MEASUREMENT METHODOLOGY AND PHENOMENOLOGY OF WET COMPRESSION OF TEXTILES

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Abstract

This paper evaluates the compaction behavior of woven carbon twill fabrics in dry and wet conditions. A wider characterization of the compaction behavior is achieved by studying three compaction cycles up to a pressure of 1 MPa. In addition, a relaxation test in dry conditions is also performed at 0.1 MPa. Square samples 90*90 mm were used, larger than the press area. For dry compaction, samples are cut from the fabric roll, aligned according to the production direction (the same surface facing upwards) and then compacted. In wet compression, layers are individually impregnated for 15 minutes and drained from the excess of oil before stacking. Silicon oil was used as a wetting liquid. The setup for dry compression consists of a self-straightening device placed on the top of a steel cylinder, whereas for wet compression the same setup is placed inside a stiff metal box design to retain the oil drained during compression. Overall, the wet compaction reduces the compaction rigidity of the preform. In dry conditions at 1 MPa, the volume fraction obtained on the first cycle for the five plies stack is by 1.7% lower in relation to the ten plies stack. However, in wet compaction, the achieved volume fraction becomes the same as for ten plies stack.

1. Introduction

The compaction behavior of fabric reinforcements determines the perform microstructure during impregnation, which affects the resin flow through the porous medium, and the attainable fiber volume fraction of the finished component [1,2]. Both properties have a significant effect on the mechanical properties of the final part. In addition, the behavior of a reinforcement subjected to a force normal to its plane has important consequences on the mold design and equipment specifications for all processes using textile reinforcements, as Resin Transfer Modeling (RTM) or Vacum infusion (VI) [3]. For those reasons a precise characterization of the compaction behavior becomes essential.

Compaction tests commonly produce data for LCM processes, in which the compaction loads are applied before the resin injection. In such manufacturing processes, the fabrics are compacted in one or multiple cycles in order to increase the fiber content of the final part [1]. It is known that dry loading and dry unloading do not resemble the compaction of preforms in the actual VI process, mainly due to the absence of lubrication effect during unloading and relaxation stages and the fact that the upper mold in non-rigid, what changes the compaction dynamics in relation to the compaction between two hard surfaces [4]. Nevertheless, the dry compaction provides information on the attainable volume fraction after one or several compactions in addition to information relative to the load necessary to close the mold in RTM. Similarly to a compressibility test with relaxation stage, in

RTM the compression occurs between two rigid surfaces and after compaction, the part thickness remains constant while the compaction pressure changes with time [4]. By studying relaxation is possible to determine the pressure variation inside the mold after its closure. Information on wet compaction can be used with prepregs compaction, This type of compaction facilitates compaction due to the lubrication effect that facilitates the movement of fabrics during compaction.

The compaction process of fabrics is widely described in the literature [1,2,5,6], briefly, the compression curves can be divided into three regimes: initial linear regime, the nonlinear regime, and final linear regime. The first regime is characterized by the rapid change of crimp and flattening of yarns, which deform with almost no resistance due to their low bending stiffness. With the increase in the compacting pressure, the number of contact points between layers increases resulting in a state where individual layers are in full contact with the neighboring ones (slight compaction), thus entering the nonlinear regime. In this stage, the pressure increase causes slippage around large voids where the stacking structure is not stable. The preform deformation comes almost entirely from the compressibility of the interstitial space caused by yarns filling the voids [2]. The compaction manly depends on the frictional resistance at the points of contact between layers because the yarns slippage only occurs when the pressure increase overcomes the internal fiber and yarn friction. Once the larger voids have been filled, more inter-fiber friction starts resisting the external compressive pressure and the remaining interstitial space is more stable. The compaction enters the last linear stage where the increase in the pressure leads to lateral compression of fibers (bundle flattening) and to a highly packet fiber assembly [5]. In this last stage, the perform stiffness increases substantially and a further decrease in thickness requires a meaningful increase in pressure.

