

Mechanical Response of Flax Rovings under Compaction: Experimental Investigation

Samir ZIDI^{1,a*}, Tiffany LARQUEMIN^{1,b}, Audrey HIVET^{1,c}, Gilles HIVET^{1,d}
and Davy DURIATTI^{2,e}

¹Laboratoire de mécanique Gabriel LaMé, University of Orléans, Chartres, France

²Depestele Group, Bourguébus, France

^asamir.zidi@univ-orleans.fr, ^btiffany.larquemin@univ-orleans.fr, ^caudrey.hivet@univ-orleans.fr,
^dgilles.hivet@univ-orleans.fr, ^edduriatti@depestele.com

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Abstract. This study investigates the compaction behavior of woven flax rovings, a crucial aspect of the preforming stage in composite manufacturing. It focuses specifically on the challenges posed by their inherent heterogeneity and structural variability. Although the durability of flax-based composites is widely recognized, accurate numerical modeling of their processing, particularly for liquid composite molding (LCM), remains limited by the lack of detailed experimental data on roving mechanical behavior, including data capturing the inherent variability of the material. This research used a combined experimental approach, comprising computational microscopy for microscale deformation analysis and macroscopic compression tests, to characterize the mechanical response of flax rovings under compaction. Results highlight the need to develop sophisticated simulation frameworks that account for statistical variations in material properties but also the specificities of the flax roving response, which differs considerably from that of synthetic fibers rovings. The experimental dataset generated provides a valuable basis for identifying material parameters and validating advanced simulation frameworks aimed at improving performance predictions of manufactured components.

Introduction

The design of modern structures is increasingly constrained by the need to develop lightweight, high-performance, sustainable solutions in an environmental context that demands reducing the ecological impact of materials and processes [1, 2]. This transition is pushing the field of engineering toward bio-based composites, which replace traditional synthetic fibers (such as glass and carbon) with renewable resources, thereby reducing dependence on fossil fuels [3]. Some of these composites are biodegradable, which contributes to a circular economy [4,5].

Bio-based composites are being adopted in many sectors, including automotive (interior components and reinforcements), aerospace, and construction (insulation and structures), as well as packaging [6]. A wide range of natural fibers (e.g., flax, hemp, and jute) is available, each with specific intrinsic properties [7].

Among the many natural fibers that have been studied for use in composites, flax is a particularly strategic material. Its importance stems from its technical and logistical advantages [8]. First, its mechanical properties, particularly its strength-to-density ratio, rival those of conventional glass fibers. This property enables the production of lightweight structures for high-tech applications without compromising structural performance. Second, flax is cultivated throughout Europe, primarily in France, which offers a considerable logistical advantage [9]. Short transport distances for raw materials reduce the carbon footprint of the finished product and boost the local and regional economies. In addition to these mechanical and logistical benefits, flax offers valuable functional advantages. It has intrinsic thermal and acoustic insulating properties in high demand for industrial applications [10, 11, 12].

It is important to note that the processing flax fibers is complex and greatly affects the quality of the final material. The performance of the resulting composites depends on controlling the steps after harvest. Key stages of the process, such as retting, scutching, and combing during sliver preparation, are particularly important. Poor management of these initial treatments can introduce variability that significantly impacts the composites' final mechanical performance [13, 14].

Despite their potential, existing models fail to predict the compaction behavior of flax slivers [15,16]. This study aims to address this gap with a two-pronged approach. First, we characterized the compaction behavior experimentally using a multi-scale approach that integrates microscopic observations and macroscopic measurements. Second, we analyzed the deformation mechanisms that occur at the fiber level. Our approach is original in that we combine innovative experimental methodologies to quantify the variability of this behavior and establish direct links among the properties of the fibers, the observed mechanisms, and the macroscopic response of the wicks. This information is crucial for developing accurate numerical models.

2. Materials and Methods

2.1 Materials. This study used woven flax rovings supplied by the Depestele Group. These rovings were used as a reinforcement material. The roving count was 520 ± 20 tex, which indicates the fineness of the fibers they contain. The average thickness of the rovings was 0.15 ± 0.05 mm, and the average width was 5.1 ± 1.4 mm. The linear density, representing the mass per unit length, was 0.52 ± 0.02 g/m. To ensure that the experimental results accurately reflect the material's commercial behavior, the rovings were used as is, without pretreatment or surface modification. Using the as-is rovings enabled us to measure this specific flax's actual compaction behavior consistently without introducing external factors that could alter the fibers' natural mechanical response.

