Improving precision in the cavity thickness measurement for fabric compaction

SOUSA Pedro[1,3a *], LIU Xiao[2,b], LOMOV Stepan V.[1,c] and IVENS Jan[3,d]

[1] Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44, BE-3001 Leuven, Belgium

[2] School of Information Engineering, Wuhan University of Technology, Wuhan 430070, China

[3] Department of Materials Engineering, KU Leuven – Campus De Nayer, J. De Nayerlaan 5, B-2870 Sint-Katelijne Waver, Belgium

[a] pedro.sousa@kuleuven.be, [b] liuxiao001@whut.edu.cn, [c] stepan.lomov@kuleuven.be, [d] jan.ivens@kuleuven.be

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Abstract. As seen in the first international compressibility benchmark, inaccuracies in the fabric stack thickness measurement, the approach to compliance correction and the non-parallelism between compaction plates resulted in highly inaccurate compression curves. The factors influencing the accuracy of thickness measurements in compaction tests were studied to provide a comprehensive guidance and measurement recommendations to improve upon the current procedures and enhance the accuracy of thickness measurements. These include the variability in the direct thickness measurements due to accuracy of the laser sensors measurements and the variability in the machine compliance measurements. In conclusion, while both thickness measurement methods yielded comparable results, it is noteworthy that the direct method exhibited greater variability in thickness measurements compared to the indirect method, which rely on the machine displacement. Minor changes in the rig's displacement or in the orientations between compaction plates due to differences in the pressure distribution during compaction, combined with other sources of variability such as external interferences or vibrations from the compaction plate led to variations in measurement´s accuracy throughout the tests.

Introduction

A common element to the majority of LCM (liquid composite molding) manufacturing processes is the compaction of a fabric reinforcement inside a rigid or flexible mold prior to the resin injection. Compaction increases the fiber volume fraction and defines the microstructure of the reinforcement for injection. This process subsequently impacts the permeability and impregnation behavior, ultimately determining the mechanical properties of the finished component [1]. Knowing the compaction behavior of a fabric reinforcement across a wide range of pressures provides valuable information for the manufacturing processes. Particularly in the design stage, knowing the compaction behavior of a fabric reinforcement – the stack thickness as a function of pressure – facilitates the selection of the manufacturing process parameters and mold design. The compaction behavior of a reinforcement is determined by compacting a fabric stack between two rigid surfaces in a UTM (universal testing machine) at a constant displacement rate while monitoring the compaction force and the distance between plates, the cavity gap. However, as was seen in the first international benchmark on textile compaction response promoted by NPL (National Physics Laboratory, UK) in the years 2017 and 2018, the variability in these measurements is considerable [2]. Alike the results obtained in the radial permeability benchmark [3] which ran simultaneously with the compressibility benchmark, the scatter in the compression curves reported by different participants was much higher than the scatter in individual measurements. Though the variability in the compression curves reported by each participant was consistent, a scatter of 38% among participants was found for the compaction pressure at the target thickness of 3 mm. In saturated conditions, the scatter among participants was 40% for the Saertex fabric (NCF multiaxial) and 50% for the Hexcel fabric (2/2 twill woven) both E-glass fabrics. The scatter in the compaction pressure was attributed to inaccuracies in the thickness measurements, the approach to the compliance correction and the non-parallelism between compaction plates. Such results showed the need for improved compressibility guidelines regarding the thickness measurement technique and compliance corrections. These challenges were tackled in a new methodology developed by the benchmark consortium, with participation of the authors, for the second international benchmarking exercise in 2022 [4]. The second compressibility benchmark, also promoted by the NPL, intended to increase the accuracy in compression test and refine the test procedure for a future standardization through the implementation of recommendations for the measurements. In this benchmark, the usage of direct thickness measurement methods – laser sensors or LVDTs – was mandatory in addition to self-aligning plates with a lockable mechanism. However, several aspects such as the placement of distance sensors in the rig, the usage of self-aligning plates, and the approach to the compliance correction require a deeper study because these can still compromise the measurement´s accuracy.