This paper studies the fabric compaction in dry and wet conditions and the effect of the number of layers. A relaxation test is also performed to determine the pressure decrease at a constant thickness. The perform thickness is measured using a non-direct thickness measurement method, which requires the measurement of the setup compliance throughout the tests. The wet compaction makes the test methodology more difficult, as one has to account for the displacements of the loading plate caused by the machine compliance and by the creation of thin oil films on the compression surfaces. The errors associated with these factors are estimated.

2. Materials and Methods

The compression tests were performed on a displacement-controlled testing machine Instron 4467 at a constant test speed 1 mm/min with a five kN load cell. To ensure the correct alignment of the compression planes during tests without samples (free compression tests) a round self-aligning pivot with a diameter of 70 mm was used. The pivot is placed on the top of a column and the load cell is also attached to a steel plate with a diameter of 80 mm, see Figure 1a). For wet compaction the set is placed inside a steel box in order to collect the fluid drained from the samples. The bottom of the box has ten mm deep groves which prevents an oil accumulation under the steel cylinder, Figure 1b). The fabric used in the tests is a carbon plain weave fabric with an areal density of 240 g/m2, Figure 1c). Considering the non-uniformity in the fiber structure and the inaccuracy in the specimen reparation, each set of the experiment was repeated with five separate specimens. The tests were performed using stacks of five and ten samples which are made of square samples with side 90 mm (± five mm). The chosen dimension ensures that all fabrics have a surface dimension greater than the press area (ø70). All layers in a stack have the 0° (warp) direction coinciding, the same surface facing upwards and the stacks were placed centrally in the press. For wet compaction, the layers are individually impregnated in silicon oil (viscosity 100 mPa·s at 20°C) for 15 minutes and then they drain the excess of oil in a mesh holder for additional 15 minutes. Two types of compaction are performed: normal compaction and compaction with relaxation stage. The first type is a compression up to 1 MPa at a constant speed of 1 mm/s followed by the unloading also at constant speed. This process is repeated 3 times. The second type of test constitutes of 3 compression cycle with a relaxation stage of 30 minutes between compression and unloading cycles at 0.1 MPa.

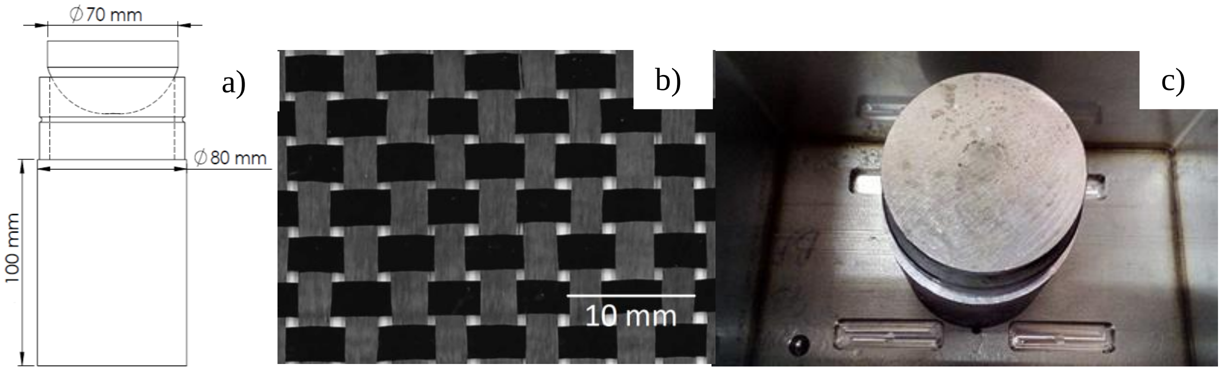

Figure 1. a) setup used for compression: a self-aligning device placed on the top of a steel cylinder b) Carbon plain weave fabric (240 g/m^2) used in the tests c) Steel box with grooves on the bottom to retain the oil drained from the fabrics in wet compression

2.1. Data processing methodology

The goal of the work is the measurement of the thickness variation as a function of the applied pressure using an indirect measurement method. This method implies the measurement of the machine displacement vs load without sample before and after each continuous test series to account for the machine and setup compliance. In case of wet compression, the calibration curve is registered after each sample because the setup can easily slide. In this process, the average curve of five free compression tests (without sample) is converted into two second-degree polynomial (one for the loading and unloading branches of the curve), providing the loading and unloading reference (calibration) equations. In this process, the curve extremes are not considered in order to minimize the average error. The standard deviation of the five calibration curves is in the range of 0.29-1.18 µm. After characterized, the compliance is excluded from the compression diagrams providing the thickness variation under a given compression load.