2.2 Compaction Test Setup. We conducted compaction tests in a Keyence VHX-5000 digital microscope equipped with a loading stage, to enable detailed observation of fiber deformation during compression. A custom-made compression stage was mounted directly onto the microscope platform to apply a controlled compressive force. The microscope had an XY resolution of 3.0–6.0 μm and an estimated Z-axis accuracy of less than 10 μm (Fig. 1). These specifications were essential for capturing subtle variations in the sample cross-section. The load capacity of the stage in the microscope was 1 kg, and the maximum observation length was 12 mm. The microscope was equipped with a high-resolution camera capable of acquiring images at magnifications ranging from 50x to 200x using transmitted light illumination. The stage guides a glass plate, allowing the load to be applied and the roving to be observed. Guidance is provided by two axes and ball bushings, ensuring parallelism, rigidity and low friction. Loading is carried out by adding masses, ensuring a discontinuous but precise control. Preliminary tests enabled verification that the glass plate does not distort the image.

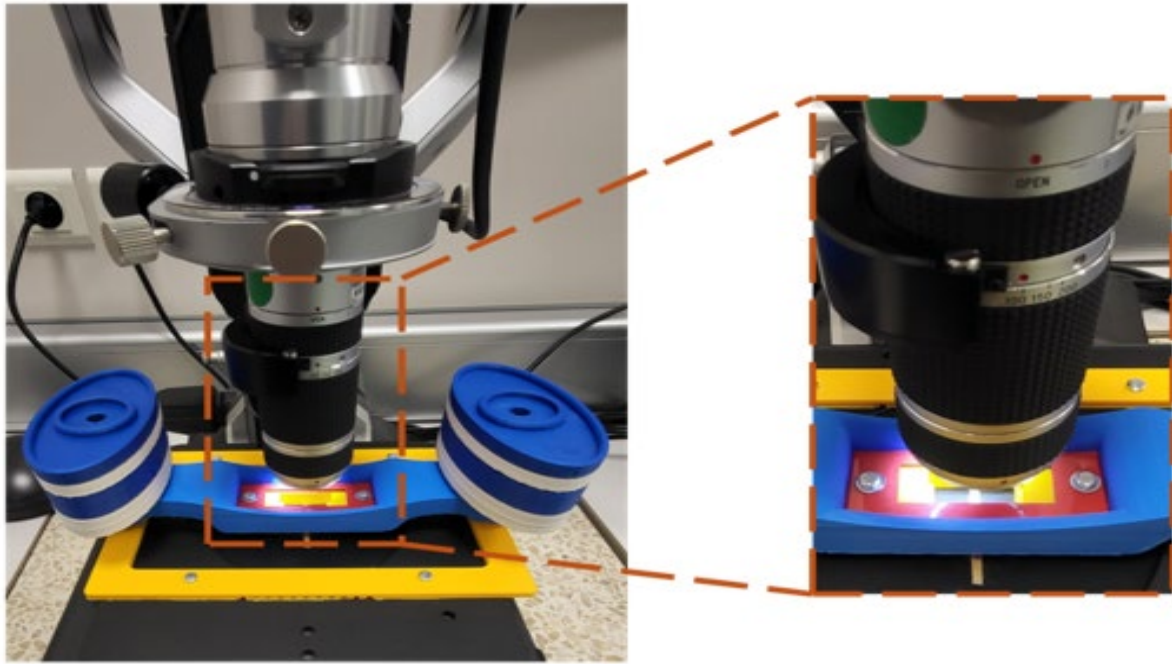


Fig. 1. Compaction device under microscope

The goal was to observe the cross-sectional variations (thickness and width) of the strand under load. The flax roving samples were carefully positioned on the compression stage to enable observation of the fiber structure as shown in Fig. 2. Acquiring and processing the images for ten measurements took approximately two hours. All tests were conducted under controlled environmental conditions of an ambient temperature of 23°C and a relative humidity of 50%.



