An evaluation of the reproducibility of ultrasonic sensor-based out-of-plane permeability measurements: a benchmarking study

David Becker*1, Harald Grössing2, Spiridon Konstantopoulos2, Ewald Fauster2, Peter Mitschang1 and Ralf Schledjewski2

1Institut für Verbundwerkstoffe GmbH, Erwin-Schrödinger-Straße, Gebäude 58, 67663 Kaiserslautern, Germany
2Christian Doppler Laboratory for High Efficient Composite Processing, Montanuniversität Leoben, Otto Glöckel-Straße 2, 8700 Leoben, Austria

Abstract Research concerning the measurement of the permeability of fabrics for polymer matrix composites has been ongoing since several decades, but remains in the focus of applied research for liquid composite molding. Today, several systems and technologies for the measurement of in- and out-of-plane permeability are available, but still no approach has gained acceptance as a common standard. A main requirement for reliable permeability measurement technology is the reproducibility of results when comparing different characterization systems. In this context, benchmark studies are an appropriate method to evaluate the reproducibility of a technology. This study presents a benchmark on unsaturated out-of-plane permeability measurement systems based on flow front monitoring via ultrasonic sensors. Two corresponding systems are compared in the study comprising carbon and glass wovens as well as non-crimp fabrics. The out-of-plane permeability was measured with both systems at three different levels of fiber volume content and three repetitive measurements. The results gained with the systems showed good compliance with relative deviation of the permeability values mostly below 50%. Textile-induced inhomogeneities and varying measurement parameters, e.g. injection pressure, were found to be main reasons for the deviations.

Keywords Permeability, Liquid composite molding, Reinforcements, Material characterization

Cite this article David Becker, Harald Grössing, Spiridon Konstantopoulos, Ewald Fauster, Peter Mitschang and Ralf Schledjewski: Adv. Manuf.: Polym. Compos. Sci., 2016, 2, 34-45

Introduction

The increasing demand of fiber-reinforced polymer composites in sectors such as aerospace, automotive, sports and wind industry fosters further development of composite processing techniques. High production quantity, complex component geometry, and large wall thickness are causing new challenges for the process design. Particularly, liquid composite molding (LCM) processes are in the focus of the composites industry as well as research institutions due their high efficiency and variability.¹ This is specifically true for the resin transfer molding (RTM) process. During RTM, a dry reinforcing structure is placed in a mold and a resin system is injected via a point or line gating system, which leads to an impregnation of the reinforcement.² Knowledge about the transmissibility of the reinforcing structure for the resin flow, quantified by the permeability, plays a key role for process design and development. Moreover, it is an important input parameter for numerical filling simulations, which are accomplished for predicting mold filling characteristics during the process stage of matrix injection. However, the accuracy of simulation results can only be as good as that of the input parameters and therefore, accurate values for matrix viscosity, preform porosity, and preform permeability are needed.³–⁵

The permeability of a porous media for the flow of a fluid is defined by the general equations of fluid flow. The Navier–Stokes Equation (NSE) is the most common approach to model fluid flow.⁶ Nowadays, the most common approach
for modeling the fluid flow in a reinforcing structure is based on Darcy’s law, which was developed in 1856 for saturated 1D flow of water through sediments. It was proven that this empirical law is a special form of the NSE and its theoretical derivation is given by Whitaker and Neumann. The permeability of a reinforcing structure can be calculated based on Darcy’s law as shown in Equation (1):

$$v_x = \frac{k_x \Delta p}{\eta \Delta x}$$  \hspace{1cm} (1)

where the superficial flow velocity ($v_x$) multiplied with the porosity) of the fluid is $v_x$, $k_x$ represents the permeability value along the measured direction, $\eta$ the fluid viscosity, and the term $\Delta p/\Delta x$ defines the pressure drop along a specific length. For a three-dimensional fluid scenario, the permeability of the porous media is described by a second-order tensor. Yet, due to the symmetric nature of fabrics, their permeability tensor can be fully described by only three values: $K_1$, $K_2$, and $K_3$ as visualized in Figure 1.

Concerning the in-plane permeability also the orientation angle ($\beta$) of the occurring ellipse can be determined as a third representative parameter of the reinforcing structure. Based on a point-injection into the center of a dry textile preform (Figure 1, left) and adequate flow front monitoring, all of the three in-plane parameters ($K_1$, $K_2$, and $\beta$) can be determined from a single experiment. The 2D permeability calculation algorithm requires the knowledge of timely flow front advancement (unsaturated measurement). Algorithms for 2D permeability calculation were published by Adams and Rebenfeld as well as by Chang and Hwang. Saturated in-plane permeability measurements. The unsaturated permeability measurement is closer to the nature of a real-world LCM process. In order to impede race-tracking at the edges of a preform, a common approach is to rely on point-injection of the fluid into a stack of textile layers, leading to half elliptical flow front advancement within the stack, which then has to be tracked. The unsaturated permeability measurement is closer to the nature of a real-world LCM process. In order to impede race-tracking at the edges of a preform, a common approach is to rely on point-injection of the fluid into a stack of textile layers, leading to half elliptical flow front advancement within the stack, which then has to be tracked. The first research work in the field of 3D (three-dimensional flow front propagation) permeability characterization was performed by Ahn et al. in 1995 using embedded fiber optical sensors for flow front tracking. Despite the fact that the diameters of the fiber optical sensors are very small, the reinforcing structure is manipulated by this procedure and thus, the calculated out-of-plane permeability value is not reliable. In 1999, Lim et al. picked up this idea and published a similar approach based on fiber optical sensors for sensing the flow front in a 3D flow experiment. In 1997, Weizenböck et al. used a method for the evaluation of the 3D permeability based on temperature-sensitive sensors for an incremental determination of the timely flow front advancement. The temperature-sensitive sensors were embedded in the reinforcing structure leading again to an invasive measurement. In 1999 Bréard utilized X-ray radiography for flow front monitoring in the reinforcing structure, which was quite elaborate but non-invasive. In 2002, Nedanov et al. used a vacuum bag covering a reinforcing structure on an acrylic glass plate and utilized a video camera in order to detect the flow front advancement on the surface with the injection point. In addition, the mass of the injected liquid was captured such that the flow front geometry can be reconstructed under certain geometrical assumptions. In 2003, Stöven et al. presented a system which is based on the continuous monitoring of the flow front using ultrasonic technology. This technology is efficient concerning the effort and the costs and is truly non-invasive. This technique is followed in this paper and explained in detail in Section Experimental setup.

