INFLUENCE OF TEXTILE PARAMETERS ON THE PERMEABILITY OF REINFORCEMENT TEXTILES

Gunnar Rieber[1], Jinhua Jiang[2], Carsten Deter[1], Daniel Kreutz[1], Maike Glawe[1], Nanliang Chen[2], Peter Mitschang[1]

1Institut fuer Verbundwerkstoffe GmbH, Erwin-Schroedinger-Strasse, Geb. 58, 67663 Kaiserslautern, Germany. Corresponding author´s e-mail: peter.mitschang@ivw.uni-kl.de

2College of Textiles, Donghua University, China Engineering Research Center of Technical Textiles, College Building 3, No.2999, North Renmin Road, Shanghai, China

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Abstract

The impregnation of the textile with matrix is characterized by the permeability. Knowledge about the permeability allows the design of a fast and reliable process by allowing the prediction of the flow directions, velocities, and pressures. There is no consistent information available about the influence of textile parameters on permeability. In the empirical part of this study, 19 woven glass fiber textiles are selected to determine the effect of the weaving type, linear density, yarn density and crimp on in-plane and out-of-plane permeability. The additional influencing parameters, filament finish and filament diameter, have been left constant. It was possible to explain the anisotropic flow behaviour of isotropically built up textiles using the crimp present in the weft and warp yarns. It was observed that a higher difference between the crimp in the weft and warp yarns leads to a higher difference between the K1 and K2 permeability values. A pattern was found to characterize textiles as dense and open weave textiles. A generally valid relationship was found between the weaving density of a textile and the slope of the K1, K2 and K3 permeability in relation to fiber volume fraction. In a comparison of three identically built up twill and satin weave textiles, it was found that the K2 and K3 permeability of twill weave textiles is significantly lower, meaning that twill weave textiles are more anisotropic. The results of this study allow the selection and tailoring of woven textiles with specific permeabilities for different applications.

1 Introduction

To manufacture continuous fiber reinforced composites the fibers have to be impregnated with polymer matrix. The resistance of the textiles to the impregnation process is described by the permeability of the specific textile. Knowledge about the permeability allows setting up a fast and reliable injection process. Based on the textile permeability the resin flow direction, flow velocities, and pressure distributions can be predicted to reduce the production time and the number of rejections. There is very little stringently certain and generally valid information available about the influence of textile parameters on permeability. In 1996 Shafi compared the permeability of two plain weave and two satin weave textiles in an optical (PMMA) permeability measurement cell [1]. He detected higher permeability values and a higher decrease of the permeability with increasing fiber volume fraction for plain weave textiles. Pearce, Guild, and Summerscales determined as well a higher permeability for textiles with more warp and weft weaving points [2] – twill weave higher permeability than 5-harness satin. Pearce et al. showed that the amount of big flow channels is lower in twill weave textiles in comparison to plain weave textiles. Pore sizes have been measured by light microscopy and image analysis software and cumulatively plotted. This supports the hypothesis that more warp and weft weaving points result in bigger pore sizes. The permeability in through-the-thickness direction seems to follow other rules. Lu, Tung, and Hwang [3] determined for the permeability in through-the-thickness direction an opposite weave-permeability order - satin has higher permeability than twill and plain weave.

Besides empirical models physical models have been used. Summerscales [4] determined that the permeability of a fiber network is higher if fibers are clustered in comparison to a homogeneous distribution by application of the hydraulic radius model.

Geometrical textile models have become much more precise in the past years and offer the adjustment of a lot of parameters [5-8]. Lomov, Verpoest, et al. showed that only by changing the degree of nesting permeability values may vary significantly [9]. This is in agreement with a study of Nedanov and Summerscales who determined, that it is insufficient only to model one textile layer [10].

The prediction of the permeability by geometrical textile models is not yet possible. Lomov, Huysmans, Luo, et al. took into account 29 different parameters of the single filament, the yarn, and of woven textiles. Nevertheless the permeability values especially at higher fiber volume fractions did not agree with experimental results [11].

The goal of this study is to correlate the textile parameters of woven textiles (weave, linear density, yarn density, and crimp) with permeability. This is achieved by measuring the crimp, the in-plane and out-of plane permeability of 19 woven textiles.

2 Materials

2.1 Woven textiles

The fiber finish can change the permeability of a textile significantly. As the woven textiles have been obtained from 4 different weaving companies the finishes of the companies had to be compared. The reason for this is not a change of the contact angle and thereby capillary pressures, but a change of the yarn stiffness influenced by the fiber finish. The yarn stiffness influences the architecture and nesting behavior of the textile. Lomov showed the influence of nesting on the permeability [9]. Different nesting results in different permeabilities.