Fig. 2. Compaction device under microscope

2.3 Compression Test Setup. Macroscopic compression tests were performed using a carefully instrumented Zwick tensile testing machine to record the force-displacement response of the flax strands under compressive load (Fig. 3). Before each compression test, particular attention was paid to determining the initial dimensions of the sample. The thickness and width of each strand were measured under initial compression test conditions using the previously described Keyence VHX-5000 digital microscope. These preliminary measurements enabled the precise calculation of the average apparent pressure exerted on the sample and the variation in thickness undergone by the tow during the test. To ensure uniform application of the compressive load, tests were carried out using rectangular PMMA plates. The quality of the parallelism was also verified using a Tekscan pressure sensor inserted between the two plates (Fig 3-B). This sensor validates the uniform distribution of pressure applied to the specimen during compression. Given the small thickness and small displacements, it is critical to maintain strict parallelism and mitigate the effects of clearances and machine rigidity, which was achieved with this protocol. A key aspect of this setup was the use of a

high-resolution camera that achieved a resolution of 0.007 mm/pixel. This high resolution enabled detailed visual tracking of sample deformation throughout the test by measuring the distance between two markers positioned on the two plates (Fig 3). The tests were performed at a quasistatic speed of 0.125 mm/min. This slow, controlled speed mitigated dynamic effects and ensured accurate measurement of the material's behavior. The main objective of this experimental protocol was to observe and understand the critical transition between two phenomena: the internal reorganization of fibers within the tow and the deformation of individual fibers resulting from locking and interactions within the tow network.

