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Shear Strength of Unbound Crop By-Products Using the Direct Shear Box Apparatus

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Abstract: The return to old building methods by mixing crop by-products with mineral binders is arousing great interest in Europe since about 25 years. The use of these bio-aggregates based materials for the design of building envelopes is a valuable opportunity to deal with increasingly demanding thermal regulations. In addition, the regulatory framework is moving towards reducing the overall carbon footprint of new buildings. Some traditional and historic buildings are based on timber framing with earth-straw as infill material for instance. Hemp concrete is a bio-based material that can be manually tamped in timber stud walls or more recently in the form of precast blocks. Owing to their low compressive strength, bio-based concretes using a large volume fraction of plant-derived aggregates are only considered as thermal and sound insulation materials. The structural design practice of wood frame walls does not assume any mechanical contribution of hemp concrete whereas it may contribute to the racking strength of the structure. In this context, more research is needed regarding the shear behavior of crop by-products and bio-based concretes. In this case, the objective of the study was to perform direct shear tests under three levels of normal pressure on hemp shiv and rice husk as unbound crop by-products. The results showed that the friction angle of the granular skeleton based on rice husk for a given relative displacement was significantly lower than that measured on hemp shiv. This is in accordance with what had been observed on bio-based concretes cast by mixing aggregates with lime and shear strength parameters measured by means of triaxial compression.

Keywords: Plant-derived aggregates; direct shear test; racking strength; friction angle; bio-based concretes

1 Introduction

To address the challenges of global climate change, there is a pressing need to work with alternative building methods based on the use of locally available and renewable resources. The building sector has to face a major environmental challenge with regard to low-carbon finished materials. The building envelope is mainly designed with widespread insulation materials as mineral wools and expanded polystyrene. Many ancestral materials (rammed earth, straw, hemp, etc.) can replace fossil and quarry materials whose the production industry is a large carbon emitter. Using bio-based concretes is a good opportunity to lock carbon dioxide inside the building and to reduce operational energy (heating and air conditioning). Hemp concrete-a mix of hemp shiv with a lime-based binder-is often cast into the walls of timber frames or inserted as a masonry infill block. This material has expanded since the 1990s, especially in Northern Europe (France, Belgium and UK). Hemp-lime concrete was first developed in order to add hygrothermal performance to medieval timber framed buildings. It can be used for the renovation of buildings as is the case of the tourism office in Troyes (France) which was initially built with a timber frame and cob (clay-straw). Bio-based concretes can be considered as an alternative to well-known systems including concrete blocks and insulation, in particular for residential houses. However, the development of such materials is still hampered by regulatory issues or even the lack of follow-up by public authorities.

Professional rules for hemp construction have been introduced and enhanced over the past decade. However, the mechanical contribution (especially in terms of racking strength) of the bio-based material is not considered in the design practice of the wall structure. There have been many studies into the lateral load-carrying capacity of timber frames with various infill materials and units [1-3]. Quinn and D'Ayala [1] reported an increase in the stiffness of the frame when using a mix of mud and straw as infill material. Similarly, Lawrence et al. [3] identified the mechanical contribution of straw bales in the shear strength of the timber frame with straw-bale walls. The change in the racking behavior of the wood frame after infilling is partly dependent on the nature of the infill material. The standard masonry blocks (such as bricks) are resistant to compression but their ductility is low. As a result, the surrounding timber frame confines the masonry due to its higher ductility, improving th resistance of the system to horizontal loads [2,4]. In addition, the timber frame provides a significant bending strength. The case is different for bio-aggregates based materials like hemp concretes characterized by an important strain capacity and post-cracking ductility. Some authors [5] stated that the presence of hemp concrete allows a reduction in timbers compared to a standard structural timber frame and reduces the need for diagonal bracing. According to Gross and Walker [6], low density hemp concrete can improve the racking performance of timber studwork frames. More recently, Wadi et al. [7] reported some conclusions about in-plane racking strength of timber frames infilled with hemp concrete. According to them, hemp concrete increased the lateral resistance of vertical stud timber frame and improved the racking stiffness. However, no contribution to the lateral strength was observed for timber frame with diagonal bracing. Furthermore, the contribution of hemp concrete to the lateral strength was found to be dependent on the rigidity of the timber and the dimensions of the wall.