The quality of a measurement technology is quantified by the reproducibility of the measurement results. Striving for an
international standard, several studies on the reproducibility of in-plane permeability measurements were performed in the past. Up to now, four in-plane permeability benchmark studies were published involving different permeability measuring methods and technologies. In a nordic round robin study executed by Lundström et al., the standard deviations of the in-plane permeability measurements were between 8 and 30%. The three involved participants used saturated and unsaturated 1D as well as 2D permeability measuring test rigs. An international permeability benchmark exercise with 11 participants has shown the great interest and importance on the topic as well as the challenges inherent to in-plane test rigs (1D and 2D). The standard deviations associated with the results gained with test rigs were about 1.000%. The research institutions involved around the globe devoted special attention to compile a way to standardization for 1D permeability test rigs. A total of 13 institutes have participated in a second worldwide permeability benchmark exercise following a specific guideline for the 1D permeability test rig implementation and ensuring fixed experimental parameters (e.g. injection pressure, test fluid viscosity, and fiber volume fraction). The scatter obtained while respecting the guidelines was below 25% between the test rigs. In 2015, Grössing et al. compared 2D capacitive based in-plane permeability measuring systems. The two systems were similar concerning the built-up, approach, and technology, but supervised at two different research institutes. The capacitive technology has the advantage that it allows flow front monitoring in a metal mold (even with electrically conductive carbon fibers when insulating coating is applied), leading to a minimum of mold deflection. The study revealed that the average deviations between the results gained at the institutes did not exceed the standard deviation associated with the results of repetitive measurements at the particular institutions (5%).

Reproducibility of out-of-plane permeability measurement results is equally important but not treated in the literature so far. This is the focus of the study presented in this paper.

**Experimental setup**

The main purpose of this study is the systematic comparison of the reliability of two out-of-plane permeability measuring systems based on ultrasonic technology. The out-of-plane permeability measuring systems are supervised and located in two different research laboratories:

- Institut für Verbundwerkstoffe (IVW) GmbH, Kaiserslautern, Germany
- Christian Doppler Laboratory (CDL) for High Efficient Composite Processing, Montanuniversität Leoben, Austria.

In the following, the basic approach of permeability measurement with ultrasonic technology is explained and the two systems involved are presented.

Figure 2 shows the schematic setup for measurement of unsaturated out-of-plane permeability utilizing ultrasonic technology.

The setup and the corresponding measurement and data processing approach were developed and patented by Stöven et al. The textile sample (preform) is placed between two plates at a specific fiber volume fraction $V_f$, which results from the cavity height $h$, the fiber material density $p_f$, the areal weight of a single ply $S_0$, and the number of plies $n$ according to Equation (2):

$$V_f = \frac{nS_0}{p_f h}$$  

(2)

The lower plate comprises a point inlet allowing a central point injection on the down-side of the preform. The injection pressure is set using a pressure vessel. A pressure sensor is positioned at the inlet to control the injection pressure. The complete measurement cell is placed on a scale, so that the injected mass can be measured and the injected volume can be calculated. Alternatively, a flowmeter can be used. The key elements of the system are an ultrasonic source, respectively, an ultrasonic receiver placed in the bottom and top plate, respectively, coaxial to the point inlet. With this arrangement, ultrasonic waves can be continuously sent through the preform and it is possible to measure their time-of-flight, which quantifies the time it takes for the wave to pass the preform and reach the receiver. Control of the process parameters and capturing the sensor data are accomplished by means of LabView software allowing for running the experiments fully automated. Figure 3 shows the theoretical development of the captured values during injection with constant injection pressure.
Stöven could show mathematically that the error can be strongly reduced when the permeability is evaluated at flow front heights greater than 6 mm.

\[ \rho \text{ is the fluid density and } m \text{ is the injected fluid mass.} \]

In case of using a flowmeter, the injected fluid volume can be implemented instead of the fraction \( m / u \).

In a second step, the out-of-plane permeability \( K_3 \) is calculated from \( K_e \) utilizing the relation from the actually measured flow front height and the flow front height in the isotropic substitute model:

\[ K_3 = \left( \frac{z_f}{r_f} \right)^2 K_e \]

With this approach, \( K_3 \) can be theoretically calculated for every time step of the measurement and it should show constant characteristics as indicated in Figure 3.