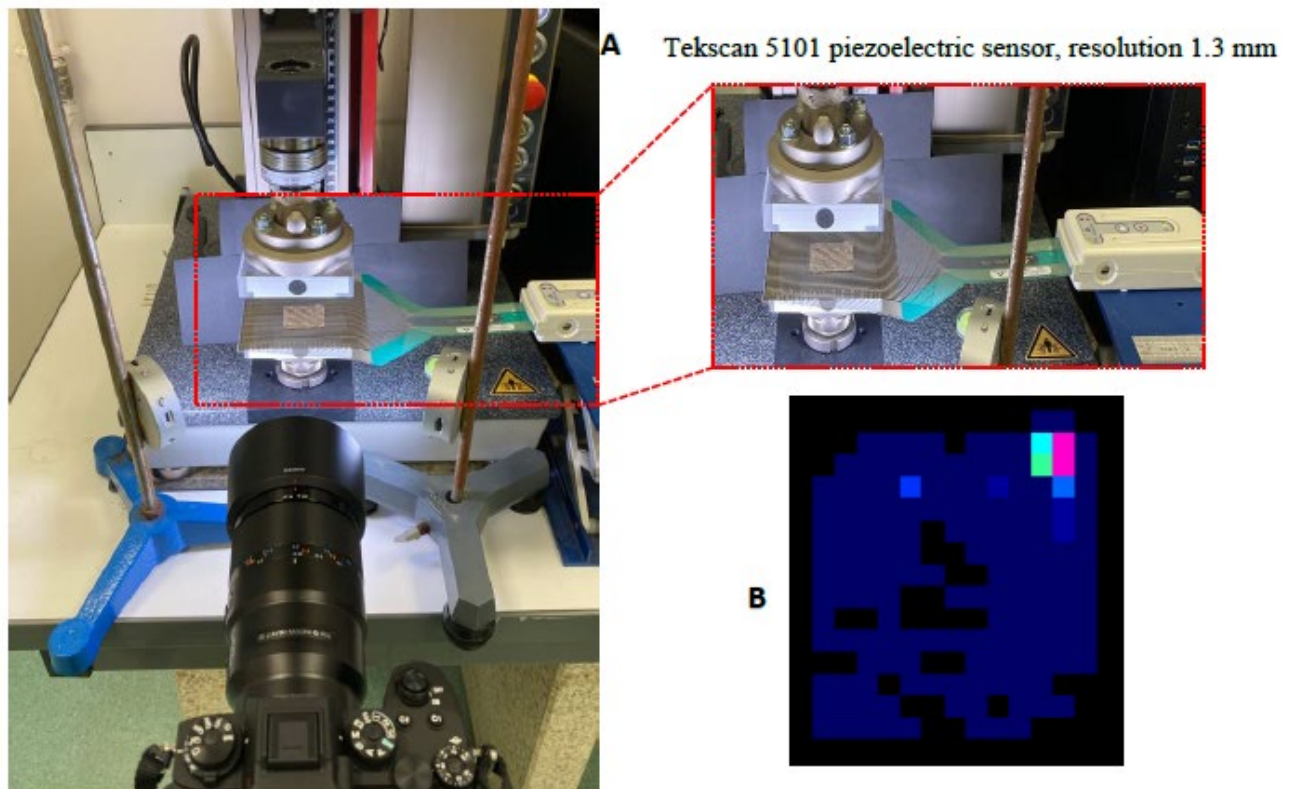


Fig. 3. Microscope (A) Compression test setup (B) Visualization of the pressure distribution observed from the Tekscan sensor during calibration of the platen orientation.

3. Results and Discussion

3.1 Compaction/Compression Test.

One of the most striking results of the compaction tests was the nearly perfect preservation of the samples' transverse geometry as the loads increased. Contrary to the usual expectation for fibrous materials under stress, there was no lateral expansion. The Coil Rovings' (CR) specimen profiles remained strictly superimposable throughout the test, with no detectable widening, as illustrated in Figs. 4 and 5. We quantified this dimensional stability by considering measurement uncertainties, especially those due to fiber protrusion and the presence of free fibers. The maximum relative error was estimated at 2%. The absence of broadening, even at low pressures (up to 0.1 MPa), demonstrates that the fiber reorganization mechanisms typically observed in synthetic fiber rovings do not exist, as shown in Fig. 4.

