, using the grey level distribution at the concerned points[19]. In fact, the surface grid of the specimens was decomposed by a set of step sizes which was then converted to a measurement unit (mm) through an expansion coefficient. Hereinafter, 7D software computes the localization of the same pattern size localized in a subset area as shown in Figure 1.b between reference and deformed image. The difference in localization of the same point between both images generates a displacement vector. Hence, the same computational methodology was applied throughout the whole surface of the specimen (15 cm height × 15 cm width).

The spatial resolution was determined according to the standard deviation which was equivalent to 0.02 pixels for a subset size of 10 pixels. An expansion coefficient of 0.08mm/pixel was established in order to convert pixel unit into a measurement unit (mm).

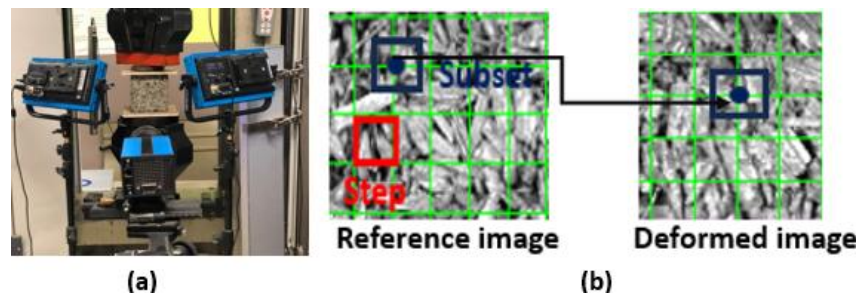


Figure 1. (a): Compression test setup, (b): Computational methodology of displacement maps between reference and deformed images.

3 RESULTS AND DISCUSSION

3.1 Mechanical behavior

The criteria used to define the major orientation of hemp shive was based on the direction of compaction during the casting process. By default, while compacting, the particles were laid in preferential stratified planes perpendicular to the compaction direction[20]. However, turning around the specimen 90 degrees after demolding changes the orientation from perpendicular to parallel. As a matter of fact, the orientation distinguishing (between perpendicular and parallel) is obvious by looking at the specimen surface as shown in Figure 2.a and 2.b. Figures 3 and 4 display the mechanical behavior of bio-based concrete in the perpendicular and parallel orientations of hemp shive, respectively. The dotted orange lines in the re-charging section of each configuration in both figures represent the Young's modulus assessing method. This latter was calculated based on floating technique method during the re-charging zone at a strain difference of 0.1%. In general, a tremendous difference can be noticed between the mechanical behavior of hemp concrete made of CEMIV mineral binder and that made of CSA. Irrespective to the close values in mechanical strength of pure cement paste after 28 days as reported in Table 1, hemp concrete made with CEMIV exhibits a better mechanical performance compared to hemp concrete with CSA cement. As a matter of fact, chemical interactions between lignocellulosic soluble components of hemp shive and hydrates of CSA cement seemed to cause deleterious effects on the mechanical performance of the resulting hemp concrete. In this regard, Cokely et al. have found that for the same hemp shive used in this study,

different influences on the hydration kinetics of CEMI and CEMIV cements were obtained[21]. For instance, hemp shive induced more delay in the peak of heat flux for CEMI compared to CEMIV[21]. Hereinafter, the sugar soluble components of hemp shive implied a more pronounced delay in the hydration mechanism of ettringite compared to calcium silica hydrates, which explains the big difference in the mechanical response between hemp concrete made with CEMIV cement and that of CSA cement.

In comparing the aggregates orientations, perpendicular-oriented aggregates exhibit a continuous ascending tendency of the mechanical behavior in their corresponding specimens. In contrast, parallel-oriented specimens experienced an early damage resulting in lower mechanical strength as strain increases as it can be seen in Figure 3. In this regard, Youssef et al. have obtained a similar findings, where hemp concrete with shive oriented perpendicular to the compaction direction demonstrated a strain hardening until the end of the test[13]. However, hemp concrete with shive oriented parallelly, break in “accordion” pattern, thereby shive layers endure buckling collapse which explains the continuous decrease in mechanical strength at an early strain rate for parallel-oriented configurations[13].