Stöven proposed to average only the values captured above a flow front height of 6 mm. Several reasons require this limitation:

- Real-world experiments show that the flow front differs from the ideal half-ellipsoid and the permeability will not be fully constant. This is mostly caused by the structural built-up of textiles which causes regions of differing permeability (e.g. in yarns and between yarns). These inaccuracies are stronger the smaller the radius of the half-ellipsoid is.
- Further inaccuracies result from the fact that the flow front height is not measured at one single spot but over a specific sensitive area of the ultrasonic system so that a strong flow front curvature can have an influence.

As can be seen in the top left diagram, the time-of-flight decreases with increasing experiment time. Stöven et al. have shown, that the time-of-flight is linearly correlated with the flow front height, which results from the higher speed of sound of ultrasonic waves in wet regions compared to dry regions. The bottom left diagram shows that at constant injection pressure the flow front height decreases over experiment time, which is due to increasing flow front area. The flow front height can be calculated from the time-of-flight according to Equation (3), where \( z_f \) is the flow front height, \( z_k \) is the total preform height, \( t_s \) is the time-of-flight in completely dry state, \( t \) is the current time-of-flight, and \( t_e \) is the time-of-flight in the completely wetted case.

\[ z_f = z_k - z_s \times \frac{t - t_e}{t_s - t_e} \]

In order to calculate the permeability, a global isotropic substitute permeability \( K_e \) is determined at first. The flow front in this case shows the shape of a half-sphere. \( K_e \) can be calculated with Equation (4):

\[ K_e = \frac{\eta \phi}{6(p_0 - p_f)} \times \left[ 2 \left( \frac{r_0}{r_f} \right)^3 - 3 \left( \frac{r_0}{r_f} \right)^2 + 1 \right] \frac{1}{t_i} \]

with \( \eta \) being the fluid viscosity (constant when a measurement fluid such as oil is used), \( \phi \) denoting the porosity, \( p_0 \) specifying the injection pressure, \( p_f \) terming the pressure at the flow front, and \( r_f \) being the half-sphere radius. \( r_0 \) is the inlet radii and corresponding to the boundary conditions of Equation (4) it should theoretically show a geometry related to the flow front shape resulting from point-injection. Therefore, a half-spherical notch in the reinforcement would be required. However, the final flow shape is of course unknown prior to the measurement and it would be different for every material. Also, it would be almost impossible to accurately implement the notch in the fiber material. To solve this problem, the method of the functional determination of the inlet radii is applied. This means for every time step \( r_g \) is calculated with Equation (5), which includes the inlet drilling in the lower plate \( R_0 \).

\[ r_g = R_0 \sqrt{\frac{z_f}{r_f}} \]

As can be seen in the top left diagram, the time-of-flight decreases with increasing experiment time. Stöven et al. have shown, that the time-of-flight is linearly correlated with the flow front height, which results from the higher speed of sound of ultrasonic waves in wet regions compared to dry regions. The bottom left diagram shows that at constant injection pressure the flow front height decreases over experiment time, which is due to increasing flow front area. The flow front height can be calculated from the time-of-flight according to Equation (3), where \( z_f \) is the flow front height, \( z_k \) is the total preform height, \( t_s \) is the time-of-flight in completely dry state, \( t \) is the current time-of-flight, and \( t_e \) is the time-of-flight in the completely wetted case.

\[ z_f = z_k - z_s \times \frac{t - t_e}{t_s - t_e} \]

In second step, the out-of-plane permeability \( K_3 \) is calculated from \( K_e \) utilizing the relation from the actually measured flow front height and the flow front height in the isotropic substitute model:

\[ K_3 = \left( \frac{z_f}{r_f} \right)^2 K_e \]

With this approach, \( K_3 \) can be theoretically calculated for every time step of the measurement and it should show constant characteristics as indicated in Figure 3.

Figure 3 Principle development of calculated results based on captured data
Prior to the permeability measurement, the oil temperature was measured and a constant temperature respectively viscosity was assumed during the permeability measurement.

**Approach**

In order to evaluate the reproducibility of out-of-permeability values determined by means of ultrasonic measurement technology, the textiles were characterized at both research institutes. Beyond 6 mm flow front height it is ensured that the sensitive sensor area is fully covered.

- Also, the mathematical equations assume that the injection point is an ellipse which corresponds to the half-ellipsoidal flow front. This is of course impossible, since the flow front shape is unknown prior to measurement and also a specific injection gate would have to be manufactured for every measurement. This leads to an error which is decreases with increasing flow front size and is absolutely negligible beyond 6 mm flow front height.

Several experimental tests have proven that the calculated permeability reaches a stable level at a certain point (Figure 7) and that the limit of 6 mm ensures that this level is reached. Thus, the proposal of Stöven is followed and only values greater 6 mm flow front height are considered.

The IVW and the CDL both work with a system following this basic principle. Yet, some differences are given as can be seen on the images in Figure 4.

Some of the main characteristics and differences are listed in Table 1. Further differences are due to the ultrasonic sensors and the corresponding periphery.

**Materials and sample preparation**

For the study presented in this paper, four fabrics were chosen, which are shown in Figure 5. Glass and carbon fiber woven and non-crimp fabrics were used due to their industrial relevance.