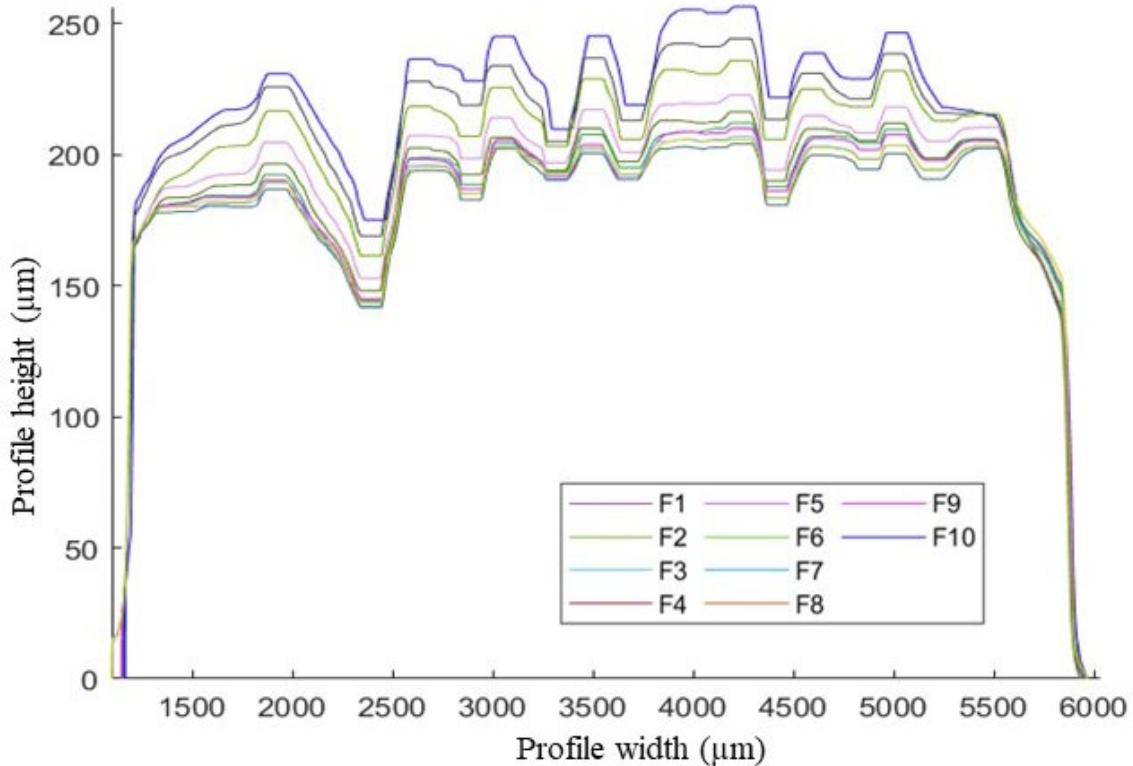


Fig. 4. Superposition and evolution during testing of a profile

Another key observation is that surface irregularities remained visible in the cross-sectional profiles throughout compaction. One might assume that with increasing pressure, the internal structure of the reinforcement would reorganize to smooth out the surface undulations, producing a more uniform cross-section. However, the results show that, although the amplitude of the irregularities decreases slightly, the overall topology of the profile remains unchanged, regardless of the type of specimen tested (Fig. 5). Initially, it seemed possible that rigid body motion limited deformation at the beginning of the test. However, under increasing pressure, this assumption loses validity, particularly around 0.1 MPa, where actual compaction would be expected. The stagnation of thickness variation in the final increments confirms this hypothesis, suggesting that maximum compaction is reached without uniforming of the external surface.

Therefore, it can be concluded that the flax rovings exhibit atypical "compaction behavior," as their microstructure reorganization differs significantly from the local densification that is classically observed for synthetic rovings due to their high fiber mobility. The atypical compaction behavior originates from the internal cohesion resulting from the roving manufacturing process which limits the relative mobility of the fibers. Furthermore, the composition of flax yarn differs significantly from that of technical rovings. Technical flax fibers consist of an assembly of short flax filaments and interfacial lamellae after the hackling step. Therefore, flax rovings cannot be considered to consist of individual filaments that are free to move relative to each other. This structure tends to form fiber clusters that move together, reducing microstructural reorganization. In conclusion, flax rovings exhibit a specific compaction behavior resulting from the particular constitution of technical flax fibers and the specificities of their manufacturing process, which reduces local mobility and microstructural reorganization. Despite the increased pressure from the flat plate, surface irregularities persist.