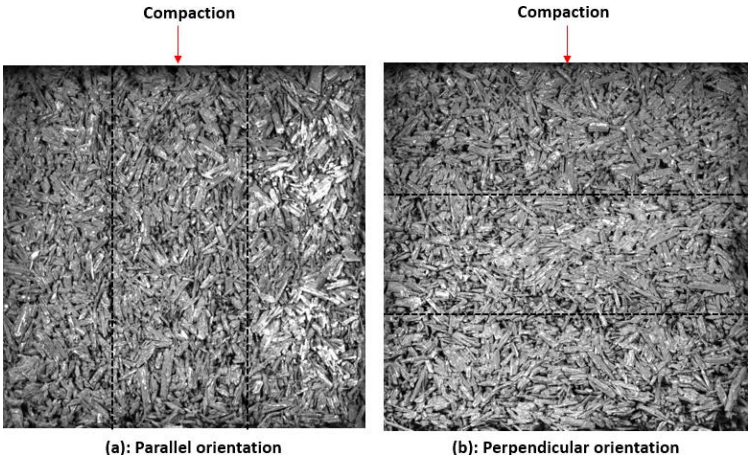


Figure 2. Criteria of orientation distinguishing between parallel and perpendicular specimens.

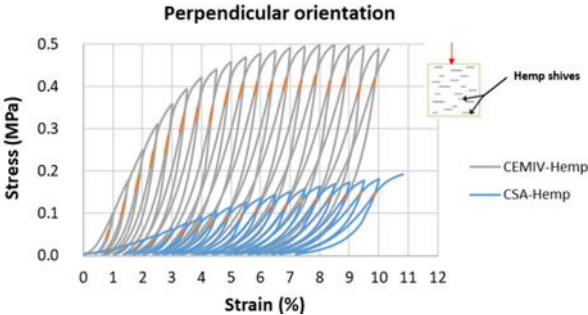


Figure 3. Mechanical behavior of hemp concrete tested in perpendicular orientation of aggregates to the compaction direction

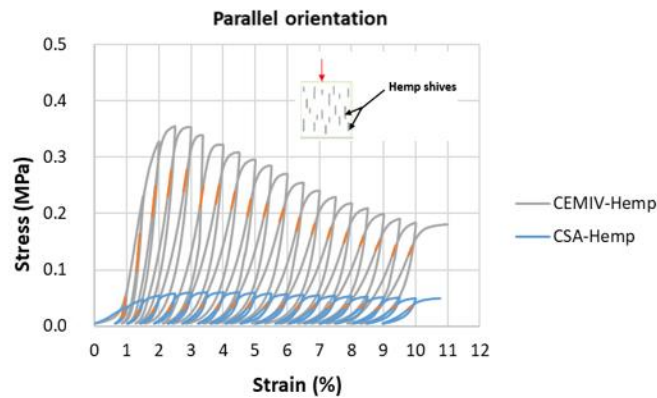


Figure 4. Mechanical behavior of hemp concrete tested in parallel orientation of aggregates to the compaction direction

3.2 Mechanical properties

3 different mechanical properties were determined in this study. The first parameter is the rigidity which corresponds to the Young's modulus computed during the re-charging section as illustrated in Figures 3 and 4. The histograms in Figure 5 represent the maximum value of the Young's modulus during the cyclic compression test for each configuration as function of their corresponding strain rate. Irrespectively of the same formulations and curing conditions of hemp concrete made with the two different mineral binders, a huge difference in terms of rigidity can be noticed between CEMIV-hemp concrete and CSA-hemp concrete. For instance, Young's modulus of hemp concrete made with CEMIV cement in perpendicular orientation was almost 40 MPa higher than 10 MPa which corresponds to the Young's modulus of CSA-hemp concrete. This tremendous difference can be explained by the pronounced interfacial transition zone caused by sugar soluble components of hemp shive on CSA cement paste.

On the other side, it can be noticed that parallel configurations of hemp concrete exhibit higher rigidity at a relatively lower deformation compared to perpendicular oriented specimens. This evidence was explained by Nozahic et al. due to the very high mechanical properties of aggregates following their longitudinal orientations compared to their tangential or radial ones[12]. Consequently, the low strain values obtained at the peak rigidity for hemp concrete in parallel orientation confirms the weakness in deformability of hemp aggregates when they are oriented parallel to the compaction direction.