All fabrics are commercially available materials – the corresponding textile parameters are listed in Table 2 according to the data sheet specifications.

Two of the fabric preforms were cut according to a uniform scheme at CDL/IVW and then shipped to IVW/CDL, where the preform stacks were prepared with utmost carefulness in order to minimize unwanted handling influences.

The measurements were performed with plant oil at both institutes (IVW: rape seed oil and CDL: corn oil). Each research site used its own oil and the temperature-dependent viscosity was measured with a spindle rheometer (IVW), respectively, a couette-rheometer (CDL). Figure 6 shows the corresponding viscosity curves. The viscosity value of the oil at room temperature is similar to the viscosity value of typical resin at processing temperature (about 70 mPas). Prior to the permeability measurement the oil temperature was measured and a constant temperature respectively viscosity was assumed during the permeability measurement.

**Approach**

In order to evaluate the reproducibility of out-of-permeability values determined by means of ultrasonic measurement technology, the textiles were characterized at both research institutes.
for the experiments in this study was primarily based on experience gained when measuring similar textiles in the past. Two aspects have been considered:

- The higher the fluid injection pressure, the higher the risk for textile deformation.
- The lower the fluid injection pressure, the stronger the influence of capillary pressure.

Therefore, the rule “as low as possible, as high as necessary” was followed. The experimental time can be used as an indicator. If the flow front reaches the top in less than 20 s the pressure can possibly be reduced. On the other side, if it takes more than 300 s for the flow front to reach the top a significant influence of capillary pressure is very likely and the fluid injection pressure should be increased. Generally, the past has shown that values between 50 and 250 kPa are reasonable. However, the decision is influenced by subjective factors to a certain amount. The target of the benchmark is to answer the question if data from system A can be compared with data from system B. In reality this means that data will be compared which was not generated as part of a benchmark – this means there hasn’t been any possibility to equalize the measurement parameters. Thus, to honestly answer the question if the generated data are comparable, the user influence must be included in the comparison. Hence, the injection pressure values were chosen independently at both institutes, in order to include variations resulting from user influence.

The number of layers in each experiment is determined by the target fiber volume content and the cavity height. The cavity height itself is adapted to the ultrasonic system. Since the cavity heights slightly differ (8.00 vs. 8.45 mm) between the research sites, also the number of layers can vary. The theory of Darcy’s law states that the flow length does not have any influence on the permeability. However, textile samples are no homogeneous porous structures since they are built-up from layers. Layers can show nesting behavior which deforms the pore space and thus the number of layers can indeed have an influence, especially when the number of layers is very small. In this study, the worst case is 13 vs. 14 layers. In this range it is assumed that no measurable influence is given.

### Results and discussion

Figure 8 shows a comparison of out-of-plane permeability values measured for the four textiles in the selected region of fiber volume content. At both institutes the grammage stated

---

Table 2 Material data of the textiles used in the study

| Textile                | Specification        | Areal weight (g/m²) | Fiber orientation | Single ply areal weight (g/m²) | Yarn titer (tex) | Yarn density (1/cm) |
|------------------------|----------------------|---------------------|-------------------|-------------------------------|------------------|---------------------|
| Schloesser und Cramer 3106 | GF-Woven fabric (twill 2/2) | 390 (± 5.1%)         | Warp              | 340                           | 6                |
| Saertex X-E-612 g/m²   | GF-NCF (pillar)      | 612 (± 5.1%)         | Weft              | 272                           | 6.7              |
| Sigmatex KDL 8049/120 (SGL) | GF-Woven fabric (plain) | 240 (± n.a.)         | Sewing thread     | 6                             | 5.7              |
| Saertex XC-588 g/m²-1270 | CF-NCF (pillar)      | 588 (± 5.1%)         | 45°               | 610                           | 6                |
|                        |                      |                     | 90°               | 290                           | 6                |
|                        |                      |                     | 0°                | 1                             | 6                |
|                        |                      |                     | −45°              | 3                             | 6                |
|                        |                      |                     | Sewing thread     | 6                             | 6                |

---

Figure 6 Temperature-dependent viscosity of the measurement fluids used

Figure 7 shows exemplarily chosen results from a single experiment on the GF NCF at a fiber volume content of 54%. Comparing the characteristics of the curves to those shown in Figure 3, it can be observed that the curves are very similar, except for the out-of-plane permeability diagram (bottom right), which clearly shows non-constant characteristics. This is due to an imperfectly shaped half-ellipsoidal flow front at the beginning of the measurement. As marked in the diagrams of Figure 7, data post-processing were restricted to the section of the last 2 mm of flow front height propagation In this region all captured and calculated values are stable.

Permeability values measured at identical values of fiber volume fraction were finally averaged and the corresponding standard deviation values were calculated.

Basically, the measurement system allows injection pressures from 0 to 500 kPa. The selection of the injection pressure sites at three different fiber volume fraction values with three repetitive measurements (nine measurements per textile and research site). While a higher number could lead to an improved security concerning the average permeability value, the value of three repetitions measurements corresponds to the common number of tests performed e.g. when measuring permeability for flow simulations. The target of the benchmark is to give a realistic and honest impression on the possibilities to compare the data generated at both research sites. Hence, standard procedures are applied to give a realistic image and three repetitions allow a significant statement about the variations measured at a single fiber volume content.