3. Results

3.1. Thickness measurement

One advantage of the non-direct methods is the fact that the machine compliance is accounted on the thickness measurements. However, the machine compliance can vary according to the way how the setup is aligned, which can be affected by simple placement and removal of samples. This is particularly an issue on the wet compaction where the presence of oil can make the setup components slide easily. Figure 2 represents the calibration curves obtained before and after a test with five samples in wet conditions. The difference between both curves in terms of displacement varies between 8.73 – 1.70 µm along the range of pressure. On the other hand, in dry conditions, the curves show a difference between 2.61 – 0.26 µm. This issue can be minimized if the calibration curves are registered after each sample. In this case, the variability decreases to an average of 2.72 µm ± 0.67 µm.

Another source of compliance is the conversion of the calibration curves into polynomials. This conversion results in an average error of 0.five µm and a maximum of 3.25 µm at the curve extremities due to the now consideration of the curve ends, Figure 3.

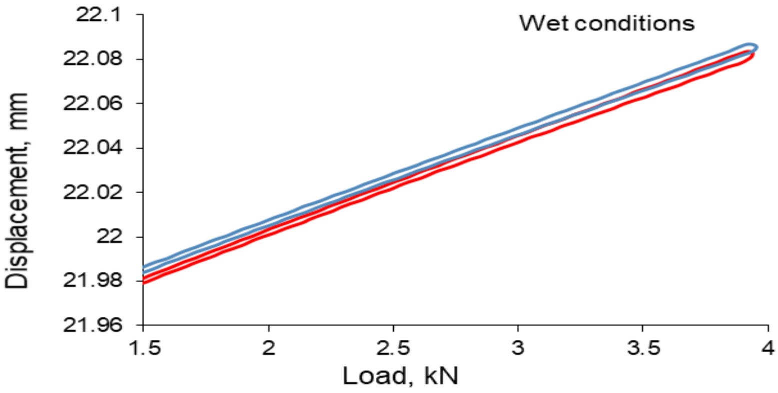

Figure 2. Calibration curves obtained during the compression of five stacks A) wet compaction B) dry compaction