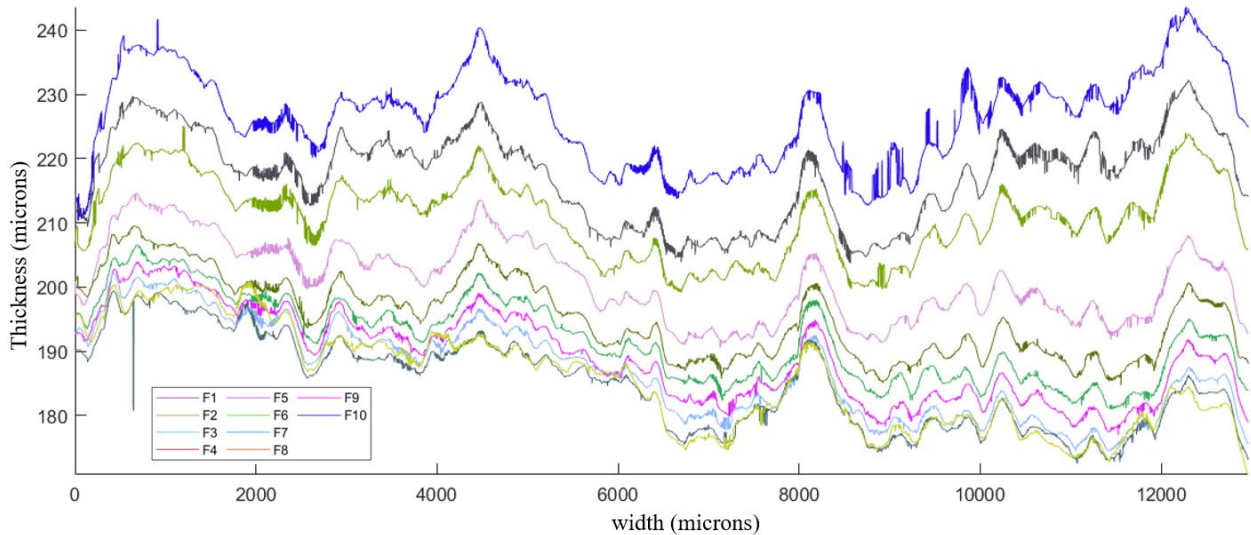


Fig. 5. Evolution of the thickness of the profiles of a sample

The compaction behavior of each sample was characterized by analyzing the experimental data with MATLAB's `lsqnonlin` algorithm, which is based on Toll's equation [17]. This approach enabled us to determine the primary mechanical parameters: initial compressive stiffness (K_c), compaction rate, and fiber surface fraction. We used two approaches for these parameters: the "apparent" approach, based on idealized geometry, and the real approach, based on measured profiles. The results show that curves derived from apparent data are smoother and more consistent due to geometric smoothing. However, parameters extracted from real data more accurately reflect the actual behavior of the material, albeit being more sensitive to local irregularities. This discrepancy underscores the importance of considering real geometry in simulations to predict the mechanical response of reinforcements accurately.

Curve fitting revealed two significant phenomena. First, there was an absence of transverse swelling during compaction. Second, surface irregularities persisted. These phenomena suggest that deformation is dominated by overall settlement rather than by local fiber reorganization (Fig. 6). These observations reflect atypical behavior strongly influenced by the size and internal structure of the roving. This finding justifies the need for in-depth studies, particularly in situ tomography, to visualize these mechanisms.

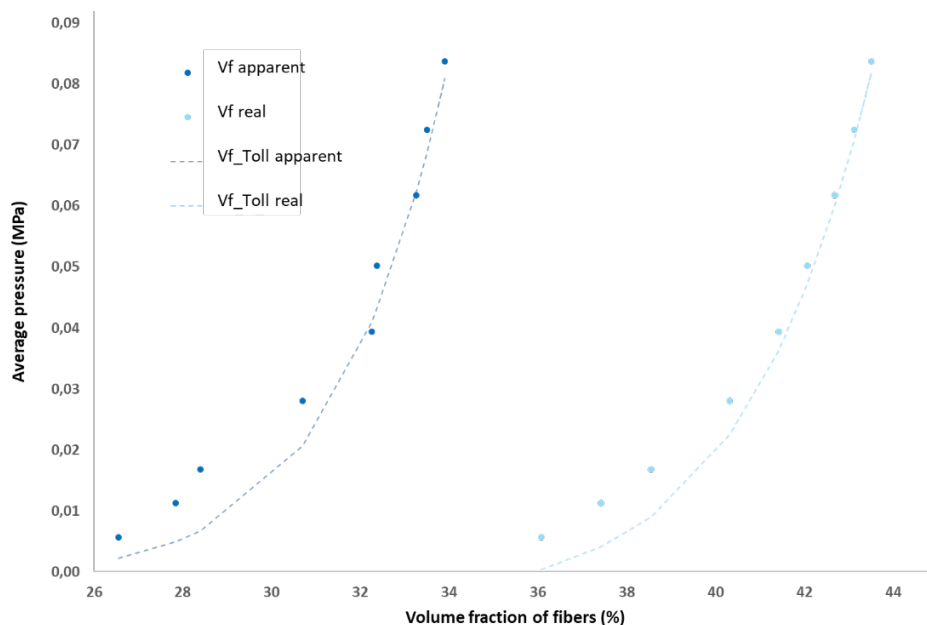


Fig. 6. Interpretation of data using Toll's equation

3.2. Compression Test Results.

Macroscopic compression tests analyzing the behavior of flax rovings extracted from coil rovings for testing provided crucial information on how they respond to applied pressure. Using marker displacement during compression followed by image analysis, we determined the apparent fiber volume fraction as a function of applied pressure, as shown in Fig. 7.

It is important to recognize the limitations of the measurement technique, especially when working with very high-volume fractions. At these stages, thickness variation becomes minimal, yet the relative measurement uncertainty of the image analysis technique increases. Thanks to the optical strategy implemented, the estimated uncertainty in the marker position at the pixel level, caused by limitations in image resolution, can lead to a totally acceptable variation (up to 2%) in the calculated fiber volume fraction even at high volume fractions.

As is often the case with fiber reinforcements, our analysis revealed significant variability in compression behavior among the tested samples (CR1, CR2, CR3, CR4, and CR5).