Figure 7 shows exemplarily chosen results from a single experiment on the GF NCF at a fiber volume content of 54%. Comparing the characteristics of the curves to those shown in Figure 3, it can be observed that the curves are very similar, except for the out-of-plane permeability diagram (bottom right), which clearly shows non-constant characteristics. This is due to an imperfectly shaped half-ellipsoidal flow front at the beginning of the measurement. As marked in the diagrams of Figure 7, data post-processing were restricted to the section of the last 2 mm of flow front height propagation In this region all captured and calculated values are stable.

Permeability values measured at identical values of fiber volume fraction were finally averaged and the corresponding standard deviation values were calculated.

Basically, the measurement system allows injection pressures from 0 to 500 kPa. The selection of the injection pressure sites at three different fiber volume fraction values with three repetitive measurements (nine measurements per textile and research site). While a higher number could lead to an improved security concerning the average permeability value, the value of three repetitions measurements corresponds to the common number of tests performed e.g. when measuring permeability for flow simulations. The target of the benchmark is to give a realistic and honest impression on the possibilities to compare the data generated at both research sites. Hence, standard procedures are applied to give a realistic image and three repetitions allow a significant statement about the variations measured at a single fiber volume content.

Figure 7 shows exemplarily chosen results from a single experiment on the GF NCF at a fiber volume content of 54%. Comparing the characteristics of the curves to those shown in Figure 3, it can be observed that the curves are very similar, except for the out-of-plane permeability diagram (bottom right), which clearly shows non-constant characteristics. This is due to an imperfectly shaped half-ellipsoidal flow front at the beginning of the measurement. As marked in the diagrams of Figure 7, data post-processing were restricted to the section of the last 2 mm of flow front height propagation In this region all captured and calculated values are stable.

Permeability values measured at identical values of fiber volume fraction were finally averaged and the corresponding standard deviation values were calculated.

Basically, the measurement system allows injection pressures from 0 to 500 kPa. The selection of the injection pressure
and 59% were interpolated. The approach is illustrated in Figure 10.

In Figure 11 the deviation of permeability values interpolated to the IVW-function $f_{IVW}(V_f)$ and the CDL-function $f_{CDL}(V_f)$ are depicted as relative error, which was computed according to:

$$\text{relative error} = 1 - \frac{f_{CDL}(V_f)}{f_{IVW}(V_f)}$$

(8)

As can be seen, the relative error is almost consistently smaller than 50% (except for the carbon fiber woven fabric) – a comparatively good result keeping in mind the results of other benchmark studies, the lack of specifications for the setup and procedure of the measurement and especially concerning the variations between repetitive measurements, which are typically higher compared to in-plane-permeability values. Exemplarily stated, the coefficient of variation for the carbon fiber non-crimp fabric at the lowest fiber volume content is 5% for $K_1$, 15% for $K_2$, and 58% for $K_3$. The main reasons for this are discussed in Section Textile inhomogeneity.

The data show that permeability functions should only be trusted in a narrow range close to the range covered by the experimental data. That means only interpolation but no extrapolation should be performed and the minimum and

Figure 7 Actual development of calculated results based on captured data for a measurement of the GF-NCF at a fiber volume content of 54% (measured at IVW)
maximum measured fiber volume contents should be seen as boundaries of the validity of the function. If this simple rule is complied, the maximum relative error for these textiles is reduced from 20.5 to 75%. Therefore, the measured fiber volume content range should always cover the complete range expected in the simulation of the process in order to have a maximum accuracy. Still, due to the given insecurity it is suitable to perform worst- and best-case simulations to cope with the variation in the measured data.

In Figure 11 it can be seen that the carbon fiber woven fabric shows a behavior opposite to the others. With increasing fiber volume content the error increases instead of decreasing. This can be accounted to the relatively strong deviation at the lowest fiber volume content. This leads to a high difference in steepness of the calculated exponential functions which therefore strongly deviate outside the range of measured fiber volume content (which was quite low for the carbon fiber woven fabric). The lower the fiber volume content, the lower the accuracy of measurement. Hence, care must be taken that especially when measurements at low fiber volume contents are included in curve calculation no extrapolation beyond the highest measured fiber volume content is performed, since this can lead to dramatic errors.

A summary of the measurement results can be found in Table 3.

In order to evaluate how the reliability can be further improved, the sources for the scatter in the results of the repetitive measurements as well as the deviations between the results gained at the two research sites are discussed in the subsequent sections.

**Textile inhomogeneity**

Although textiles are manufactured with a fixed set of manufacturing parameters, variations in the quality appear. This gets quite clear by considering the areal weight. The manufacturer specifies a variation of ±5.1% for the total grammage in the material data sheet. Due to the strong influence of the fiber volume content on permeability values such variations...
**Table 3** Summary of experimental results