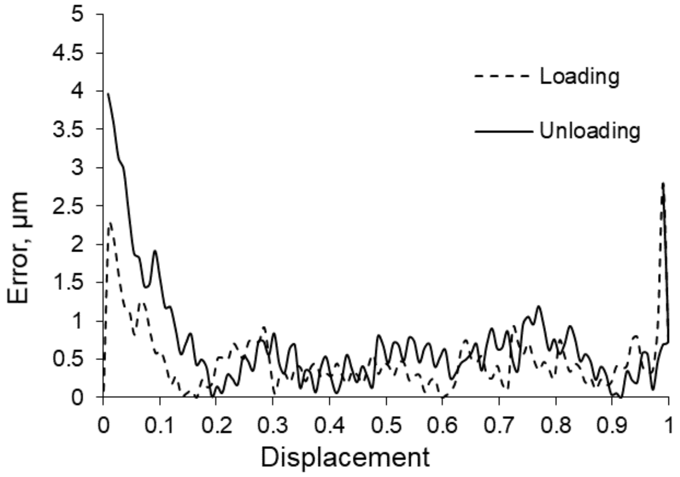

Figure 3. Error in function of the normalized displacement

3.2. Normal compression in dry and wet conditions

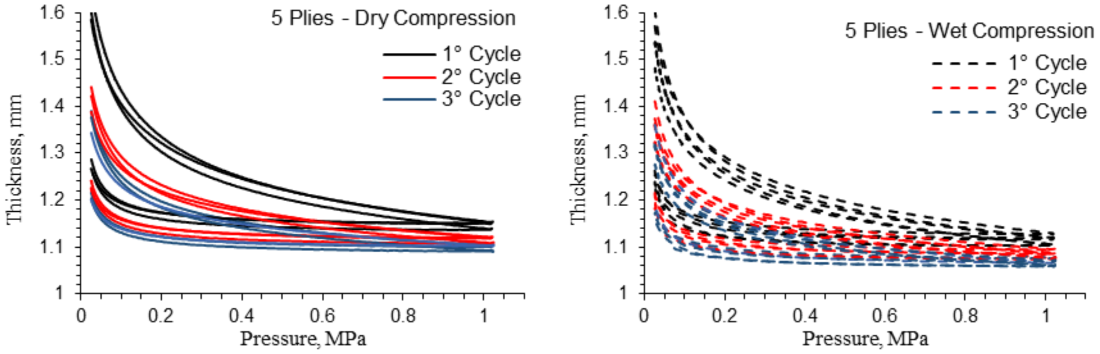

Figure 4. five Plies stack: results for three compressive cycles in dry and wet conditions. The curves for five tests shown together

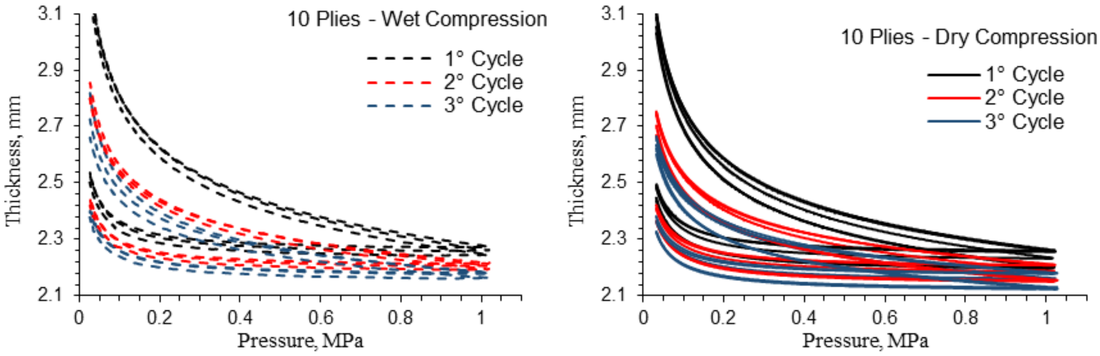

Figure 5. Ten plies stack: results for three compressive cycles in dry and wet conditions. The curves for five tests shown together

Figures 4 and 5 illustrate the compression curves obtained in normal compaction for dry and wet conditions. These curves follow the shape commonly described in the literature. As expected, the compaction of the preform progressively increases with successive compaction cycles, i.e. decreases nesting and increases volume fraction, see Table 1. However, the degree of compaction (thickness decrease in successive compaction cycles) is not affected by the type of compaction. For both stacks five and ten plies, in dry and wet conditions, the decrease in thickness from the first to the second compaction cycle is 1.5% ± 0.1% and 0.9% ± 0.1% from the second to the third cycles. The five plies stack shows a greater compaction rigidity due to a faster compaction time and less thickness decrease during compaction. In result, the volume fraction at 1 MPa, obtained after three compression cycles, is 1.7% lower in relation to the stack of ten plies. Due to the small thickness decrease from the second to the third compaction cycle, it can be said that the fabric achieves a considerable degree of compaction on the second compaction cycle. Considering the first compaction cycle, it is noticeable that the increase in the number of plies results in a greater scatter (differences in thickness at maximum pressure). The ten plies stack shows a variability of 115 µm in dry conditions and 62 µm in wet conditions, while for the five Plies stack the maximum variability is around 24 µm for wet conditions and 14 µm for dry conditions.

The compaction of a five plies stack in wet conditions shows an improvement on the compressibility, see Figure 6. The volume fraction increases in average 1.7% for all compression cycles, see Table 1. In wet conditions, one compression cycle is enough to obtain the same volume fraction as in dry conditions for two compression cycles. After three compression cycles in wet conditions, the five plies stack achieves the same volume fraction as the ten plies stack. On the other hand, the wet compression show no effect on the ten plies stack, see Figure 7. The curves obtained in dry and wet compaction can be overlapped in all range of pressure.