In Table 2 the textile parameters of all 19 glass fiber woven textiles used in this study are shown. As there is evidence in the literature that the single filament diameter of multifilament textiles has a significant influence on the permeability [4] all plain and twill weave textiles selected for this study have a single filament diameter of 9 µm. 14 of the 19 measured woven textiles are commercially available.

No.	Manufacturer and notation	Finish	Weaving type	Yarn-density in warp [filament/cm]	Yarn-density in weft [filament/cm]	Linear density in warp [g/km]	Linear density in weft [g/km]	Areal weight (measured) [g/m²]	Filament (warp/weft)	K1 (fvc[%]) results from [13]	K2 (fvc[%]) results from [13]	K3 (fvc [%]) results from this study
1	PGTex #1	A	twill 2/2	7,45	7,45	272	272	408,54	EC9-34x2	2.42E-11(49.2)	2.26E-11(49.2)	1.72E-12(50.1)
2	PGTex #2	A	twill 2/2	7,45	7,45	136	136	202,83	EC9-34x2	3.10E-11(49.6)	3.65E-11(49.6)	1.41E-12(50.7)
3	PGTex #3	A	twill 2/2	7,45	7,45	272	136	305,73	EC9-34x2	3.78E-11(49.1)	2.63E-11(49.1)	2.37E-12(49.5)
4	PGTex #4	A	twill 2/2	7,45	7,45	136	272	303,45	EC9-34x2	2.47E-11(48.8)	2.02E-11(48.8)	1.47E-12(50.6)
5	PGTex #5	A	twill 2/2	7,45	7	204	204	291,76	EC9-34x2	2.38E-11(50.8)	1.70E-11(50.8)	1.68E-12(48.6)
6	P-D 92105	B	plain	12	11,5	68	68	161,02	EC9-68	2.89E-11(49.3)	1.67E-11(49.3)	7.54E-13(48.9)
7	P-D 92110	B	twill 2/2	12	11,5	68	68	160,13	EC9-68	2.82E-11(49.6)	3.81E-12(49.6)	5.32E-13(48.7)
8	P-D 92626	B	8-harness satin	22	21	68	68	286,4	EC6-68	1.05E-11(51.3)	9.53E-12(51.3)	6.78E-13(49.1)
9	SCC 3106	B	twill 2/2	6	6,7	340	272	386,4	EC9-68x5	3.76E-11(48.0)	1.80E-11(48.0)	1.34E-12(49.2)
10	Hexcel 1102	C	twill 2/2	7	7	204	204	284,79	EC9-68x3	3.38E-11(51.3)	6.74E-12(51.3)	1.16E-12(48.9)
11	Hexcel 7781	C	8-harness satin	23	21	68	68	296,13	EC6-68	1.20E-11(51.5)	9.92E-12(51.5)	9.50E-13(49.4)
12	Hexcel 7581	C	8-harness satin	22	21	68	68	295,7	EC9-68	1.89E-11(51.5)	1.54E-11(51.5)	1.15E-12(49.3)
13	P-D 92125	B	twill 2/2	7	6,5	204	204	280,48	EC9-68x3/204	2.63E-11(51.4)	5.51E-12(51.4)	7.58E-13(49.5)
14	Hexcel 1113	C	twill 2/2	5,9	6,6	340	272	385,22	EC9-68x5/136x2	4.54E-11(50.4)	8.19E-12(50.4)	1.89E-12(49.1)
15	Hexcel 1265	C	plain	5,9	6,6	340	272	389,46	EC9-68x5/136x2	5.17E-11(51.0)	3.31E-11(51.0)	2.29E-12(49.6)
16	Hexcel 1103	C	plain	7	7	204	204	285,68	EC9-68x3	4.24E-11(51.4)	2.83E-11(51.4)	2.07E-12(49.0)
17	Hexcel 1035	C	twill 2/2	14,7	14,7	68	68	202,81	EC9-68	3.39E-11(50.1)	7.63E-12(50.1)	1.42E-12(48.7)
18	Hexcel 1039	C	twill 2/2	11,8	11,5	68	68	159,55	EC9-68	4.55E-11(48.1)	4.55E-12(48.1)	8.09E-13(48.5)
19	Hexcel 1038	C	twill 2/2	7,35	7,35	408	408	612,3	EC9-136x3	1.34E-10(48.7)	5.90E-11(48.7)	5.93E-12(51.0)

Table 1: Textile parameters of the evaluated woven textiles taken from the technical data sheet

Remarks: PD: P-D Interglas Technologies; SCC: Schlösser & Cramer

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2 Methods

2.1 Measurement of crimp

The crimp is the degree of undulation (or waviness) of the yarns inside woven textiles. According to DIN 53 852 "Determination of yarn length percentages in woven textiles" [12] crimp is defined by formula 1.

$$A = \frac{(l_f - l_w)}{l_w} \quad (1)$$

The relation between warp and weft yarn tension during textile production affects the yarn crimp. This allows to use the crimp of warp and weft yarn to determine the influence of the unknown yarn tension during production. This parameter has an influence on the permeability.
To define an average crimp each warp and weft yarn has been measured four times.

