Compaction of Dry and Lubricated Reinforcements

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SUMMARY: This paper presents an experimental investigation into the quasi-static compaction behavior of carbon fiber reinforcement fabrics. The reinforcements tested included several non-crimp fabrics, a five-harness satin-weave fabric and a plain-weave fabric. Stacks with from two to ten layers, both dry and lubricated with water-diluted glycerine, were tested. The compaction tests were conducted on an MTS machine, using crosshead movement to measure compaction, with careful correction for machine compliance. Power model curves were able to fit the compaction data reasonably well. The non-crimp fabrics and five-harness satin fabric compacted more easily than the plain-weave fabric. Thicker stacks were found to compact more easily than thinner stacks. Lubricated stacks compacted more easily than dry stacks. It was found that the carbon fiber reinforcements tested have similar compaction behavior. A procedure to predict the compaction thickness under higher pressures by using the thickness measured at 100 kPa, such as under a vacuum bag, is also presented.

KEYWORDS: Carbon fiber fabrics, reinforcement fabrics, compaction, volume fraction.

Introduction

The compaction of stacks of dry reinforcement to a desired thickness (and perhaps a desired permeability) is an important aspect of many composite manufacturing processes, especially liquid molding processes. Therefore, measurement or prediction of the compaction behavior of reinforcement stacks provides important processing data.

This paper describes a procedure for conducting quasi-static compaction tests first devised by Liu and Triantafillou [1]. This procedure has been progressively modified to minimise any errors from machine compliance. The procedure has been used as described here to measure quasi-static compaction behavior of carbon fiber reinforcements, including non-crimp, satin-weave and plain-weave fabrics. The reinforcements were tested in the usual dry condition, and a "lubricated" condition, partially impregnated with water-diluted glycerine.

Experimentation

Materials

Details of the fabrics tested are given in Table 1. The fabrics were cut to either 200 × 200 mm squares or 175 mm diameter rounds using templates. Stacks of 2 plies, 4 plies, 6 plies and 10 plies were made up. Some stacks were lubricated with water-diluted glycerine (1 part water to 3 part glycerine by weight, with a viscosity of approximately 50 cPs at room temperature). The lubricant was poured onto each layer of fabric and carefully brushed across the surface until the fabric was saturated. A summary of the test matrix is given in Table 2.

Table 1: Details of carbon fiber fabrics tested

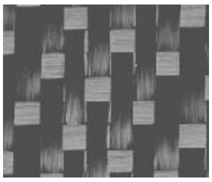
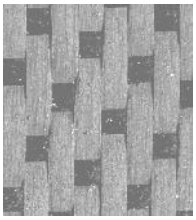
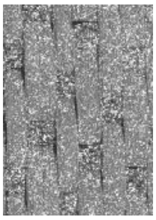
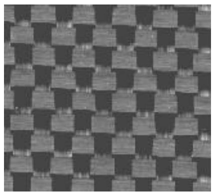
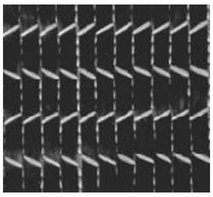
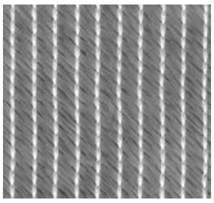
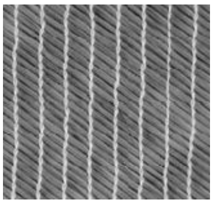
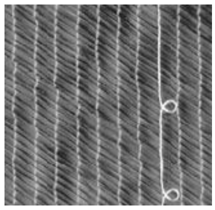
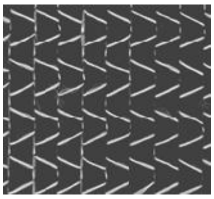
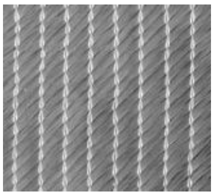
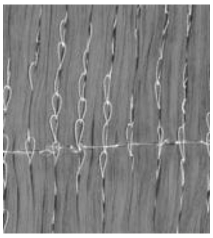
Fabric	**Supplier**	**Fabric Style**	**Areal Weight (g/m^2)**	**Fiber Orientation**
G926	Hexcel	6K 5H satin weave (no binder)	370	0/90
RC200P	SP Systems	3K plain weave	195	0/90
FCIM156	Formax	T700 12K-FOE quadraxial NCF	1068	0/-45/90/+45 (even dist'n)
XC411	SP Systems	12K biaxial (double bias) NCF	408	+45/-45
SQ1091R	Saertex	12K quadraxial NCF (right hand version)	1091	0/+45/90/-45 (even dist'n)
SQ1090L	Saertex	12K quadraxial NCF (left hand version)	1091	0/-45/90/+45 (even dist'n)
NC2	Hexcel	12/24K biaxial NCF	930	0/90/0 (83.9% in 0 dir'n)