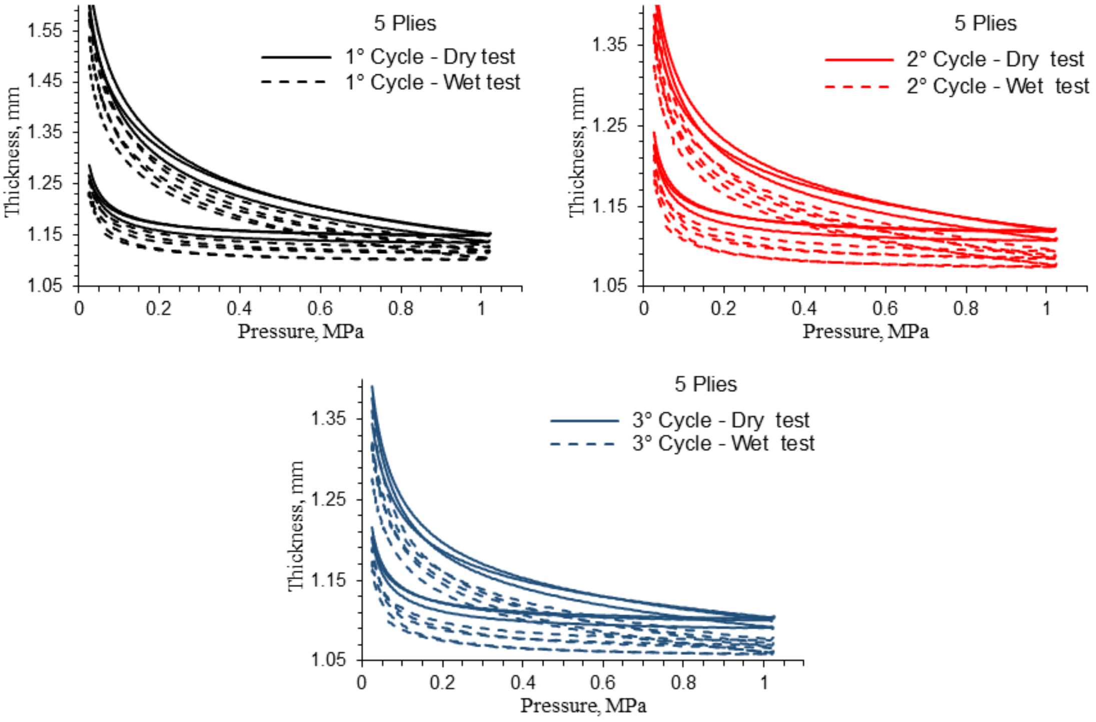

Figure 6. Five plies stack: comparison between dry and wet compression for three compression cycles