| Fiber volume content (%) | Number of layers | Injection pressure (bar) | K3 average value \( (m^2) \) | Coefficient of variation (%) |
|--------------------------|-----------------|--------------------------|-----------------------------|-------------------------------|
| Glass fiber woven fabric|                 |                          |                             |                               |
| I                        | 49.71           | 26                       | 1.0                         | 9.41E−13                      | 3.0                           |
| V                        | 53.53           | 28                       | 1.0                         | 4.90E−13                      | 41.4                          |
| W                        | 55.44           | 29                       | 1.5                         | 3.78E−13                      | 6.0                           |
| C                        | 49.74           | 28                       | 1.0                         | 8.96E−13                      | 19.2                          |
| D                        | 53.30           | 30                       | 1.0–1.5                     | 3.25E−13                      | 25.1                          |
| L                        | 57.11           | 32                       | 2.0–2.5                     | 1.65E−13                      | 29.7                          |
| Glass fiber non-crimp fabric|             |                          |                             |                               |
| I                        | 48.00           | 16                       | 0.5                         | 3.60E−12                      | 54.2                          |
| V                        | 51.00           | 17                       | 1.0                         | 2.57E−12                      | 18.3                          |
| W                        | 54.00           | 18                       | 1.0                         | 1.30E−12                      | 41.7                          |
| C                        | 47.74           | 17                       | 1.0                         | 6.82E−12                      | 26.8                          |
| D                        | 50.90           | 18                       | 1.5–2.0                     | 3.98E−12                      | 17.3                          |
| L                        | 53.53           | 19                       | 0.5–2.5                     | 1.56E−12                      | 29.9                          |
| Carbon fiber woven fabric|                 |                          |                             |                               |
| I                        | 48.88           | 29                       | 1.0                         | 7.68E−13                      | 24.9                          |
| V                        | 52.25           | 31                       | 1.0                         | 2.78E−13                      | 35.7                          |
| W                        | 55.62           | 33                       | 1.5                         | 1.24E−13                      | 13.9                          |
| C                        | 49.46           | 31                       | 1.5                         | 1.24E−13                      | 13.9                          |
| D                        | 52.66           | 33                       | 2.0                         | 5.36E−13                      | 11.6                          |
| L                        | 54.25           | 31                       | 2.0                         | 1.66E−13                      | 10.6                          |
| Carbon fiber non-crimp fabric|             |                          |                             |                               |
| I                        | 53.68           | 13                       | 1.0                         | 2.31E−12                      | 76.6                          |
| V                        | 57.81           | 14                       | 1.0                         | 3.82E−13                      | 58.9                          |
| W                        | 61.94           | 15                       | 1.5                         | 1.53E−13                      | 26.8                          |
| C                        | 54.02           | 14                       | 1.5                         | 1.42E−12                      | 10.2                          |
| D                        | 58.04           | 15                       | 2.5                         | 2.10E−13                      | 11.1                          |
| L                        | 61.70           | 16                       | 3.0                         | 1.18E−13                      | 9.2                           |

*Only one measurement due to material shortage.*
Table 4 Influence of deviations of the areal weight on the permeability values obtained from regression functions

| FVC for actual areal weight (−1%) (%) | Corresponding permeability ($f_{v,m}$, $V_f = 49.5\%$) | Corresponding permeability ($f_{v,m}$, $V_f = 50.5\%$) | Deviation between max. and min. |
|----------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------|
| GF-WF                                  | 49.5                                                          | 9.21E−13                                                    | +18.4%                          |
| GF-NCF                                 | 49.5                                                          | 2.49E−12                                                    | +18.5%                          |
| CF-WF                                  | 49.5                                                          | 3.46E−12                                                    | +84.7%                          |
| CF-NCF                                 | 49.5                                                          | 1.87E−12                                                    | +38.9%                          |

directly impact the scatter in measurement results of different samples of the same textile. Within the present study, the weight of each preform was measured, in order to track the mass homogeneity of the textiles. The variation in the mass referring to the arithmetic average value was between −3.9 and +1.3%. Although the real mass can differ from the value specified in the data sheet by several percent, the mass of the single samples, obtained from one textile roll is relatively close together. For the four textiles, the deviation of the single samples from their mean value was between 0.3 and 1.3%. So using an experimentally obtained average value for each batch would already strongly improve accuracy. Yet, the influence on the permeability is still huge, which can be shown by a short example: if one wants to measure the permeability at 50% fiber volume content, a deviation of only ±1% of the actual areal weight from the nominal areal weight can lead to an actual fiber volume content of 50 ± 0.5%. Using the exponential functions fitted to the data measured at the IVW the effect of this fiber volume content change on the permeability can be estimated. Table 4 shows the corresponding permeability values which would be measured and the deviations which can result only from textile inhomogeneity.

From this example, it can be concluded that the textile inhomogeneity has a great influence on the reproducibility of out-of-plane permeability values measured with one single system, since it leads to a high variability between samples. If one looks at the error bars of the measurements at certain fiber volume content values in Figure 8, one can see that the variation between the results from the two research sites is always smaller than the standard deviation of the measurements performed at a single research site (except for the carbon fiber woven fabric). This further supports the assumption that the effect of the textile homogeneity explains a great amount of the deviation between the research sites. Thus, it is of utmost importance, that the fiber volume content given in permeability measurement, simulation, and of course the manufacturing process is as similar as possible. Again, it is suggested to include these variations in process and tool design, by performing worst- and best-case simulation.

It has to be mentioned that of course the samples can fringe out at the edges which adds to the weight variation without having direct influence on the permeability measurement, which do not depend on edge effects since the flow takes place in the center area of the preform. Nevertheless, the variations are high enough to explain a great amount of the permeability variations.

A further problem in going together with textile inhomogeneity is the relatively small flow length (about 8 mm in height) compared to in-plane permeability measurements (typically > 150 mm in length). The shorter length minimizes averaging of the effect of inhomogeneities leading to greater variation compared to in-plane permeability measurements.