This paper presents a methodology for obtaining and analyzing data in compression tests with simultaneous use of direct (laser sensors) and indirect (UTM) thickness measurement methods. This study shows how several variability sources related to the measurement's methodology can be decreased to narrow the differences in the accuracy of both measurement methods. Good measurement practices are proposed to improve the measurement´s accuracy, aiming to the establishment of a standardized and consistent approach to fabric compaction measurements.

The implementation of the testing protocol

The compressibility rig

The compaction tests were performed on a radial-permeability rig [5] installed in a UTM, an Instron 4467 displacement-controlled machine with a load cell capacity of 30 kN (±0.5%). The compaction rig is comprised of an upper compaction plate, a cylindrical aluminum plate 250 mm in diameter, and a lower plate, a square glass plate (Herasil 102) with dimension of 300 mm x 300 mm. Both plates are 30-mm thick as shown in Figure 1. A ball-and-socket joint system attached to the upper compaction plate allows the free rotation of this plate, ensuring the correct parallelism between plates when the plates are pressed against each other. Once the desired load is achieved, the ball joint is locked in place by a threaded clamp. The distance between compaction plates, the cavity gap, is measured by three laser sensors (UR, UB and UF), model CP08MHT80 from Wenglor®, resolution of 8 µm, installed on the top of the upper compaction plate, 90º out of phase with each other. Red electrical and aluminum tapes were placed on the glass plate to improve the laser back reflection. The aluminum tape removes the plate´s transparency, and the electrical tape facilitates the cleaning and its replacement during tests. In saturated tests, a 4-mm thick layer of masking tape was placed in front of the reflective tapes to prevent oil from covering these tapes and interfering with the laser´s reflection. The sensors output is digitized by a USB-6210, a multifunction I/O Device from National Instruments programmed in LabVIEW. When the pre-set cavity thickness is detected by two of the three laser sensors, the UTM´s crosshead movement direction is automatically reverted. The arrangement around the compaction plate results in three compression curves measured on the right, back, and front sides of the rig, allowing to define a plane on the compaction plate surface and monitor its parallelism with the glass plate below.

Materials and methods
The compression tests were performed with a Saertex multiaxial NCF E-glass reinforcement centrally distributed to the benchmark participants. The fabric stacks were compacted up to a target thickness of 3 mm at a constant speed rate of 1 mm/min in dry and saturated conditions on five specimens. At the target thickness of 3 mm, as measured by the direct thickness method, the compaction process was reverted, and the stack unloaded at the same displacement rate. Square fabric samples with side 150 mm (± 1.9 mm) were cut from the fabric roll with a fabric shears and stacks of 10 layers were formed. All layers in the stacks had the 0° (warp) direction coinciding and the same surface facing upwards. The fabrics dimensions are smaller than the compression surface area as requested in the measurement procedure; therefore, the load values measured by the UTM were converted to applied pressure by dividing them by the area of the specimen surface, which has a value of 150±1.9 cm². An areal density of 452 ± 3.5 g/m^2 was determined by measuring the area of each fabric layer with a ruler and weighed in a Mettler AE 24 scale (± 0.1 gram).