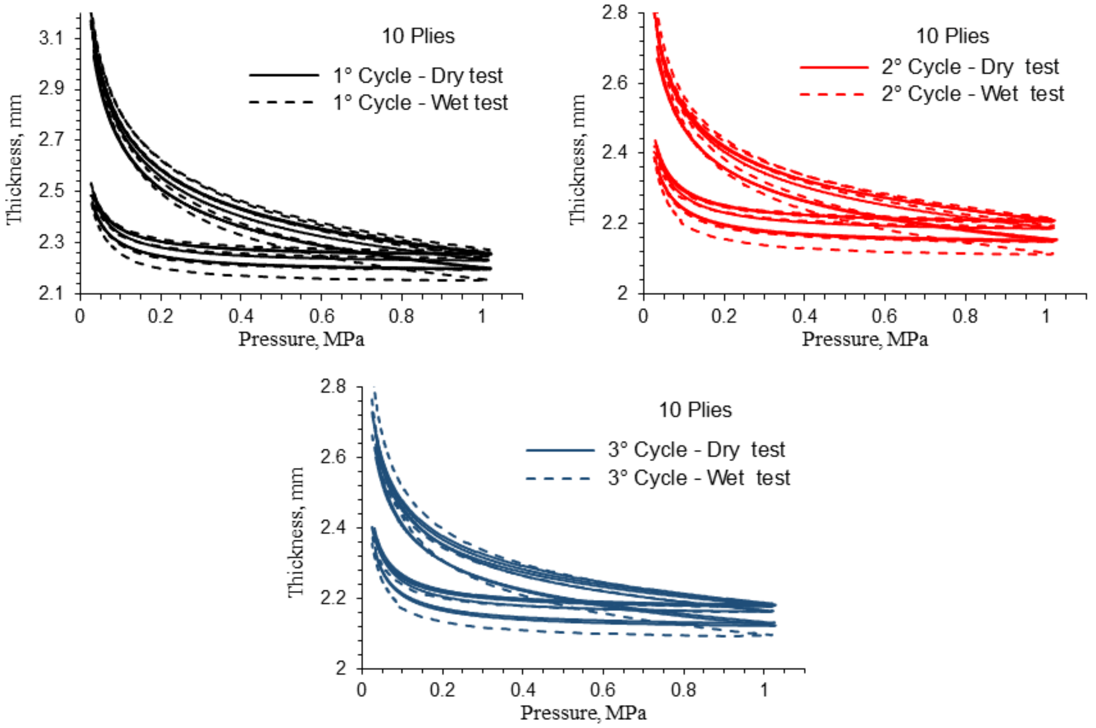

Figure 7. Ten plies stack: comparison between dry and wet compression for 3 compression cycles

Table 1. Volume fraction and nesting at 0.1 MPa and 1 MPa, for ten plies and five plies, dry and wet

0.1 MPa	*ten plies Dry*		*ten plies Wet*		*five plies Dry*		*five plies Wet*	
	Vf (%)	Nesting	Vf (%)	Nesting	Vf (%)	Nesting	Vf (%)	Nesting
1° Cycle	49.1% ± 0.7%	0.22	49.3% ± 0.8%	0.17	47.5% ± 0.7%	0.19	49.1% ± 0.9%	0.17
2° Cycle	53.6% ± 0.7%	0.20	53.4% ± 1.0%	0.15	52.4% ± 0.5%	0.18	54.0% ± 0.8%	0.16
3° Cycle	55.0% ± 0.7%	0.19	55.0% ± 0.7%	0.14	54.0% ± 0.5%	0.17	55.6% ± 1.1%	0.15

1 MPa	*ten plies Dry*		*ten plies Wet*		*five plies Dry*		*five plies Wet*	
	Vf (%)	Nesting	Vf (%)	Nesting	Vf (%)	Nesting	Vf (%)	Nesting
1° Cycle	60.1% ± 0.7%	0.24	60.1% ± 1.1%	0.24	58.4% ± 0.3%	0.23	60.0% ± 0.5%	0.20
2° Cycle	61.4% ± 0.7%	0.23	61.6% ± 1.1%	0.24	60.0% ± 0.3%	0.22	61.7% ± 0.4%	0.20
3° Cycle	62.2% ± 0.7%	0.23	62.4% ± 1.0%	0.23	61.0% ± 0.3%	0.22	62.7% ± 0.4%	0.20

3.3. Compression with the relaxation stage

For the experiment presented in this paper, the maximum compaction pressure does not exceed 0.1 MPa, which corresponds to the vacuum pressure. Once this pressure was reached, the position of the machine head was kept constant, and the evolution of the compaction pressure was recorded for half hour. Results show a major decrease in the compaction load, it decreases from 392.9 kN ± 0.000254 kN to 112.5 kN ± 0.00104 kN (71.4% ± 0.25%) on the first compaction cycle, 392.9 kN ± 0.000691 kN to 143.23 kN ± 0.005958 kN (63.5% ± 0.68%) on the second compaction cycle and 395.9 kN ± 0.00054 kN to 156.22 kN ± 0.0068 kN (60.5% ± 0.52%) on the third compaction cycle. The fact that the load decreases 60.five% after three compaction cycles indicates that at 0.1 MPa the fabrics have space enough to rearrange themselves, dissipating pressure. The decrease in thickness, in this case, is not significative, on the first relaxation stage, the thickness decreased 14 µm ± 0.33 µm. More information on the thickness decrease during relaxation can be found in [7].