**Injection pressure**

Fluid injection pressure values were independently chosen at the two research sites ranging between 50 and 250 kPa. However, they were kept constant for experiments at distinct values of fiber volume content. The flow processes were assured to be within a laminar region, so that velocity-dependent turbulences can be excluded as reasons for deviations. The problem rather concerns the fact that textiles are not perfectly rigid but deformable. While a textile is impregnated, textile compaction occurs due to decreasing fluid pressure along the flow length. The result is an inhomogeneous fiber volume content distribution or even an increase of the total fiber volume content. Thus, the deformability has tremendous effects on the out-of-plane permeability characteristics.

First of all, the deformability can lead to systematic deviations if different injection pressure values are applied. Several studies have shown an influence of injection pressure. Becker et al. verified experimentally for the glass fiber woven fabric used in this study, that this influence is also given at low injection pressure in combination with high pre-compaction. Additionally, the deformability influence is an issue even if the same pressure drop is applied at both institutes. This is because the compaction behavior of the different stackings can vary due to several reasons such as geometrical inhomogeneities, differing storing and transport conditions, differing handling history, etc. Due to the deformability influence, the variations concerning the compaction behavior add to the deviation between repetition measurements. These findings are further confirmed by the fact that the standard deviation gets smaller with increasing fiber volume content. This can be accounted to the reduced deformability of the textile lay-up with increasing compaction. As a result, it can be concluded that the deviation between two systems can be reduced, when equal injection pressure values are applied and the measurements are performed at the same fiber volume contents. Specific care must be taken for measurements at relatively low fiber volume content values. However, the calculations in Section Textile inhomogeneity and the results shown in Table 3 indicate that the main influence is given by the textile homogeneity since it leads to by far greater variation in the pore space compared to the deformations induced by pressure drop variations.

**Summary and conclusion**

Using ultrasonic technology the flow front propagation in a lay-up of textile layers can be monitored non-invasively. Both, IVW and CDL have set up measurement systems which utilize this technology for the measurement of out-of-plane
permeability values in order to investigate the reproducibility of these permeability values, four textiles were characterized at both research sites and the results were compared.

With regard to the well-known challenges concerning the accuracy of unsaturated out-of-plane permeability measurements, the results of IVW and CDL showed a good compliance with deviation mostly below 50%. Textile inhomogeneity and varying injection pressures were found to be the main reasons for the deviations. For a maximum reproducibility between repetitive measurements but also between the two systems the areal weight should be measured for each material roll instead of relying on nominal values specified in the material data sheet. Moreover, the injection pressure should be equal and the accuracy of the cavity geometry should be checked. Summarizing, the technology is very promising for reliable out-of-plane permeability measurements and the reproducibility can be further improved in the future. Correspondingly, a second benchmark is planned, with more strict guidelines developed on the basis of the findings of this study.

As a result of the findings in this study, it is proposed to perform best-case/worst-case simulations to cope with the possible variations. Also, when using permeability functions the experimental data on which they are based should cover the complete fiber volume content range expected, since extrapolation can lead to strong deviations.

**Nomenclature**

- **CDL**: Christian Doppler Laboratory
- **CF**: carbon fiber
- \( f_{\text{CDL}}(V_f) \): permeability function derived from data measured at CDL
- \( f_{\text{IVW}}(V_f) \): permeability function derived from data measured at IVW
- **GF**: glass fiber
- **h**: cavity height
- **IVW**: Institut für Verbundwerkstoffe GmbH
- **m**: mass of injected fluid
- **n**: number of plies
- **\( \eta \)**: fluid viscosity
- **NCF**: non-crimp fabric
- \( K_x \): global isotropic substitute permeability
- \( K_y \): permeability value along the measured direction
- **K1**: highest in-plane permeability
- **K2**: lowest in-plane permeability
- **K3**: out-of-plane permeability
- **\( \rho \)**: fluid density
- \( \Delta p \): pressure drop along a specific flow length
- \( \rho_i \): injection pressure
- \( \rho_f \): fiber material density
- \( p_f \): pressure at the flow front
- \( r_o \): radius of the point inlet
- \( r_f \): half-sphere radius
- \( S \): areal weight of a single ply
- \( t \): current time-of-flight
- \( t_{z_f} \): time-of-flight in the completely wetted case
- \( t_{z_i} \): time-of-flight in completely dry state
- \( V_f \): specific fiber volume fraction
- \( v_f \): superficial flow velocity
- **WF**: woven fabric
- \( z_f \): flow front height
- \( z_t \): total preform height
- \( \phi \): porosity

**Funding**

H. Grössing, S. Konstantopoulos, E. Fauster and R. Schledjewski kindly acknowledge the financial support provided by both the Bundesministerium für Wirtschaft, Familie und Jugend in Austria, the Christian Doppler Laboratory and the FACC Operations GmbH.