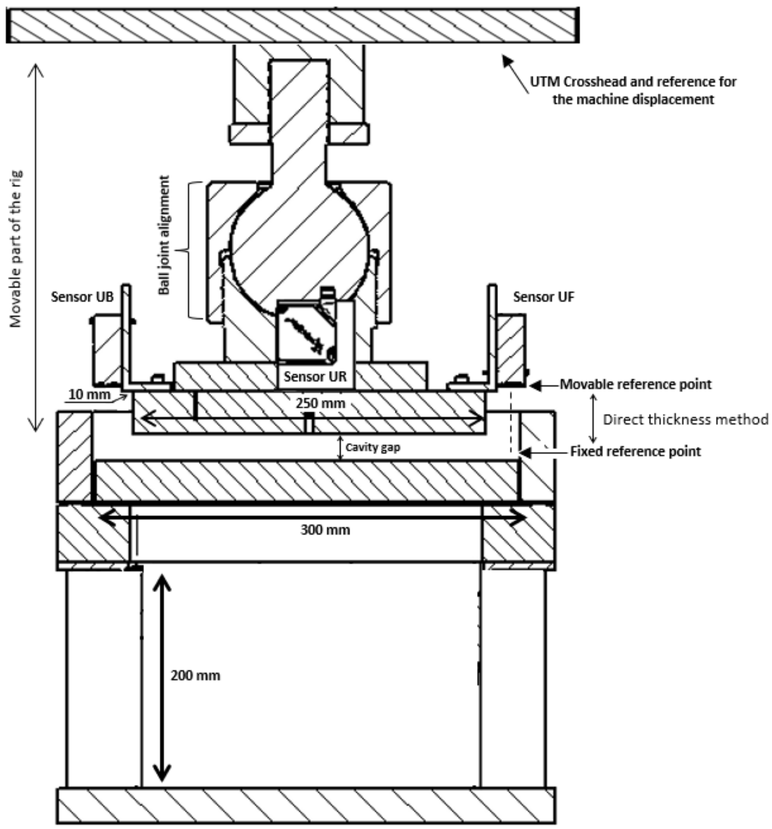

Figure 1: The rig´s installation in an UTM allows to compress a fabric stack at a constant displacement rate up to a pre-set pressure or thickness. The upper compaction plate, a cylindrical aluminum plate 250 mm in diameter, is self-aligning with the glass plate below by a ball-and-socket joint. The cavity gap measured by the indirect thickness method is obtained from the crosshead position with a correction for the rig´s compliance, while the direct thickness method measures the cavity gap by calculating the difference between a fixed and movable reference point measured outside the cavity.

The compaction in saturated conditions was conducted by submersing an entire fabric stack in a silicone oil bath, Dow Corning® Xiameter PMX 200/100 cS, 0.96 kg/l, for 15 min at an oil bath temperature of 22.4 ± 0.3 °C and a room temperature of 23.1 ± 0.2 °C. The temperature within the rig cavity was measured before placing a fabric stack, revealing an average of 23.8 ± 0.3 °C. At these temperatures, the oil viscosity ranges between 93.7 ± 0.5 mPa.s and 94.2 ± 0.5 mPa.s at the lowest and highest registered temperature, respectively. The temperature in the rig cavity is slightly higher than the room temperature due to heat being generated by the machine electronics, placed below the machine bench, and conducted upwards through the rig.

Results

Machine compliance measurements

The usage of compaction plates with locking mechanisms is essential to ensure the correct parallelism between plates during compression because non-locked compaction plates do not retain the parallelism during compaction. The plates were pressed together at a displacement rate of 0.5 mm/min up and locked at a load of 28 kN (0.57 MPa), the maximum pressure allowed by the system. The locking load is higher than the load encountered during compression tests to prevent a plate realignment. This load criterion is important because the compaction load lowers the clamping pressure in the ball-joint which allows the plate to readjust its position. Based on the observations made during the tests, it is recommended that the locking load be set at a minimum of 25% higher than the compaction load to prevent readjustments during compaction. However, locking the compaction plate at a greater load carries the risk of calibrating the rig at a higher deformation level, which can impact the zero-thickness point in direct methods and compromise the accuracy of the calibration. To ensure that the displacement measured by the laser sensors remains constant as the pressure increases, the machine compliance was measured by the laser sensors and by the UTM up to the locking pressure of 0.57 MPa. Before registering the first compliance curves with the laser sensors, the rig is compressed 10 times in a cyclic manner to eliminate the non-sample displacement in the loading system resulting from squeezing the self-aligning ball joint.

The machine compliance measured by the UTM is characterized by a nonlinearity below 0.1 MPa, followed by a linear region where the compliance increases at a constant factor, and again nonlinearity above 0.4 MPa, see Figure 2A. The initial nonlinearity is mainly due to small tolerances in the threads and pin joints attached to the UTM crosshead that slow down the load increase. Only when all parts are in their lowest position and the contact between plates is established, the load shows a linear increase with displacement. In terms of repeatability, the difference between successive compliance curves was below 2 µm. The maximum difference between the initial and the compliance after tests was of 3.5 ± 0.24 µm, registered under dry conditions. Overall, the compliance registered by the UTM remained constant through tests.