Table 2: Summary of test matrix

Fabric	Ply Number	Lay-up	Specimen Number	
			Dry	Wet
G926 (no binder)	2	$[0]_2$	2	1
	4	$[0]_4$	1	1
	10	$[0]_{10}$	2	1
RC200P	4	$[0]_4$	2	2
	10	$[0]_{10}$	2	2
FCIM156	4	$[0,0_F,0,0_F]^*$	2	2
XC411	2	$[0]_2$	2	4
	10	$[0]_{10}$	2	2
SQ1091R + SQ1090L	4	$[0_R,0_{LF},0_R,0_{LF}]^*$	2	1
NC2	2	$[0]_2$	3	2
	6	$[0]_6$	2	1

* R = right hand, L = left hand, and F = ply flipped over

Table 3: Photographs of reinforcements

 G926 (no binder)	 G926 (P03 binder)	 G926 (HP09 binder)	 RC200P
 FCIM156 upper surface	 FCIM156 lower surface	 XC411 upper surface	 XC411 lower surface
 SQ1091 upper surface	 SQ1091 lower surface	 NC2 upper surface	 NC2 lower surface

Areal Weight of Reinforcements

The nominal areal weight is specified in each case by the material supplier. It was found that the areal weight of the non-crimp fabric specimens differed significantly from the supplier's value, and for these fabrics the measured areal weight was used in calculations.

Experimental Apparatus

The compaction tests were conducted on a 250 kN MTS machine. The reinforcements were compacted between an upper circular steel platen 150 mm in diameter and a lower circular steel platen 200 mm in diameter.

Thickness reduction measurements were obtained using cross-head displacement. These measurements were carefully corrected for machine compliance as described below.

Compliance of Experimental Apparatus

Test machine compliance was measured by running the test (carefully) without a reinforcement stack. A typical load-displacement curve from the machine compliance tests is shown Figure 1. It can be seen that there is an initial non-linear curve "foot", followed by a linear compliance. The non-linear initial stage is believed to be caused by slight departures from parallelism of the two platens. Some force must be applied before full contact: thereafter, the apparatus deforms elastically. It was found that machine compliance could be easily varied by common setup operations such as releasing and reapplying hydraulic pressure to the grips, or releasing and reapplying the cross-head lock to the top platen. The test system was also found to sometimes exhibit a slight amount of slip during the day. Therefore, a compliance test was run at the start of the day, and at the end of the day, as a minimum.

Difficulty was encountered in establishing a clear zero-load reference point for use in correcting the crosshead displacement measurements for machine compliance. Therefore the test crosshead displacement measurements were corrected by the machine compliance curve using a common reference point corresponding to a load such as 3 kN clearly within the linear portion of the compliance curve.

Although the machine compliance was found to be non-linear at low loads, it was found that ignoring the non-linearity at low loads caused less than 1% error in specimen thickness calculations, even for thin specimens, and only at low loads. Therefore the machine compliance was treated as being fully linear for the purposes of establishing the "zero-load" displacement and correcting the crosshead displacements.