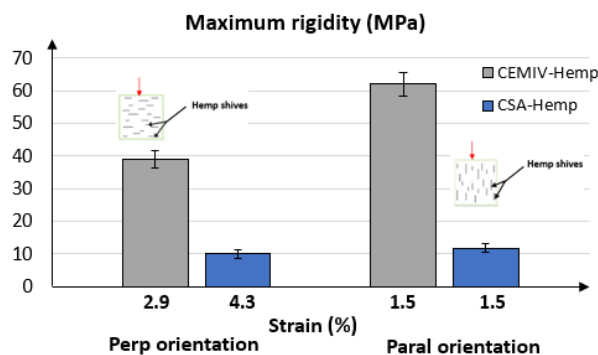


Figure 5. Maximum rigidity of hemp concrete as function of corresponding strain for perpendicular and parallel orientation of aggregates

The radar diagram in Figure 6 represents the two other mechanical properties which correspond to the compressive strength (CS) and the useful strength (US) of hemp concrete among the different configurations. Since no standards were established on the assessing method of compressive strength yet[11], the authors have computed the compressive strength (CS) at a strain of 5% during the strain hardening area similar in range to previous studies in the literature[22], [23]. Indeed, the yield strength methodology developed by the model of Lam and Teng on FRP (fabric reinforced polymers) [24] and followed in numerous studies on hemp concrete[13], [23] was not considered in this study since it does not take into consideration the strain hardening phase which quietly impacts the mechanical performance of these materials. However, the useful strength (US) corresponds to the strength of hemp concrete when this latter reaches its maximum rigidity. This parameter (US) is not very common in the literature, yet it's a very helpful parameter as it provides the strength of hemp concrete at its ultimate mechanical performance. Irrespective of the binder nature, it can be noticed that perpendicular orientations of shive demonstrated higher values of compressive strength (CS) and useful strength (US) in their corresponding specimens compared to their parallel orientation. This evidence can be explained by the flat layup of the particles in case of perpendicular orientation which led to quasi-pure uniaxial compressive stress. However, the cyclic compression loading applied on defect lines (2 layers during the fabrication process) in the case of parallel orientation led to a buckling effect in the vicinity of these layers, resulting in the splitting of hemp particles between the layers. Indeed, the perpendicular orientation of shive provides a key factor in the particle packing optimization similar to what was found by Huang et al. who revealed that the critical optimization of the mechanical properties of bio-based concrete (typically Young's modulus E) in three stages lied between a θ angle of 0° (parallel orientation) and 90° (perpendicular orientation)[20].

The increased CS in perpendicular orientation compared to parallel one is due to the more pronounced hardening effect of the binder in perpendicular orientation, while the parallel orientation experienced tensile collapse. The useful strength of parallel-oriented specimens denotes the in service-strength, evaluating the particles/binder affinity just before damage. For instance, the useful strength of parallel-oriented CEMIV-hemp concrete was 0.28 MPa, compared to 0.07 MPa for parallel-oriented CSA-hemp concrete, indicating a stronger bond at the shive/CEMIV interface than at the shive/CSA interface. In addition, US was always lower than CS no matter what configuration was evaluated. This finding is related to a large extent to the computational methodology of CS where this latter was exploited during the strain hardening area. Hence, the mechanical strength of hemp concrete keep on increasing beyond its ultimate mechanical performance (maximum rigidity) as a result of the high flexibility of aggregates in dissipating more mechanical energy by their vertical displacement, thereby reducing relatively the contact surface between the plates of the testing machine.