The machine compliance measured by the laser sensors showed a constant displacement across the pressure range (< 4 µm) for sensors UR and UB, while sensor UF measured a displacement decrease of 12 µm up to a pressure of 0.1 MPa (5 kN) before remaining constant as the two other sensors, see Figure 2B. The maximum increase in displacement between the lowest pressure of 0.03 MPa and a pressure of 0.1 MPa was 20 µm, remaining constant above 0.1 MPa up to the maximum pressure of 0.6 MPa. The difference among the three curves implies that the two compaction plates are parallel within a tolerance of 20 µm. A constant displacement with pressure was only achieved with the laser sensors installed on the top of the compaction plate, 10 mm from the plate, because the rig´s deformation is smaller in this region in comparison to other regions of the rig further from the compaction plate. Additionally, it is important to place the sensors close to the cavity gap to minimize the measurement distance, thus reducing the linearity error associated with the measurement distance. Because the compliance curves registered by the laser sensors showed a constant displacement with pressure, the zero-thickness point necessary for direct thickness measurements can be registered at any pressure value. However, as can be seen in Figure 2B, sensor UF one of the compliance curves shows a major deviation in the measured displacement. In dry conditions, the maximum magnitude of these “shifts” was 25 µm, while in saturated conditions a magnitude of 50 µm was registered after a series of compression tests. These shifts in displacement can either be constant along pressure, decrease below the sensor´s accuracy limit at a higher pressure, or also being below the sensor's accuracy limit for the entire pressure range. The source of these shifts can either be related to small readjustments to the rig´s components or in the orientation between compaction plates; however, the randomness of these deviations did not allow to pin-point its source. To comprehend this variability, further investigation will be necessary.

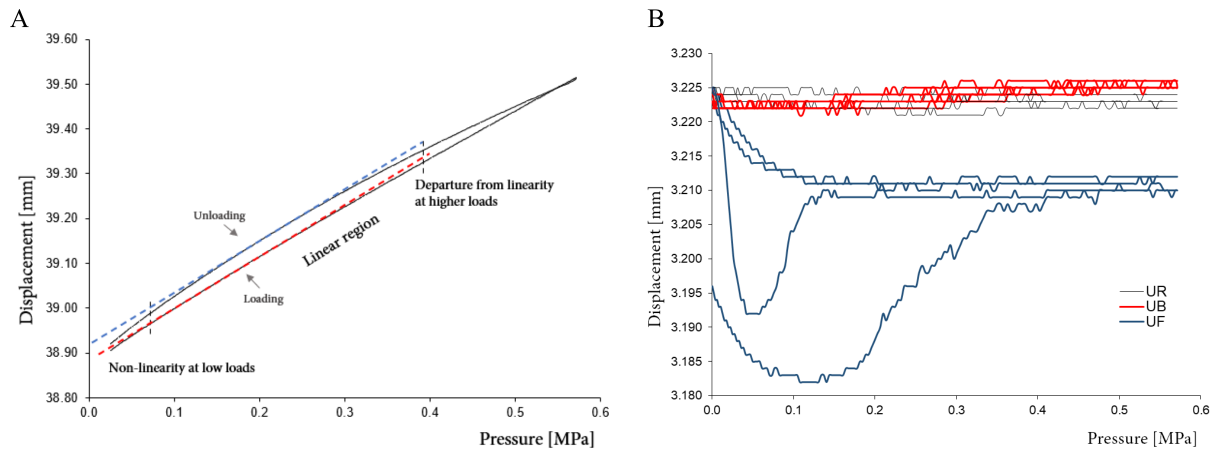

Figure 2: Machine compliance measurements A) Compliance measured by the UTM B) Compliance measured by the laser sensors in three locations around the compaction plate.