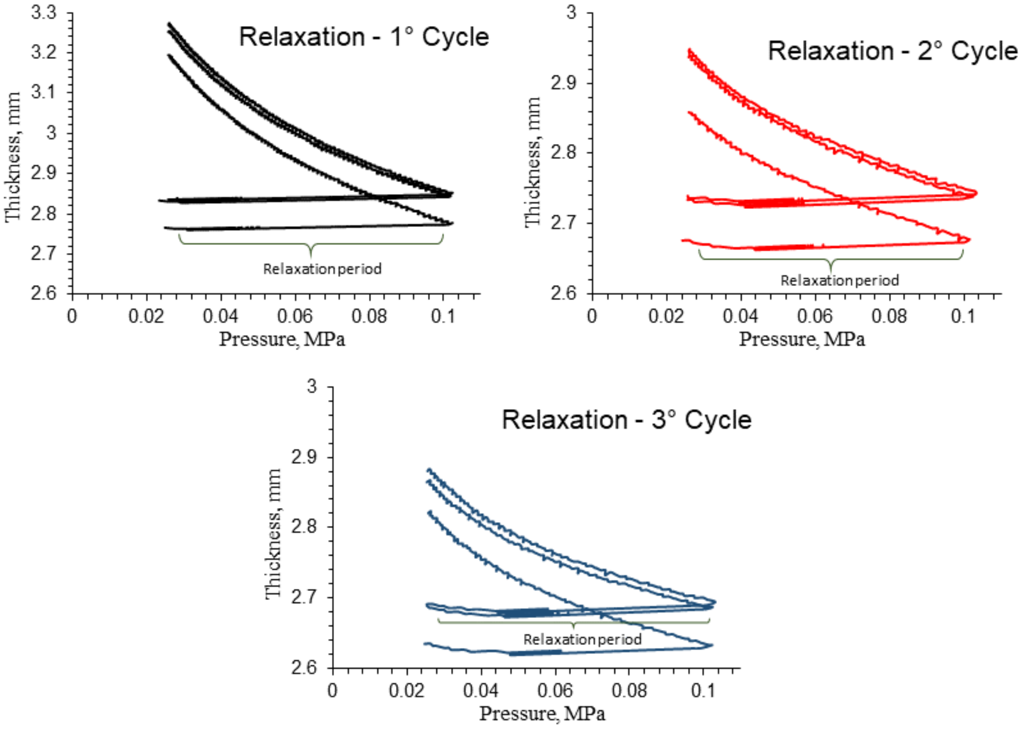

Figure 8. Relaxation tests with three compression cycles, a typical test

4. Conclusions

The wet compaction can have a negative effect on the machine compliance due to oil that accumulates between surfaces. This compliance can be minimized if the machine compliance is constantly registered. With a constant monitorization, the compliance in wet conditions only increases around 4 µm in relation to the dry conditions.

The number of layers shows to have a significant effect on the compaction behavior, based on the volume fraction at high loads for dry conditions, it can be said that increasing the number of layers the space between yarns in the fabric also increases. More layers result in greater opportunities for nesting and greater volume fraction [8]. An increase in the number of layers increases the slippage and movement of the yarns in the fabric structure, what decreases nesting but improves volume fraction.

The change in fiber volume fraction under compression is significantly reduced after the first load cycle because the compaction at the beginning of the second cycle is higher than for a virgin specimen. This effect is not so significant for the subsequent compression cycles [2]. This suggests a permanent reordering of the fiber bundles in the fabric structure during the first compression. In all tests the fabrics showed to be easily compressible, achieving a volume fraction greater than 50% on the second compression cycle. This is due to the large gaps between yarns that seems to allow the yarns movement in the fabric structure and a free flow of oil from the fabrics during wet compaction.

Overall, it can be said the presence of oil seems to increase the compressibility of the stiffer stack. The lubrication reduces the friction between yarns what improves their movement, increasing compressibility.

Acknowledgments

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