2.3 Measurement of permeability

The measurement fluid is filtered rapeseed oil with a temperature dependent viscosity $\eta = -0.0026T^3 + 0.2997T^2 - 12.403T + 221.56$ where T is the oil temperature.
The in-plane measurement cell is described in detail by Kissinger [13, 14]. The flow front is tracked by 8 capacitive linear sensors. The patented [15] procedure is based on the linear correlation of the sensor length that is covered with oil and the output signal of the sensors (change of dielectric). Measurements have been conducted with constant pressure. Upper and lower mold half consist of 160 mm thick aluminum. The textiles are cut computer controlled to 465 mm x 465 mm. Fiber volume fractions were adjusted by 15 interchangeable aluminum spacer frames (1 mm – 7 mm). The calculation of K1- and K2- permeability data follows the publication of Adams and Rebenfeld as well as Russel [16, 17]. Each textile was measured three times at three different fiber volume fractions. A hole was punched into the center of the preform with a radius of 6 mm. The number of layers depending on the given fiber volume fraction varied from 5 to 20. Within this range the number of layers has no influence on permeability as shown by Rieber and Mitschang in [18]. All layers were oriented in warp direction. The averaged permeability data were plotted versus the fiber volume fraction. For better clarity the permeability axis is plotted logarithmically [19-24] and the three data sets are approximated by a linear regression line. If the three points are approximated well they are all close to the regression line [21-24].

The through-the-thickness measurements were executed with an apparatus enabling the continuous monitoring of the flow front of a liquid medium, which is point-injected (circular shaped, diameter: 1.18 mm) into a stack of unsaturated fabrics. The height of the flow front in the out-of-plane direction is measured through an ultrasonic sender and an ultrasonic receiver, which are coupled and arranged oppositely on the z-axis, on both sides of the stack.
While the flow front proceeds the time for an acoustic wave, sent out by the ultrasonic sender, to reach the receiver (time-of-flight, TOF, tR) decreases. This is caused by the higher sound speed in the saturated fabric (c2) compared to the unsaturated fabric (c1). The TOF decreases proportional to the height of the flow front in z-direction (zf = flow front height; zR = cavity height). With T_0 being a test rig dependent time offset the correlation can be mathematically expressed as (symbols illustrated in Fig. 1):

$$t_R = \frac{z_f}{c_2} + \frac{z_R - z_f}{c_1} + T_0 \quad (2)$$

Besides the flow front progression there is also a continuous measurement of the injected liquid mass which has a known density and viscosity, so that at any time during the injection a statement can be made about the height of the flow front and the volume of the liquid in the fabric. Using this data the out-of-plane permeability can be calculated through a mathematical model which correlates the measured data and the constant injection pressure with the three-dimensional geometrical shape of the flow front. Based thereon a standardized measurement process was developed, including a computer-based calculation-tool. Hereby a high consistency of the results at a minimum effort could be ensured.

3 Results

3.1 Influence of the single filament diameter on in-plane and out-of-plane permeability

Two textiles of this study only varied in their monofilament diameter. It was found that more fine diameter of only 6 µm led to a lower K1, K2 and K3 permeability.

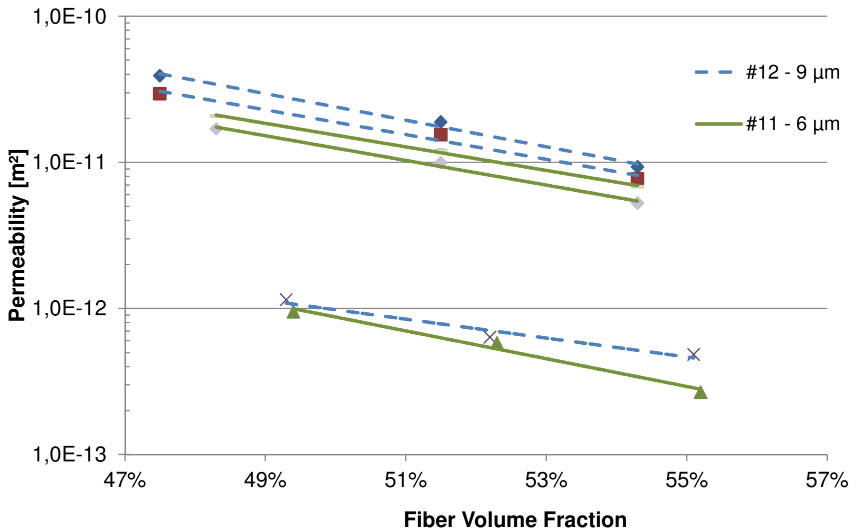

Figure 1: K1, K2 and K3 permeability of textile # 11 and textile # 12. These textiles only vary in their single filament diameter