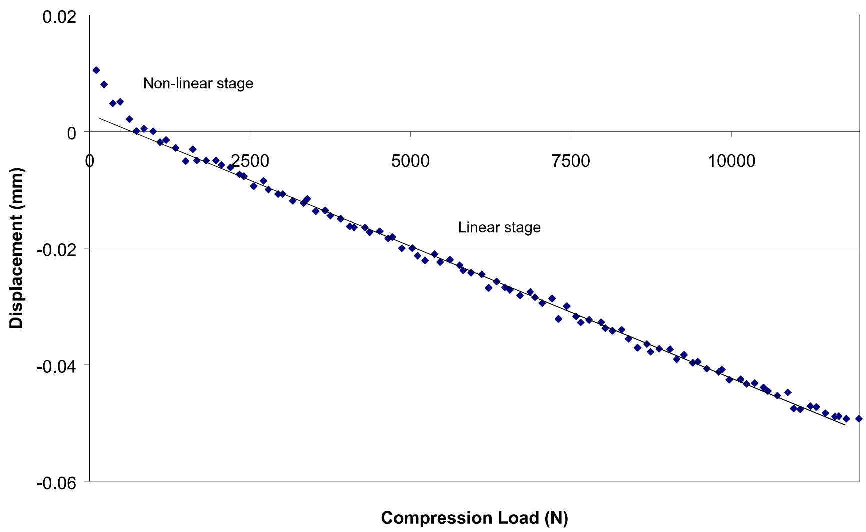


Figure 1: Typical machine compliance curve

Procedure

All compaction tests were conducted at room temperature. A machine compliance test was first conducted. The bottom platen was then lowered to form a 9 mm gap for insertion of the compaction specimen. The compaction specimen was placed centrally on the lower platen. It is known from previous testing at CRC-ACS and elsewhere that compaction behavior of the stack is "viscoelastic" [2,4]. This is believed to be caused by the time-dependant rearrangement of the fibers and fiber bundles under compaction. This work was intended to produce compaction data for use in liquid molding processes where the compaction loads are applied well before the resin is injected. Therefore loads were held at 50, 100, 200, 300, 400, 500, 600, and 700 kPa for 5 minutes [2,4] to allow for the relaxation of the fabric stack [2] and generate "equilibrium" compaction curves.

Fiber Volume Fraction (V_f) was calculated using Eqn 1 below [3]. N = number of layers, A = fabric areal weight, ρ = carbon fiber density (1780 g/m^3), and t = thickness of specimen:

$$V_f = \frac{AN}{\rho t} \tag{1}$$

RESULTS AND DISCUSSION

Compaction Curves

The V_f achieved by compaction for five minutes at the nominated pressures is shown in Figures 2 to 8. The compaction response can be expressed by the following two-parameter power model, where K is the "initial" V_f (V_f achieved at P_0) and m the stiffening index [2]. In this work, P_0 is defined as 100 kPa, so that when P = 100 kPa, $K = V_f$.

$$V_f = K\left(\frac{P}{P_0}\right)^m \tag{2}$$

This simplifies the analysis of the compaction data, and allows easier prediction of compaction behavior as explained later. Regression analysis was conducted to fit power model curves to the experimental compaction results. The power model parameters obtained are listed in Table 4, with σ being the standard deviation of the fitted parameter. The power models curves appear to fit the compaction responses of the reinforcements quite well, although it can be seen that the Power Law fit is slightly low at around 200 kPa and slightly high at 700 kPa.