Very few studies have been made on the shear behavior of bio-based concretes [8,9]. In a previous investigation [8], it has been shown that the huge strain capacity of such materials makes it difficult to use the analogy with soil mechanics to determine the shear strength parameters. The shear behavior of hemp and rice husk-based concretes was analyzed by means of axisymmetric triaxial compression. It is known that the shear strength is the result of friction and interlocking of granular particles (plant aggregates) and cementation between them (the mineral binder herein). Nevertheless, the critical state friction angle (shear stress and volume remaining constant while shear strain continues to increase) was hard to identify on the basis of stress-strain responses. It is likely that samples did not reach the critical state within the strain limits of the triaxial test. In addition, due to the drainage at air pressure (i.e. samples tested without water saturation), the volume change could not be measured accurately. The shear strength at constant volume is independent of the initial stress state of the sample (density and packing arrangement). Furthermore, the axial strain at failure of bio-based concretes could reach more than 20% [8]. At this strain level, the binder does not provide any more cohesion and the shear strength is likely due to frictional properties of plant aggregates. From there, it may be interesting to access the friction angle of unbound plant aggregates (i.e., without the lime-based binder). Some authors [10-12] interested in the shear strength of grain masses and crop by-products. Aloufi and Santamarina [10] measured the peak friction angle of rice grains using the triaxial shear test. As a matter of fact, their deviatoric curves (deviatoric stress versus axial strain) indicate a peak deviatoric stress and the post-peak behavior shows a decrease in the deviatoric stress before stabilizing. Stasiak et al. [11,12] studied shear strength properties of sawdust and woodchips using the direct shear test. It was noticed that shear stress did dot stabilize with the horizontal displacement.

In this paper, two different aggregates (rice husk and hemp shiv) were tested with the direct shear box. Compared to the triaxial test, one disadvantage of the direct shear box apparatus is that failure occurs along a predetermined plane but it is widely used in geotechnical engineering due to its ease application. The results will be compared to those reported in the paper about triaxial compression of bio-based concretes designed with the same plant aggregates [8].

2 Materials and Methods

2.1 Materials

Two kinds of crop by-products were used in this work: defibered hemp shiv (Fig. 1(a)) and raw rice husk (Fig. 1(b)).

(a) (b)

Figure 1: (a) Hemp shiv, (b) Rice husk

These bio-aggregates can be considered as granular materials. Prior to testing, materials were dried at 40°C until mass stabilization and kept in airtight bags since the moisture content can affect the maximum shear stress [11,13]. Contrary to materials of mineral origin, moisture easily penetrates inside the aggregates, leading to changes in the physical properties.

Some properties of aggregates (size distribution, shape, particle density, porosity, etc.) are reported in Tab. 1. The grading range for length and width was determined using an image analysis method as recommended by the RILEM TC in bio-aggregate-based building materials [14]. The particle density was measured by Nguyen et al. [15] on a hemp stem and by a paraffin method for rice husk [16].

Table 1: Morphological and physical features of plant aggregates

Aggregate	Hemp shiv	Rice husk
Shape	Cuboid	Semi-ellipsoid
Thickness	Quite thick (~1 mm)	Very thin (50-100 μm)
Length (mm)	2-25	5-8
Width (mm)	2-4	1-4
Bulk density ($g.cm^{-3}$)	0.1	0.09
Particle density[1] ($g.cm^{-3}$)	0.26 [14]	0.65 [16]
Inter-granular porosity	0.62	0.86
Flexibility	Low	Significant

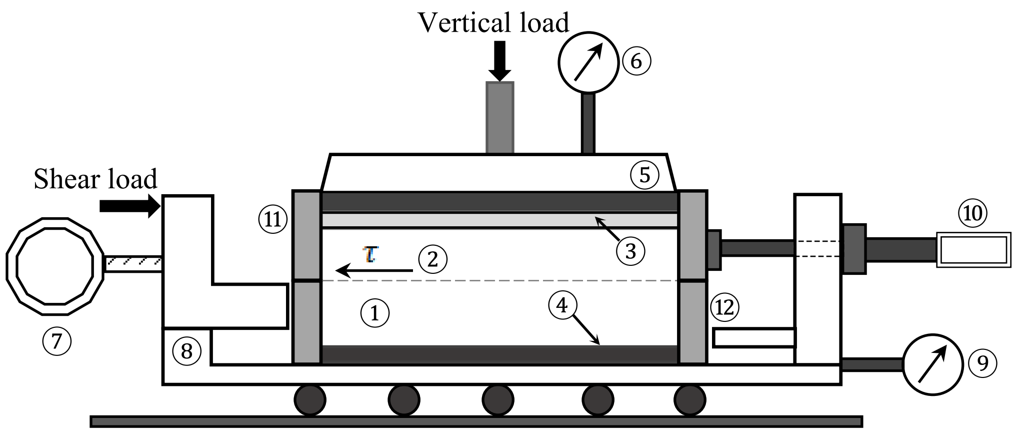
[1]Apparent density of a single particle