The compliance curves registered before and after the compression tests were compared to access their variability. Sensor UB registered an average difference of 19.5 ± 2.4 µm and 35.4 ± 1.2 µm in dry and saturated conditions, respectively. Sensor UF, on the other hand, recorded a difference of 43.4 ± 10.5 µm in dry conditions and 1.6 ± 2 µm in saturated conditions. Finally, Sensor UR exhibited the lowest difference, with 1.3 ± 1 µm in dry conditions and 9.8 ± 1.7 µm in saturated conditions.

Overall, the compliance measurements taken with the laser sensors exhibited a larger variability than those recorded by the UTM. This discrepancy can be attributed to the sensors' higher sensitivity to minor changes in the plate's orientation, as well as their susceptibility to external interferences or vibrations from the compaction plate's movement. On the other hand, the UTM's displacement measurements are less susceptible to such interferences and are unaffected by the plate's orientation.

To account for the variability in the compliance measured by the laser sensors during compression, the zero-thickness point was registered and changed after each compression test. The zero-thickness point was obtained from compliance curves with a constant displacement along pressure to ensure its accuracy. In dry conditions, the zero-thickness points remained within the variability range of 20 µm, which was consistent with the variability observed in the compliance measurements. In saturated conditions a 40-µm deviation was observed immediately after the first zero-thickness point, remaining constant (within 10 µm) until the last measurement.

Currently, no guidelines exist to help reduce the variability associated with direct methods beyond frequent compliance measurements. As a result, it is important to keep in mind the potential limitations of using laser sensors for compliance measurements. In contrast, UTM displacement measurements may provide more stable results; however, it is worth noting that UTM measurements may not fully capture the changes in compliance that occur during compression, because the laser sensors have demonstrated higher sensitivity to such changes.

Compression curves

The compression curves obtained with the laser sensors were processed with a curve-fit to smooth out oscillations in the curves, see Figure 3A. These oscillations have a maximum amplitude of 20

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µm, measured as the difference between the displacement in the curves and the displacement provided by the curve fitting, see Figure 3B. These oscillations are likely due to a wobble in the plate´s downward movement because it disappears above a pressure of 0.14 MPa, appearing again in the unloading branch below a pressure of 0.12 MPa. For that reason, these oscillations are not visible in the compliance measurements when the plates are pressed against each other. Smoothing these oscillations using the curve-fit technique facilitates the further analysis and interpretation of the obtained results. All the subsequent results obtained with the laser sensors are presented in terms of the smoothed curves.

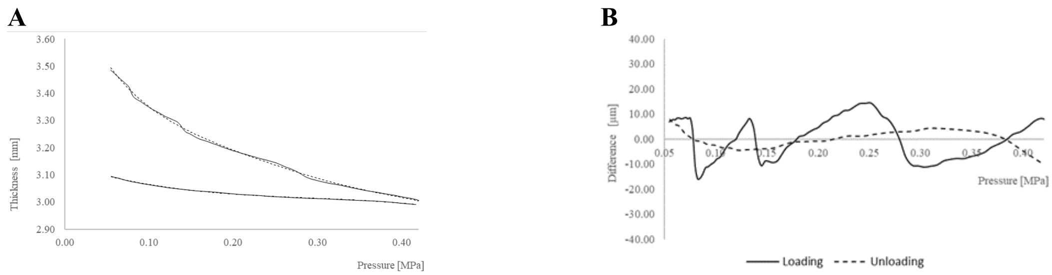

Figure 3: The compression curves obtained by the laser sensors showed interferences in the form of oscillations A) These oscillations were smoothed-out with a curve fit B) Difference between the fit-curve and the compression curve in both loading and unloading curve branches.