3.2 Influence of the weave on in-plane and out-of-plane permeability

Three textile pairs (#6 - #7, #14 - #15 and #10 – #16)of this study only varied in their weave. For clarity the results of two pairs are displayed in figure 2. In every case the plain weave textiles showed higher permeability values in comparison to twill weave textiles.

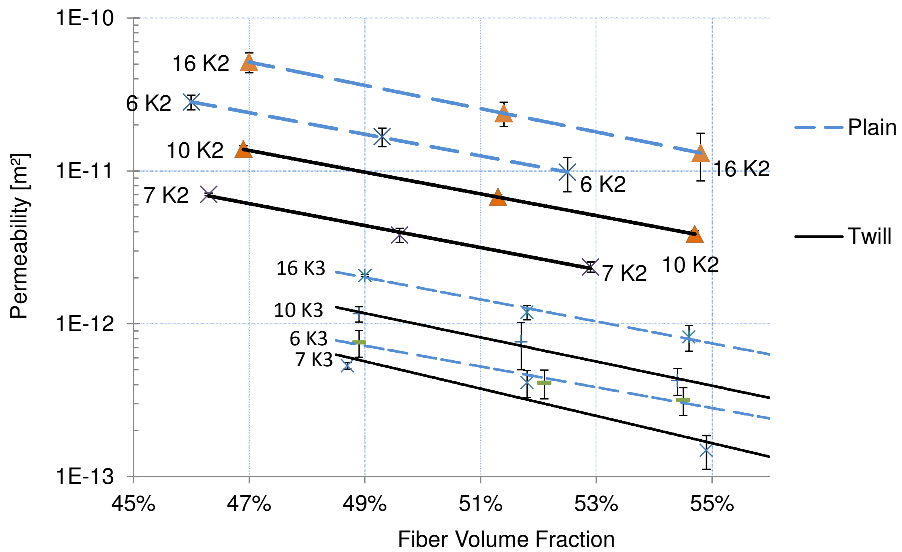

Figure 2: K2 and K3 permeability of two plain weave/twill weave pairs. Textile # 6 and 7 and textile #10 and #16 only vary in their weave.

3.3 Influence of the linear and yarn density on in-plane and out-of-plane permeability

The linear density and the yarn density have to be considered jointly. It is not possible to investigate them independently. As it is the combination of yarn density and linear density that is of importance for each textile, the averaged warp and weft yarn density is plotted versus the averaged warp and weft yarn linear density as shown in figure 3.

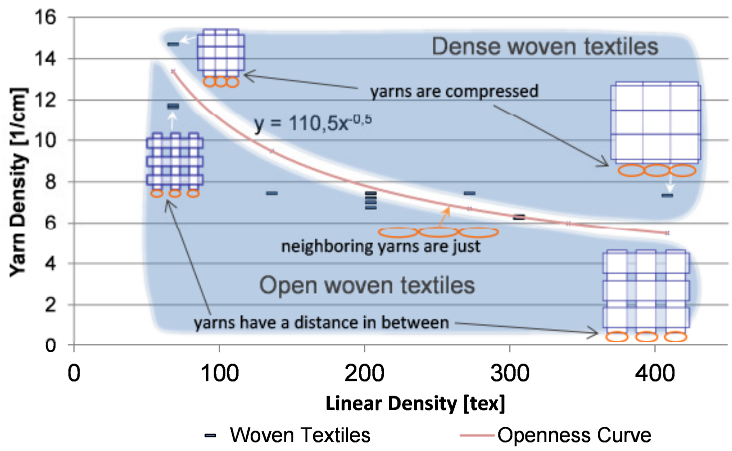

Figure 3: Averaged warp and weft yarn densities of all 19 textiles plotted versus the averaged warp and weft yarn linear densities. The continuous line classifies the woven textiles into dense and open weave textiles; this is the "Openness Curve".