The initial compression phase, exhibited a very small stiffness, thus finite strains under low loads. This step is primarily due to fiber reorientation and void filling within the roving structure under pressure. This initial phase is crucial because it determines the material's initial stiffness and consolidation behavior, two parameters that influence the final composite's performance.

Additionally, the variability observed in compressive response highlights the inherent complexity of natural fiber structures compared to more uniform synthetic fibers. Differences in compressive response are likely strongly influenced by heterogeneity in the microstructure and packing density. These trends have important implications for modeling the overall behavior of composite materials, suggesting the need for models capable of accounting for the stochastic nature of natural fiber arrangements.

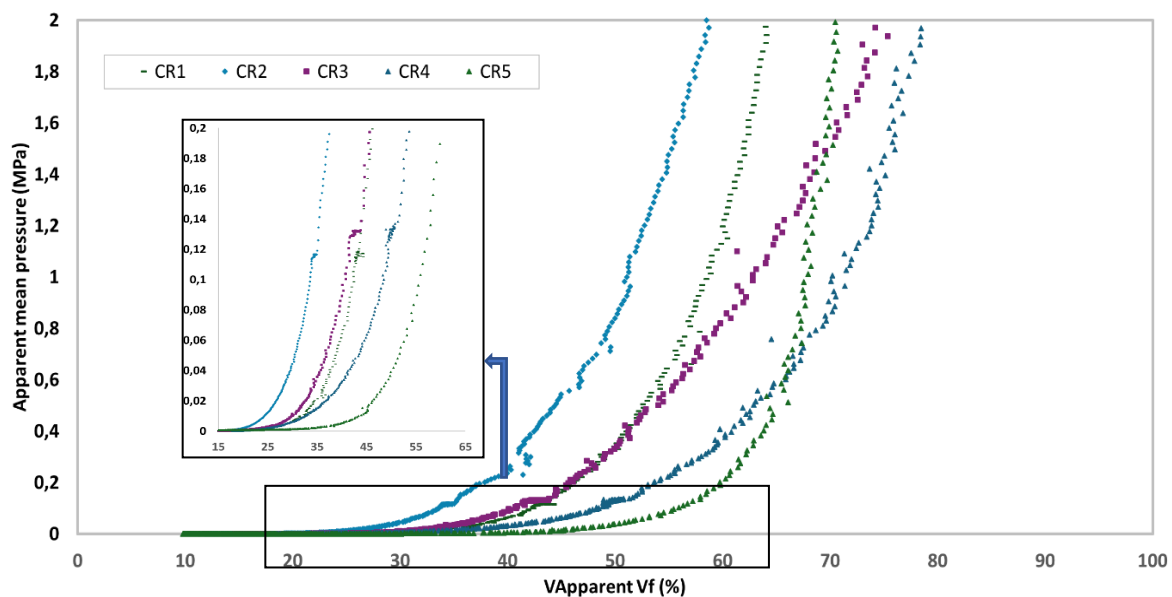


Fig. 7. Compressive behavior obtained for different samples from image analysis and zoomed in the view of the behavior of the samples over the 0-0.2MPa range.

To evaluate the applicability of existing compaction theories, we applied Toll's equation to our experimental results. While the model generally reproduces the shape of the compression curves, it deviates considerably from the values measured during the initial low-load phase, as illustrated in Fig. 8. This poor fit suggests that the physical assumptions underlying the Toll and Manson models [18], that compaction results exclusively from fiber sliding in voids and direct contact, are insufficient for this initial stage. In reality, the initial compressive strength is governed by many subtle factors, including fiber instability, organization within bundles, inter-fiber friction, and surface coating adhesion. The divergence observed in the low-stress domain confirms that while the Toll and Manson

equation provides a usable basis of reference for the overall response, it fundamentally lacks the ability to describe the dynamic structural changes that flax cables undergo during initial densification.