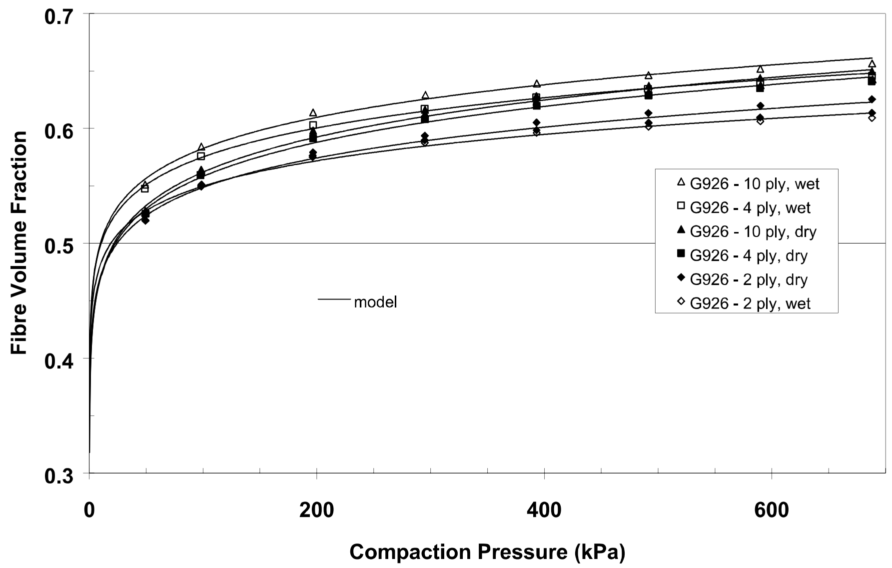


Figure 2: G926, experimental data and Power Law fit

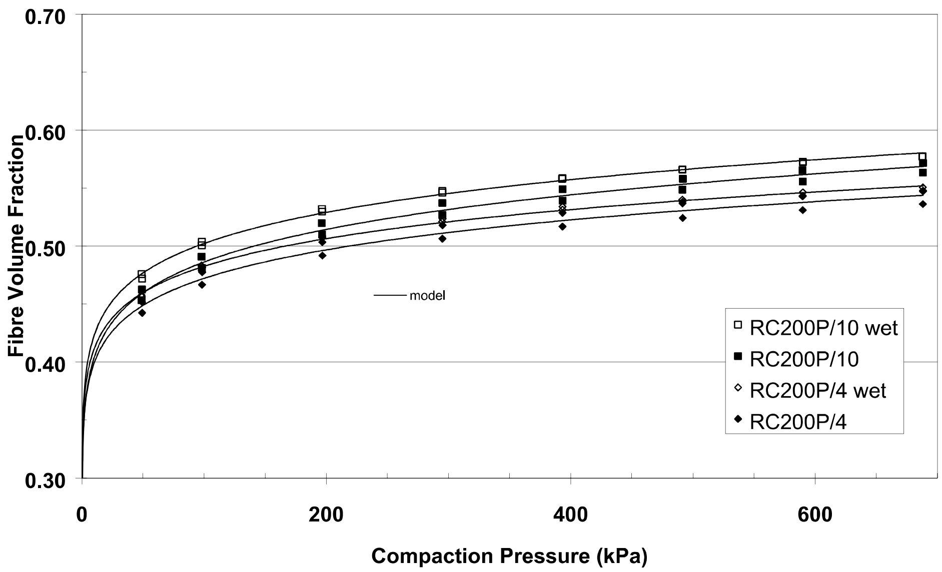


Figure 3: RC200P, experimental data and Power Law fit

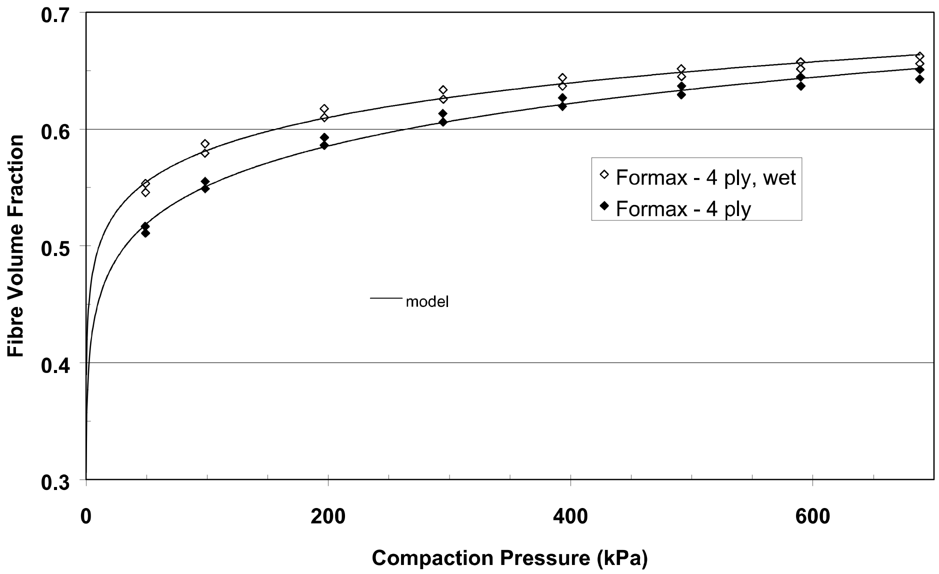


Figure 4: FCIM156, experimental data and Power Law fit

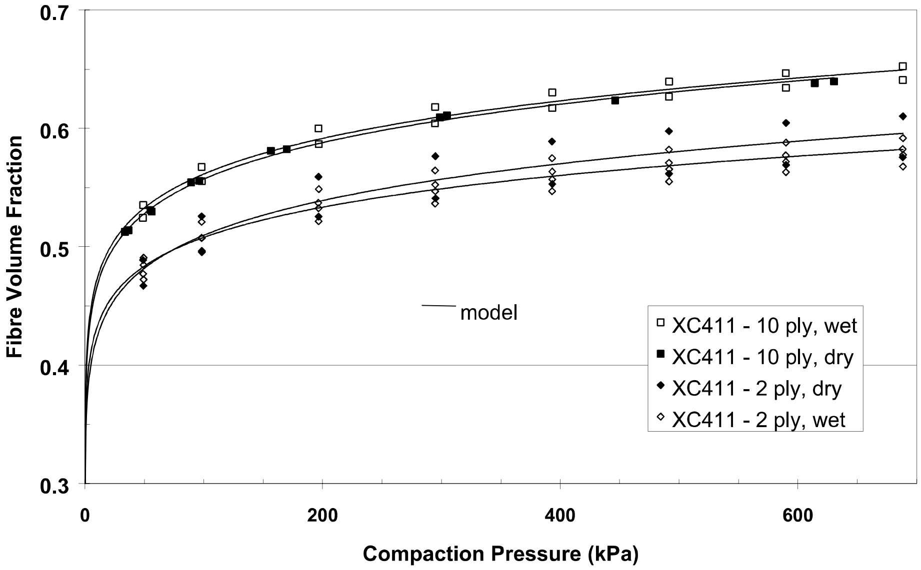


Figure 5: XC411, experimental data and Power Law fit

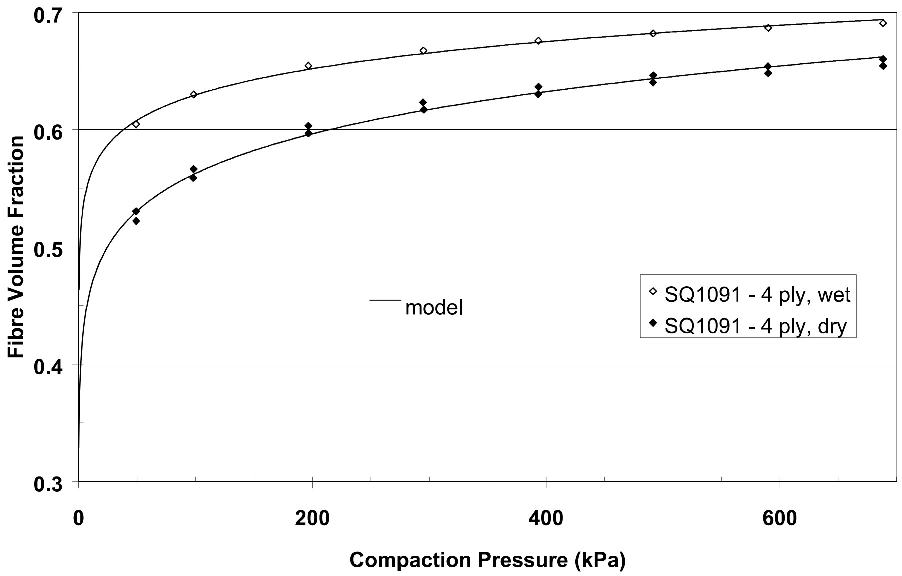


Figure 6: SQ1091R + SQ1090L, experimental data and Power Law fit

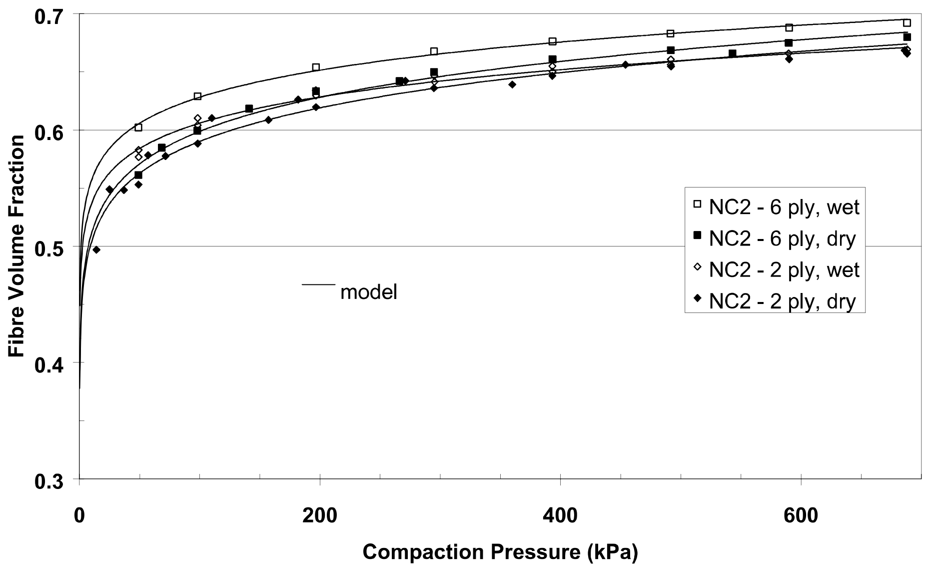


Figure 7: NC2, experimental data and Power Law fit

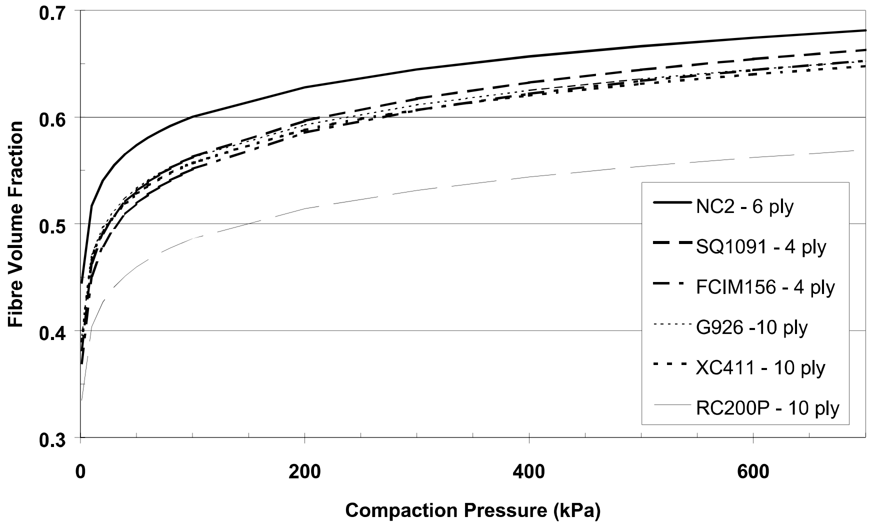


Figure 8: Comparison of all reinforcements (thickest stacks)

Table 4: Power Law parameters, $P_0 = 100$ kPa

Reinforcement	**Number of layers**	***K***	**σ for *K***	***m***	**σ for *m***
G926 (no binder) dry	10	0.5621	0.0034	0.0764	0.0023