The direct thickness measurements are obtained by the thickness readings of three laser sensors, leading to three compaction curves. When these curves are superimposed, instead of three overlapped curves, the results show two of the curves overlapped while the third one is offset, see Figure 4A. The offset curve was either UB, UF, or UR, changing on a sample-to-sample basis which indicates that the compaction plate settles in a slightly different manner with each compression. The average overlap and offset between curves were estimated from the differences in thickness at the same compaction pressure. Under dry conditions, the two curves overlapped by an average of 14.7±8.9 µm during loading and 22.9±6.2 µm during unloading. Under saturated conditions an average overlapping of 21.6±13 µm was obtained during loading, while the overlapping during unloading was 29.2±14 µm. The overlapping between curves falls within the uncertainty found in the compliance measurements registered by the laser sensors, therefore within the achievable accuracy with this rig.

Regarding the offset curve, on average, it was shifted on average 51.2±16.4 µm from the furthest curve, while in saturated conditions, the offset was of 61.2±22 µm. A similar offset was detected in the compliance measurements registered by the laser sensors; however, the offset curve was constantly UF, and the magnitude of this deviation was just 12±1.9 µm. This offset suggests that the compaction plates have a certain level of mobility, resulting in more displacement when the glass plate is centrally loaded with fabrics.

Despite the common use of both direct and indirect thickness measurement methods, the results from these methods are often not reported together and directly compared in the literature. Consequently, the variability affecting these methods was not yet the target of a study, leading to inaccuracies when results obtained by these methods are compared. The average thickness determined by three laser sensors was compared to that obtained through the indirect method, aiming to eliminate the influence of the platen tilting and determine the difference between the two methods.

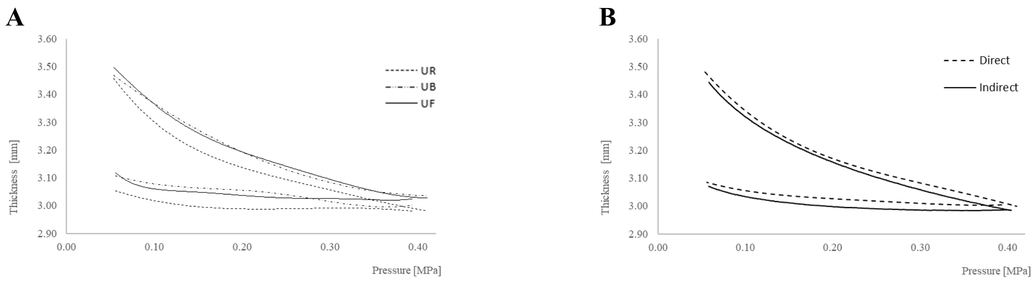

Figure 4: Compression in dry conditions with three laser sensors A) The compression curves as measured by the laser sensors showed two overlapped compression curves while one of them is offset. B) The three compression curves were averaged, resulting a single direct thickness curve, and compared with the thickness measured by the indirect measurement method corrected for the machine compliance.

Overall, both methods provided similar measurements within the accuracy allowed by the laser sensors, see Figure 4B. The average differences between methods stayed below 35 µm for all tests except one test in dry conditions which showed an average difference of 38.6±4.2 µm between curves, see Figure 5. While the compliance curves showed greater variability under saturated conditions, this variability did not impact the thickness measurements as frequent compliance measurements were taken to mitigate potential discrepancies.

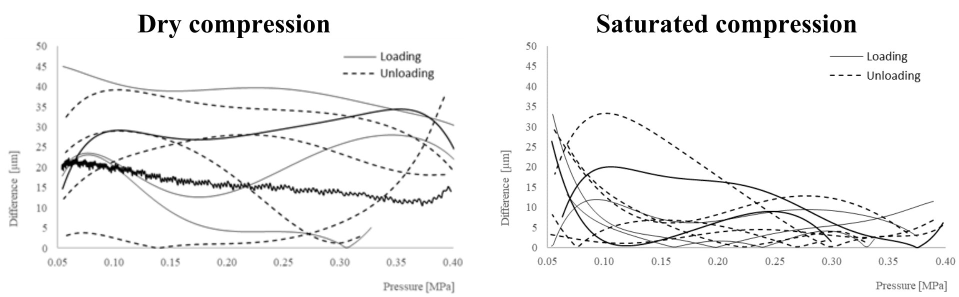

Figure 5: Difference between the thickness obtained through direct and indirect methods at the same compaction pressure.