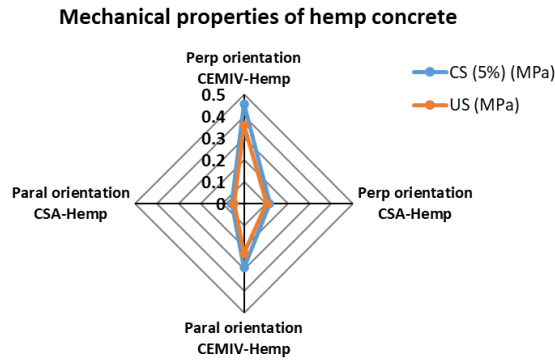


Figure 6. Compressive strength (CS) and useful strength (US) of hemp concrete

3.3 Vertical displacement maps

Figures 7.a and 7.b highlights the mean values of vertical displacement by line for a CSA-hemp concrete specimens in perpendicular and parallel orientation of aggregates, respectively. It is worth noting that the displacement maps were computed at a strain rate of 3.4%. The dotted blue lines on the schematic representation in both figures correspond to the displacement vector lines computed as previously explained in section 2.4. Hereinafter, for a better visualization of these displacement vectors, the data plotted in Figure 7.a and 7.b denote the mean value per each line (blue dotted line) with respect to their location along the vertical axis of the specimen. At the same strain rate, hemp concrete with perpendicular-oriented aggregates was more displaced than parallel-oriented configuration, since high portion of cumulative vertical displacement data ranged between 0.1 mm and 0.12 mm as illustrated in Figure 7.a. This difference can be further explained by the Poisson coefficient attributed to each configuration as perpendicular-oriented CSA-hemp concrete demonstrated a Poisson coefficient of 0.22 less than 0.34 which corresponds to the Poisson coefficient of parallel-oriented CSA-hemp concrete. Hereinafter, the buckling effect on parallel-oriented specimens resulted in more pronounced horizontal displacement which limit their vertical displacement motion under cyclic compression loading. This is evident since hemp particles were capable to deform better on their major length axis (perpendicular orientation) compared to their minor width axis (parallel orientation). Hence, the mean values of the vertical displacement obtained in both configurations explains the difference in tendency of the mechanical response of hemp concrete between perpendicular and parallel orientations of hemp shive.

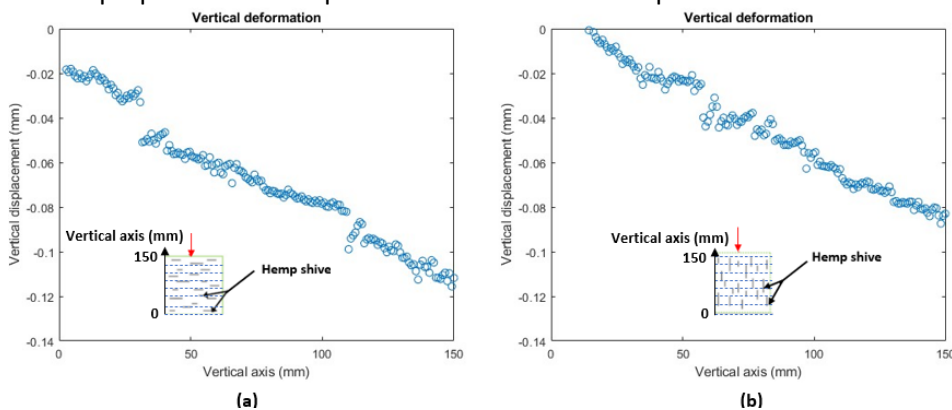


Figure 7. Mean values of vertical displacement of CSA-hemp concrete for (a): perpendicular orientation, and (b): parallel orientation

4 CONCLUSION

Based on the coupling between the experimental results and the DIC findings in this study, the following points can be concluded:

- Hemp concrete made with CSA cement exhibits a very poor mechanical performance due to the chemical effect between lignocellulosic components of hemp shive and hydrates of CSA. In contrast, chemical interaction between pozzolans and hemp shive enhances the mechanical properties of hemp concrete as in the case of the coating strength between aggregates and CEMIV hydrates.
- Hemp concrete tested in perpendicular orientation exhibited a strain hardening due to particle package optimization and binder hardening whereas parallel-oriented specimens demonstrated a buckling effect between the layers followed by tensile collapse of the binder.
- Hemp concrete tested in parallel orientation of aggregates demonstrates a higher rigidity at lower strain rate compared to perpendicular-orientated specimens due to longitudinal properties of aggregates.
- Unlike rigidity, compressive and useful strengths were higher for perpendicular orientated hemp concrete compared to parallel one. Perpendicular-oriented specimens demonstrated a quasi-pure uniaxial compression test whereas the mechanical strength of parallel-oriented specimens was limited due to splitting of particles between layers.
- At the same strain rate, DIC results show that perpendicular oriented specimens are able to deform better than parallel oriented specimens. This is consistent with the difference between the local Poisson coefficient between parallel-oriented and perpendicular-oriented hemp concrete.

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