Furthermore, it should be noted that the compressibility of bulk aggregates is sizeable. When particles are subjected to a vertical load, they rearrange themselves to form close packing. Then, elastic and plastic deformations can occur, allowing the particles to flow into smaller void spaces [17,18]. The physical features reported in Tab. 1 are all factors that will contribute to the compressibility and the shear behavior of aggregates.

2.2 Experimental Procedure

The shear strength of unbound plant aggregates was measured using the direct shear test (according to the French standard NF P94-071-1 [19]). The equipment (see Fig. 2 for details) consists of a cylindrical shear box with 60 mm diameter. The shear box is split into two halves, along the horizontal shear plane. The lower half is fixed while the upper one can move. Aggregates are placed into the box, from the base plate to the top edge of the upper half (i.e., 45 mm). The vertical load is applied through a load frame with a lever arm and weights. This load remains constant during the test. The horizontal load is applied using a screw jack activated by an electric motor and a variable-speed transmission that make the sample to shear along the split plane.

The mass of hemp shiv or rice husk introduced into the box was set at 15 g in order to work with a same initial bulk density which was around 0.12 g.cm^{-3} after a slight compaction of the poured aggregates with the pressure pad (Fig. 2). The selected speed for shearing was 0.4 mm.min^{-1}. The shearing was conducted under three different normal stresses: 50 kPa, 100 kPa and 150 kPa. For each one, the test was performed at least three times to check the repeatability.



(1) Aggregates	(5) Pressure pad	(9) Dial gauge (horizontal)
(2) Shear plane	(6) Dial gauge (vertical)	(10) Shear load cell
(3) Porous stone	(7) Motor	(11) Shear box-Upper half
(4) Base plate	(8) Outer box	(12) Lower half

Figure 2: Shear box apparatus

3 Results and Discussion

3.1 Shear Behavior

The stress-displacement curves for both bio-aggregates and for each normal stress are shown in Fig. 3. The horizontal displacement (ΔL) is divided by the diameter of the shear box (D) for the x-axis. It should firstly be noted that the repeatability of the tests was suitable. For small horizontal strains, the shear stress strongly increases. Thereafter, a change in the slope of curves occurs and the shear stress increases more smoothly. It can be seen that curves do not reach a peak and even dot not stabilize towards an asymptotic value. This behavior is quite easy to understand since plant-derived aggregates are loose materials with a high inter-granular porosity (Tab. 1). Moreover, the particles show an important deformability. These characteristics lead to a volume contraction on shearing. The shear stress increases with the normal stress for both aggregates. However, it increases more strongly for hemp shiv. The gap between rice husk and hemp shiv becomes particularly significant for a normal stress of 150 kPa. In their work, Aloufi and Santamarina [10] succeeded in measuring a stabilization of the deviatoric stress with strain when using rice grains. In spite of the same morphological properties and size distribution, rice husk does not have the stiffness of grains. On the contrary, rice husk is flexible. The stress-strain behavior obtained for rice husk as for hemp shiv is very close to that reported in the paper of Stasiak et al. [11] dealing with woodchips and sawdust.

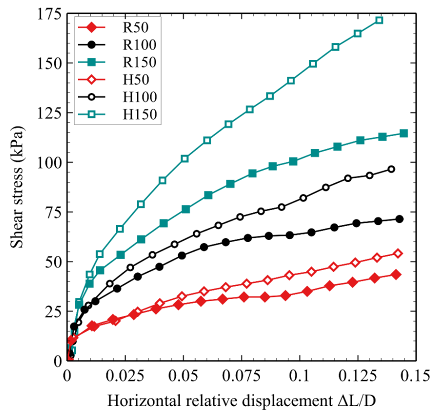


Figure 3: Experimental curves from the shear test on plant aggregates. R: rice husk-H: hemp shiv-50, 100 and 150 are normal stresses in kPa