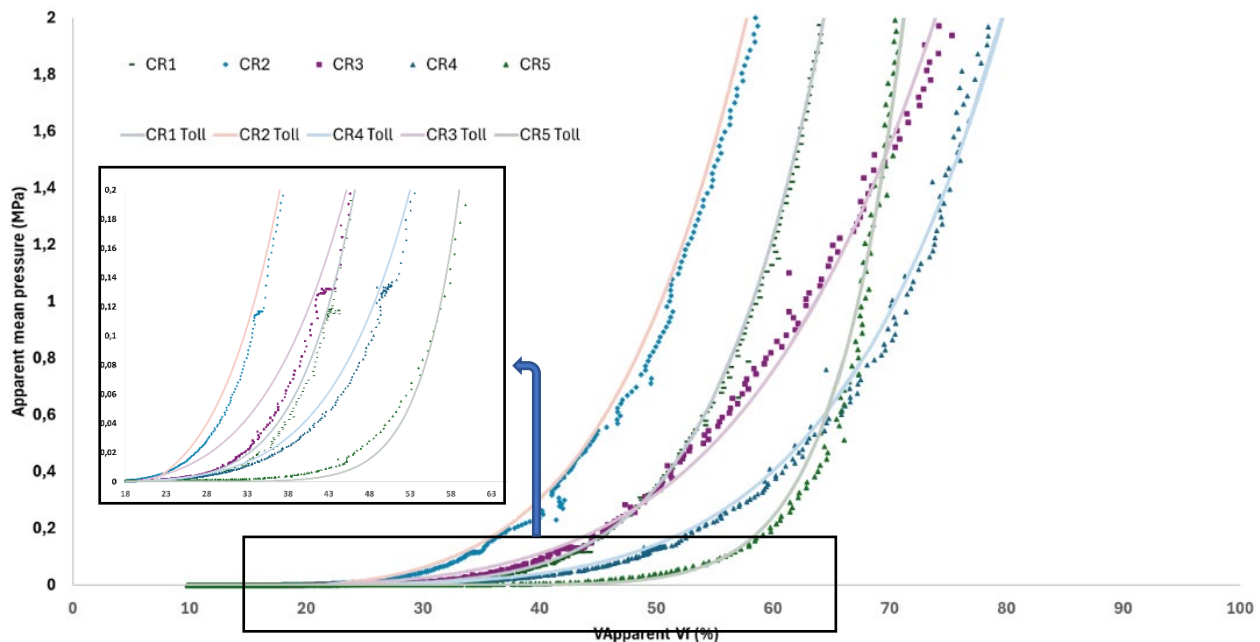


Fig. 8. Fitting compression behavior by the Toll model.

4. Conclusion

Compaction/Compression tests have been performed on flax rovings. The use of a high-resolution numerical microscope and in-situ compaction measurement enabled the tracking of the evolution of the external microstructure under low pressure. Results revealed atypical mechanical behavior. The samples maintained their cross-sectional geometry exceptionally well under increasing load. Contrary to conventional fiber materials, there was no significant lateral expansion, and surface irregularities persisted throughout compaction, even at high pressure. This dimensional stability, with a maximum relative variation of 2%, suggests that the classic reorganization and local densification mechanisms observed in synthetic fiber rovings do not occur. This therefore leads to considering the difference between the apparent pressure and the real contact pressure in the analysis and modeling of the compression behavior of flax reinforcements.

This behavior can be explained by the flax rovings' specific internal cohesion. The manufacturing process involves specific flax yarn composition consisting of short filaments and interfacial lamellae that form fiber clusters rather than individual filaments. This process significantly limits the relative mobility of the fibers. The intrinsic rigidity of the fiber network limits microstructural reorganization and fiber fluidity under stress.

Compression tests were also performed to obtain the compression behavior at high pressure, complementing the previous compaction tests. The two types of test proved to be consistent. The lack of internal reorganization and the persistence of surface heterogeneities suggest that conventional compaction models based on the assumption of high fiber mobility are inadequate for accurately describing the behaviors of these materials. Thus, macroscopic compression tests revealed significant variability between samples and highlighted the limitations of the traditional Toll model in capturing the nuanced deformation mechanisms of flax rovings.

While Toll's model may be used as a first approximation, it is necessary to look for other models to account for the specificities of flax rovings.

These observations have important implications for modeling and predicting the behavior of flax-based composites. Although the observed variability in response is uncorrelated with fiber orientation within the reinforcement, it highlights the importance of considering the stochastic nature of natural fiber arrangement for precise modeling.

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