In dry conditions the curves obtained by the direct method are on average 22.4±10 µm shifted up in relation to the indirect method, see Figure 6. No specific trend was observed in the difference between curves because the difference between methods can either be constant along the pressure or decrease with pressure. The thickness measured at the maximum compaction pressure showed a comparable level of accuracy between the direct method (3.00±0.02 mm) and the indirect method (2.99±0.01 mm). Under saturated conditions, both methods provided the same thickness within an accuracy of 1.7%. The compression in saturated conditions showed little effect on the compaction process due to the presence of stitches. The presence of stitches reduces the mobility of the fiber bundles and prevents nesting [6]. For that reason, the compression tests performed under saturated conditions showed little difference to those performed in dry conditions. The compaction pressure at the target thickness of 3 mm is similar in both cases, 392.8±38.7 kPa in dry conditions and 359.6±40.9 kPa in saturated conditions.

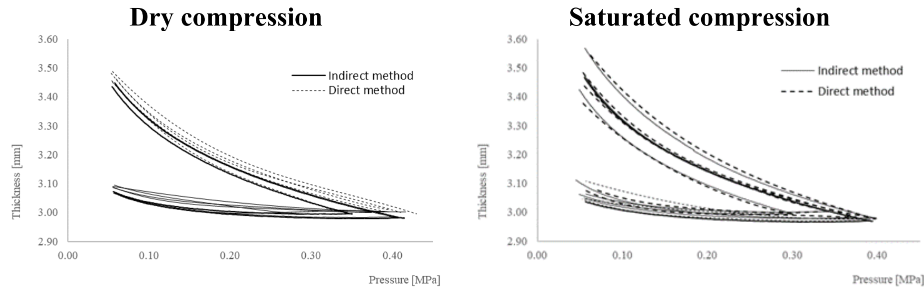

Figure 6: Compression curves obtained with direct and indirect thickness, Samples 1 to 5.

The variability among compression curves was more significant in saturated conditions. At a pressure of 0.1 MPa, the direct method measured 3.34±0.02 mm, while the indirect method measured a thickness of 3.31±0.04 mm in dry conditions. In saturated conditions, a thickness of 3.32±0.05 mm was measured by the indirect method, while the direct method measured 3.33±0.06 mm. In both cases, the measured thickness was similarly independent of the measurement method.

The parallelism between compaction plates

The parallelism between plates was checked with a Fujifilm Prescale® Ultra Low-pressure pressure-sensitive film. Squared sheets with side 260 mm were cut from the roll and placed in the cavity between compaction surfaces. The cavity was then closed with a pressure of 0.41 MPa, which is close to the specified pressure limit for this paper, set at 0.5 MPa. The cavity was then opened, and the pressure film revealed the pressure distribution profile that occurred between the two surfaces. The color intensity exhibited by the pressure film is directly proportional to the magnitude of the applied pressure, with a visual accuracy of approximately ±10% and a spatial resolution between 5 and 15 microns.

The impression left on the paper showed a uniform and consistent pressure only along the edges of the compaction plate, see Figure 7A. A significant portion of the compaction surface did not exhibit any contact, indicating a concave shape in the round compaction plate. This condition can be related to the surface finish which appears not to have been appropriately flattened and smoothed. The surface roughness was measured with a profilometer resulting in an average Ra of 1.00 μm, which indicates a certain roughness. The compression curves measured by the laser sensors indicated a certain level of mobility when fabrics are compacted. For that reason, the pressure distribution was also checked with fabric layers in the cavity. For this measurement, three layers of the twill 2/2 fabric used in the first compressibility benchmark were placed in the cavity and compressed up to a pressure of 0.41 MPa, see Figure 7B. The pressure distribution shows a slightly darker color on the left side of the paper indicating a different pressure distribution. This difference can be related to the concave shape of the compaction plate; therefore, this verification needs to be repeated once the plate is flattened.