	4	0.5583	N/A	0.0747	N/A
	2	0.5488	0.0095	0.0658	0.0054
G926 (no binder) wet	10	0.5825	N/A	0.0656	N/A
	4	0.5752	N/A	0.0619	N/A
	2	0.5497	N/A	0.0568	N/A
RC200P dry	10	0.4861	0.0063	0.0811	0.0011
	4	0.4721	0.0048	0.0732	0.0003
RC200P wet	10	0.5022	0.0059	0.075	0.0027
	4	0.4824	0.0001	0.0696	0.0006
FCIM156 dry	4	0.5512	0.0026	0.0869	0.0002
FCIM156 wet	4	0.5818	0.0065	0.0683	0.0013
XC411 dry	10	0.5570	0.0019	0.0775	0.0009
	2	0.5096	0.0089	0.0809	0.0029
XC411 wet	10	0.5615	0.0068	0.0754	0.0004
	2	0.5092	0.0088	0.0707	0.0035
SQ1091R + SQ1090L dry	4	0.5626	0.0068	0.0843	0.0018
SQ1091R + SQ1090L wet	4	0.6297	N/A	0.0504	N/A
NC2 dry	6	0.6002	0.0222	0.0650	0.0095
	2	0.5899	0.0169	0.0666	0.0048
NC2 wet	6	0.6283	N/A	0.0525	N/A
	2	0.6059	0.0059	0.0528	0.0013

Table 5: Relaxation factors

Reinforcement	Number of layers	Relaxation factor	
		Dry	**Wet**
G926 (no binder)	10	0.0280	0.0400
	4	0.0260	0.0340
	2	0.0210	0.0380
RC200P	4	0.0265	0.0345
	10	0.0285	0.0385
FCIM156	4	0.0200	0.0370
XC411	2	0.0180	0.0255
	10	N/A	0.0360
SQ1091R + SQ1090L	4	0.0175	0.0250
NC2	2	0.0290	0.0380
	6	0.0310	0.0330

For all fabrics tested, *K* was higher with an increased number of layers in the stack: this is expected because of the greater opportunities for nesting with more layers. Other testing by Kruckenberg [5] has indicated that, for fiberglass plain-weave fabrics using this test technique, the V_f is also higher as the number of layers in the stack is increased. The stiffening index *m* was more often slightly higher with an increased number of layers: compaction at the later stage became easier. If the reinforcement was lubricated, *K* was higher with a thicker stack, but the stiffening index *m* decreased: further compaction became harder.