With regard to vertical displacement, a first consolidation stage occurs instantly after vertical loading, due to the high compressibility of both plant aggregates. This settlement can be up to 5 mm. Thereafter, the vertical displacement plotted against the horizontal relative displacement is reported in Fig. 4 for the shearing stage (after the upper box just began to move). These curves allow the assessment of the change in the sample volume as the shear test progresses. One can see the decrease in vertical displacement as the shear stress increases for hemp shiv and rice husk. This can be taken as a contractive behavior since the same trend is observed for loose sand [20]. For hemp shiv, the decrease in volume is not as significant as that measured with rice husk. Moreover, the curves reported for hemp shiv seem to reach an asymptotic behavior (especially for the lower normal stress) whereas those of rice husk show an ongoing decrease of the vertical displacement until the end of the shear test. After vertical loading, the average immediate settlement is 3.5 mm. From the density of particles (Tab. 1) and geometric dimensions of the circular box, it is possible to calculate the inter-granular porosity into the sample just before shearing (i.e., after the initial settlement). The latter is about 0.5 for the skeleton based on hemp shiv whereas it is 0.8 for rice husk. This porosity undoubtedly plays an important role in the lower shear stress recorded for rice husk, compared to hemp shiv (as was observed in Fig. 3), inducing a lower inter-particle friction. Nevertheless, the higher vertical displacement during shearing is assumed to be strongly linked to the elasticity of rice husk particles which are bendable, unlike hemp shives which are more rigid. The different packing arrangement (with a more dispersed distribution of length for hemp shiv as stated in Tab. 1) added to the more elongated shape and stiffness of hemp shiv lead to a stronger granular interlock between particles thus giving this different behavior for the shear stress as for the volume change on shearing.

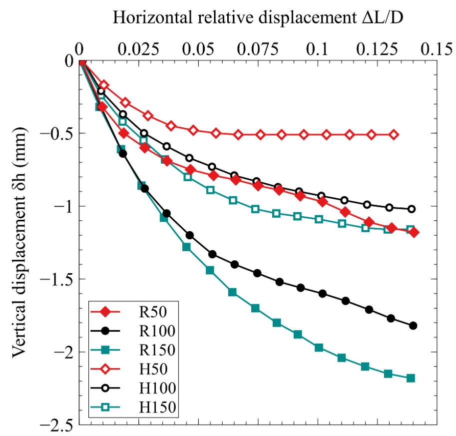


Figure 4: Vertical displacement versus horizontal relative displacement during the shearing stage. See Fig. 3 for the caption

3.2 Friction Angle

It is assumed that the shear strength of plant aggregates follows the Mohr-Coulomb failure criterion of plasticity. It is one of the constitutive models of granular materials for which the shear strength is a linear function of the normal stress. By analogy with the behavior of soil shear strength, the shear stress is expressed in Eq. (1):

$$\tau = \sigma \tan(\varphi) + C \quad (1)$$

where τ is the shear stress on the failure plane, σ is the normal stress, φ is the friction angle and C is the cohesion strength.

The cohesion index is in fact the required stress to break the bond when there is no normal load [2]. Therefore, in the case of unbound plant aggregates, it is advisable to plot the linear failure envelop from the zero cohesion. In view of the absence of peak shear stress (Fig. 3), the friction angle is determined for an horizontal displacement that reaches 12% of the box diameter (ΔL/D = 0.12). The linear regression of the failure envelope is reported in Fig. 5 for the three shear stresses achieved at this level of horizontal displacement depending on the intensity of the normal stress.

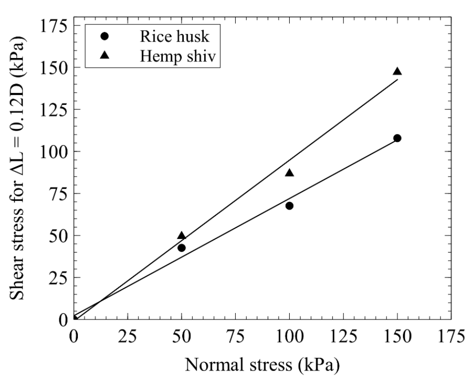


Figure 5: Shear stress for ΔL = 0.12D versus normal stress

The friction angle of unbound plant aggregates for ΔL = 0.12D is calculated from Fig. 5 and reported in Tab. 2. The latter is clearly higher for hemp shiv. Furthermore, this friction angle value is compared with that calculated from the triaxial shear tests on plant-based concretes studied in a previous paper [8]. Rice husk and hemp shiv were mixed with a commercial lime-based binder and tamped into moulds by vibro-compaction. Then, specimens were cured during 60 days at 23°C and 65% RH before being tested in triaxial compression with drainage at air pressure. Fig. 6 shows the photograph of one of these specimens.