**References**

1. R. Lässig, M. Eisenhut, A. Mathias, R. T. Schulte, F. Peters, T. Kühmann, T. Waldmann and W. Begemann: ’Serienproduktion von hochfesten Faserverbundbauteilen’; 2012, Amsterdam, Roland Berger Consultants and Verband Deutscher Maschinen- und Anlagenbau e.V.
2. K. N. Kendall, C. D. Rudd, M. J. Owen and V. Middleton: Compos Manuf, 1992, 3, (4), 235–249.
3. F. Trochu, R. Gauvin and D. M. Gao: Adv. Polymer Technol., 1993, 12, (4), 329–342.
4. H. Grössing, N. Stadlmajer, E. Fauster, M. Fleischmann and R. Schledjewski: Polym. Compos., 2015. doi: http://dx.doi.org/10.1002/pc.23474.
5. X.-L. Liu: Composites Part A, 2000, 31, (12), 1295–1302.
6. S. Whitaker: Transport in Porous Media, 1986, 1, (1), 3–25.
7. H. Darcy: ’Les Fontaines Publicques de la Ville de Dijon’ [The public fountains of the City of Dijon]; 1856, Paris, Libraire des Corps Impéraires des Ponts et Chausses et des Mines.
8. S. P. Neumann: Acta Mech., 1977, 25, (3), 153–170, doi: http://dx.doi.org/10.1007/BF01376989.
9. K. L. Adams and L. Rebenfeld: Text. Res. J., 1987, 57, (11), 647–654.
10. K. L. Adams, W. B. Russel and L. Rebenfeld: Int. J. Multiphase Flow, 1988, 14, (2), 203–215.
11. A. W. Chan and S. T. Hwang: Polym. Eng. Sci., 1991, 31, (16), 1233–1239.
12. R. S. Parnas: ’Liquid composite moulding’; 2014, Munich, Carl Hanser Verlag GmbH KG.
13. F. D. Dungan and A. M. Sastry: J. Compos. Mater., 2001, 36, (13), 1581–1603.
14. G. Francucci, E. S. Rodríguez and A. Vázquez: Composites Part A, 2010, 41, (1), 16–21.
15. R. Arber, J. Beraud, C. Binetruy, L. Bizet, J. Bréard, S. Comas-Cardona, C. Demaria, A. Endruweit, P. Ermanni and F. Gommer: Composites Part A, 2011, 42, (9), 1157–1168.
16. K. Okonkwo, P. Simacek, S. G. Advani and R. S. Parnas: Composites Part A, 2011, 42, (10), 1283–1292.
17. P. Ouagne, T. Ouahbi, C. H. Park, J. Bréard and A. Saouab: Composites Part B Engineering, 2013, 45, (1), 609–618.
18. S. Scholz, J. W. Gillespie and D. Heider: Composites Part A, 2007, 38, (9), 2034–2040.
19. T. Stöven, F. Weyrauch, P. Mitschang and M. Neitzel: Composites Part A, 2003, 34, (6), 475–480.
20. F. Stedile: ’Felt permeability testing apparatus’, Patent, 1971.
21. R. S. Parnas, J. G. Howard, T. L. Luce and S. G. Advani: Polym. Compos., 1995, 16, (6), 429–445.
22. K. K. Han, C. W. Lee and B. P. Rice: Compos. Sci. Technol., 2000, 60, (12–13), 2435–2441.
23. D. Becker, M. Brzeski, D. Linster and P. Mitschang: ’Preform compaction and deformation during through-the-thickness impregnation’, ICCM19, Montreal, 28 July–02 August 2013.
24. D. Becker and P. Mitschang: ’Metrological consideration of flow-induced preform compaction during out-of-plane permeability measurement’, TextComp11, Leuven, 19–20 September 2013.
25. S. H. Ahn, W. I. Lee and G. S. Springer: *J. Compos. Mater.*, 1995, **29**(6), 714–733.
26. S. T. Lim and W. I. Lee: *Compos. Sci. Technol.*, 2000, **60**(7), 961–975.
27. J. R. Weitzenböck, R. A. Shenoi and P. A. Wilson: *Composites Part A*, 1998, **29**(1–2), 159–169.
28. J. Bréard, A. Saouab and G. Bouquet: *J. Reinf. Plast. Compos.*, 1999, **18**(9), 814–826.
29. P. B. Nedanov and S. G. Advani: *J. Compos. Mater.*, 2002, **36**(2), 241–254.
30. T. S. Lundström, R. Stenberg, R. Bergström, H. Partanen and P. A. Birkeland: *Composites Part A*, 2000, **31**(1), 29–43.
31. N. Vernet, E. Ruiz, S. Advani, J. Alms, M. Aubert, M. Barburski, B. Barari, J. Beraud, D. Berg and N. Correia: *Composites Part A*, 2014, **61**, 172–184.
32. H. Grössing, D. Becker, R. Schledzewski, P. Mitschang and S. Kaufmann: *eXPRESS Polym. Lett.*, 2015, **9**(2), 129–142.
33. T. Stöven: ‘Verfahren zur rechnergesteuerten Bestimmung von Verlaufsdaten einer Fließfront und Vorrichtung dazu [Procedure for the computer-based determination of flow front propagation and a corresponding measurement system]’, Patent, 2005.
34. T. Stöven: ‘Beitrag zur Ermittlung der Permeabilität von flächigen Faserhalbzeugen [Contribution to the determination of the permeability of plane semi-finished fiber products]’, PhD thesis, IVW Schriftenreihe Band 45, Kaiserslautern: IVW GmbH, Kaiserslautern, 2004.
35. D. Becker, J. Broser and P. Mitschang: *Polym. Compos.*, 2015. doi: http://dx.doi.org/10.1002/pc.23479.