The curves for the thickest stacks for each reinforcement are shown in Figure 8. The NC2 fabric was the easiest to compact: the RC200P was the most difficult. The remaining non-crimp fabrics and the G926 had similar compaction behavior.

Relaxation of Reinforcements

The amount of relaxation during the five-minute hold was also of interest. A "relaxation factor" was measured at 100 kPa. This was defined as below, where t_i is the initial thickness, and t_f is the final thickness after 5 minutes at 100 kPa. As shown in
Table 5, the relaxation factor was found to increase with more layers in the stack, and with lubrication. The SQ1091 showed the least relaxation, and the G926 the most. Non-crimp fabrics would be expected to have less relaxation than woven fabrics because there is less bending of fibers, and less possibilities for the fiber network to reorganize.

$$\frac{t_i - t_f}{t_i} \tag{3}$$

Prediction of Compaction Curves

The reader will have noticed the similarity in the shape of the compaction curves presented. This suggests that a good working prediction of the compaction curve could be made by measuring only the thickness under a compaction pressure of 100 kPa (this could be a simple compaction test under a vacuum bag), and predicting the shape of the compaction curve using typical values of *m*. To investigate the usefulness of this proposal, Figure 9 below shows all the dry compaction curves measured in this work, plotted with a normalised *K* of 0.6.

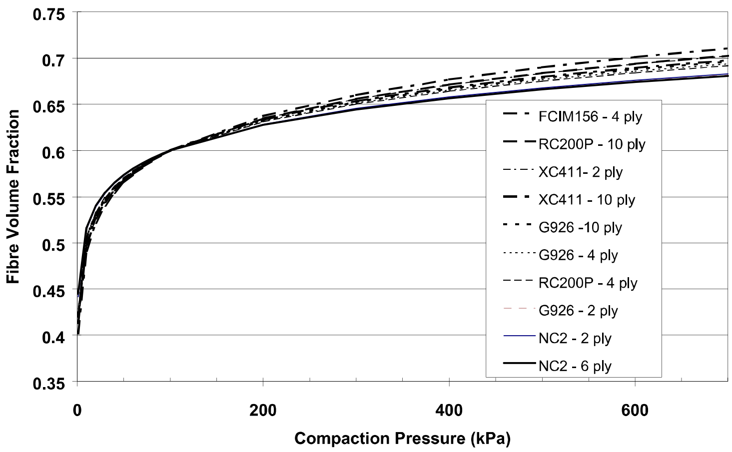


Figure 9: Compaction curves plotted with $K = 0.6$ in all cases.

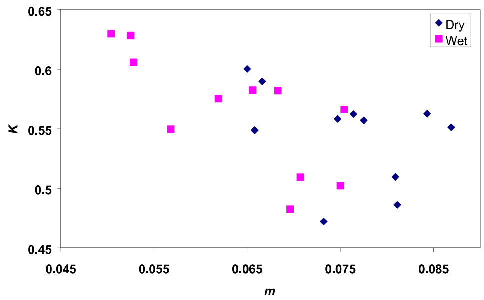


Figure 10: Values of *m* for dry and wet fabrics

It can be seen that the spread is low, (<3% at 700 kPa), especially if thicker stacks are considered (and NC2, which has a low *m*, is left out). Typical values of *m* can be chosen for groups of fabrics: Figure 10 shows that the spread of *m* is different for dry and wet fabrics.

Conclusion

The compaction test procedure described here appears to work well, if carefully applied, with frequent calibration of the machine compliance.

Thicker stacks are easier to compact, as are lubricated stacks. The similarity of compaction curves shown here suggests that a useful prediction of the compaction curve could be made on the basis of a single compaction test under a vacuum bag.

Acknowledgements

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References

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