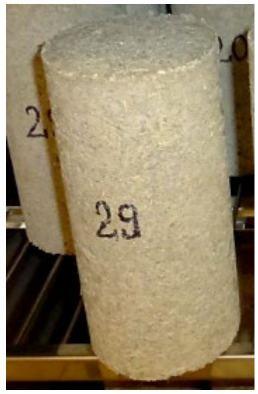


Figure 6: Specimen of a bio-aggregate-based concrete

The friction angle calculated for the peak shear strength of bio-based concretes is secondly reported in Tab. 2. The latter appears to be close to that of unbound aggregates, especially for hemp shiv, further confirming the strong relationship between the peak friction angle of bio-aggregate-based concretes and the friction properties of granular biomasses with which concretes were designed.

The angle of internal friction of sands from direct shear tests is often reported to be higher compared to the triaxial compression tests [21-23]. This is the case for rice husk as plant aggregate. The peak friction angle measured on concretes with triaxial testing is not only dependent on the stress path but also on their density after casting. The compaction intensity to cast hemp concrete was significantly higher compared to rice husk concrete due to the lower inter-granular porosity of hemp shives [8]. This can explain the strong value of the peak friction angle measured on hemp concrete more closely related to the dense packing of shives than inherent friction properties of bulk aggregates as is the case with the shear box test. Initial inter-granular porosities just before shearing are reported in Tab. 2 for unbound aggregates and bio-based concretes.

As was seen with concretes, the granular skeleton made up of rice husk particles shows a lower shear strength owing to the large inter-granular porosity and the properties of rice husk (elasticity, shape and size distribution) that hinder the rearrangement of particles during the shearing process in comparison with hemp shiv. Consequently, rice husk is definitely less resistant to friction forces whereas the granular skeleton based on hemp shives is more stratified and particles are thick and rigid, thus resulting in higher friction forces. From Tab. 1, one may note that the slenderness ratio (length on width) of hemp shiv can be up to 12 whereas that of rice husk is more limited. This implies a strong horizontal alignment for hemp shiv. According to some authors [24-26], depending on particle shape (i.e., slenderness, eccentricity) and inter-particle friction, the angle of plant particules to the shearing direction will increase towards a normal alignment, contributing to a significant shear strength, especially with a dense packing as it is probably the case with the higher normal stress (150 kPa).

Table 2: Friction angle of aggregates for $\Delta L = 0.12D$ compared to peak friction angle of concretes

Unbound aggregate	Rice husk	Hemp shiv
φ for $\Delta L = 0.12D$ (°)	35	44
η_{Inter}[1]	0.8	0.5
Concrete	LRC[2]	LHC[3]
φ_{PEAK} (°) [8]	29	46
η_{Inter}[1] [8]	0.5	0.07

[1]Inter-granular porosity; [2]Lime and Rice husk Concrete; [3]Lime and Hemp Concrete

4 Conclusion

Hemp shiv and rice husk were tested with the shear box apparatus to assess the shear strength of these plant aggregates dedicated to bio-based materials for green building. As would be expected, the stress-displacement curves were not stabilized after a relative displacement of almost 0.15 due to the high deformability of plant particles and significant inter-granular porosity in bulk aggregates. However, it was possible to compare two kinds of plant-derived aggregates with very different geometrical and mechanical properties. The results highlighted the best behavior of hemp shiv under shear stresses. The higher stiffness of shives combined with their slenderness ratio can explain the trend. Moreover, an interesting similarity was noted with the peak friction angle of concretes cast with plant aggregates mixed with a small volume fraction of binder using the triaxial shear test.

It should be noted that a shear box with a larger diameter would be more appropriate in view of the maximum length of some plant particles in order to limit the border effect [27].

Furthermore, the compressibility of bio-aggregates is an important property that could undoubtedly help to understand the mechanical behavior of such materials. In this field, the paper of Viel et al. [28] gives promising opportunities.

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