Comparison with the benchmark results

The accuracy of the compression measurements was assessed by a comparison with the results reported by other benchmark participants. While the results from the latest benchmark are yet not available, the fabric is of the same type as the fabric used in the first benchmark exercise [2]. Although this fabric is from a different batch, the results are still comparable to some degree.

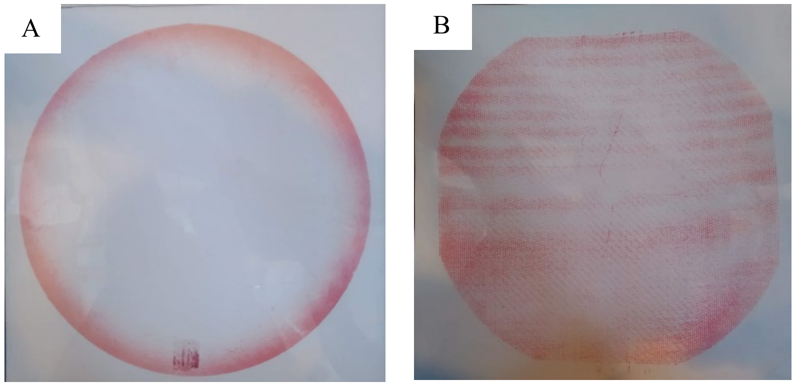

Figure 7: Contact (A) between compaction plates, and (B) between three layers of Twill 2/2 (Hexcel fabric)

An average thickness of 3.45±0.1 mm at a pressure of 0.1 MPa was reported in the first benchmark exercise under dry conditions, while in saturated conditions, the average thickness was 3.39±0.14 mm. In this study, at a pressure of 0.1 MPa a thickness of 3.31±0.01 mm and 3.34±0.02 mm was measured by the indirect and direct thickness methods, respectively. In saturated conditions, an average thickness of 3.33±0.06 mm was measured at this pressure. No significant differences were observed between the direct and indirect thickness measurement methods. The target thickness of 3 mm was reached at a compaction pressure of 393±39 kPa under dry conditions, while the reported participant´s average is 370±141 kPa. Under saturated conditions, the target thickness was achieved at a pressure of 360±41 kPa, which is also comparable to the reported pressure of 317±127 kPa.

Summary

This study showed that both direct and indirect thickness measurement methods are reliable options for measuring thickness during compressibility measurements, provided that the potential sources of variability are carefully considered. Overall, the compliance measurements taken with laser sensors exhibited a larger variability in comparison with those recorded by the UTM. This discrepancy can be attributed to the sensors' higher sensitivity to minor changes in the plate's orientation, as well as their susceptibility to external interferences or vibrations from the compaction plate's movement.

The compression curves measured by the laser sensors showed a shifted curve changing on a sample-to-sample basis suggesting that the compaction plates have a certain level of mobility, resulting in more displacement when the glass plate is centrally loaded with fabrics. The parallelism between plates was checked with a pressure-sensitive paper, showing a nonuniform pressure distribution when a three-layer fabric stack was compressed. The surface finish of the compaction plate is likely causing a nonuniform pressure distribution. However, the obtained results are comparable to those reported in the first compressibility benchmark where the same fabric reinforcement was used.

Based on the findings reported in this paper, a list of practical recommendations and guidelines for calibration and accuracy assessment of both direct (laser sensors) and indirect (UTM) thickness measurement methods can be withdrawn:

- When using compaction plates with locking mechanisms, the compaction plate must be locked at a load at least 25% higher than the compression loads during testing to prevent any further readjustments during compaction.

- To eliminate any non-sample displacement that may result from squeezing the self-aligning ball joint, it is advisable to compress the rig in a cyclic manner up to the same load as in the compliance curves after locking the compaction plate.

- Register the machine compliance up to the locking pressure using both distance sensors and the UTM. This will check for compliance differences caused by locking the compaction plate at a higher load than the load encountered during testing.

- To achieve accurate results and set the achievable accuracy, frequent compliance measurements should be taken to monitor changes and minimize their impact in both direct and indirect methods. Compliance curves can easily change due to common rig operations becoming important to monitor compliance changes regularly.

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