The so called ´Openness Curve´ is not a regression curve but has been calculated with the assumption, that a woven textile can be classified as 'dense' as soon as neighboring yarns are just touching each other. The curve is based on a yarn height to width ratio of 1:9 (in uncompacted state). This ratio has been determined by µCT pictures and leads to the curve equation f(x) = 110.5*x-0,5. A classification into dense and open textiles is of importance as this determines the intensity by which the permeability decreases with increasing fiber volume fraction. The permeability of dense woven textiles declines much faster with increasing fiber volume fraction as the permeability of open woven textiles. An example for this is shown in Figure 4. Textile No. 19 is much more dense in comparison to textile No. 2 and therefore, the K1- and K2-permeability declines much faster.

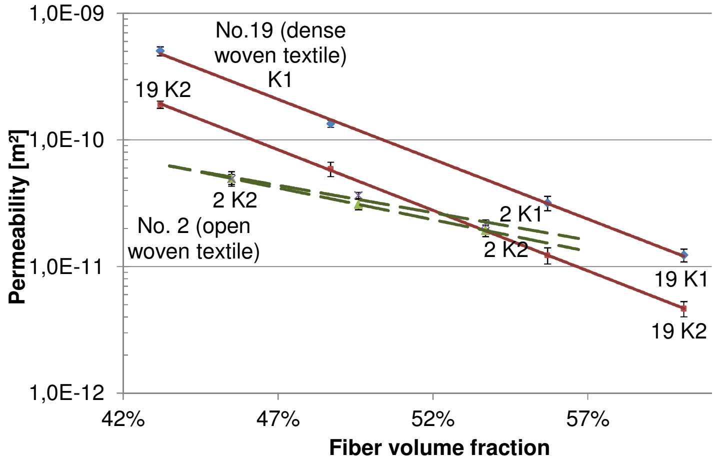

Figure 4: Comparison of the permeability-fiber volume fraction gradient of textile #19 and #2

Figure 5 shows the slope of the permeability-fiber volume fraction-curve for all measured textiles versus the deviation (shortest distance) of the textiles from the Openness Curve shown in Figure 3. The deviation, d, is calculated by the formula

$$d = \sqrt{\frac{\left(\frac{1}{yd} - \sqrt{ld} \times m\right)^2}{1+m^2}} \qquad (3)$$

where m is the linear slope of the Openness Curve that can be obtained by plotting the reciprocal of the yarn density, yd, versus the square root of the linear density, ld.
Even though there is some scatter a general trend can be seen.

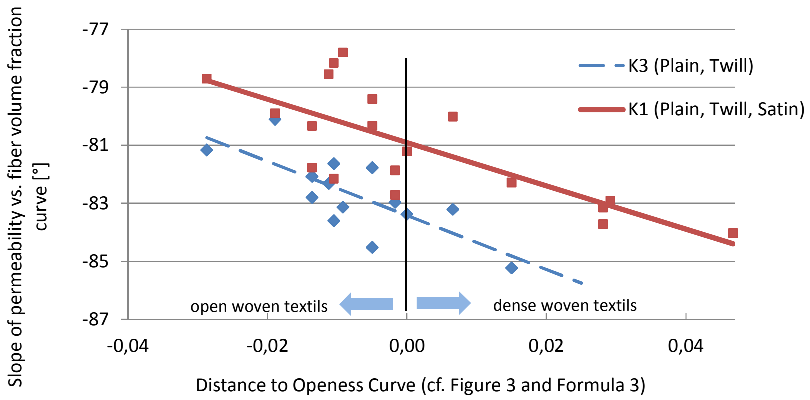

Figure 6: Slope of the in-plain permeability- and through-the-thickness permeability-fiber volume fraction curves (in degrees) of all textiles plotted versus the distance of the textiles from the Openness Curve

3.4 *Influence of the crimp on in-plane permeability*

The relation between the two in-plane permeability data, K2 divided by K1, is described as anisotropy. For this study the 15 textiles where the K1-permeability was in warp direction were selected. As described the crimp is dependent on the warp yarn tension during manufacturing, the linear density and the yarn density in warp and weft. The measured crimp of all textiles is shown in Table 2.

Material No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Company description	PGTex #1	PGTex #2	PGTex #3	PGTex #4	PGTex #5	PD 92105	PD 92110	PD 92626	SCC 3106	Hexcel 1102	Hexcel 7781	Hexcel 7581	PD 92125	Hexcel 1113	Hexcel 1265	Hexcel 1103	Hexcel 1035	Hexcel 1039	Hexcel 1038
Crimp in weft [%]	1.01	0.89	1.27	0.54	0.84	1.08	0.76	1.04	1.18	0.83	0.83	0.67	0.94	0.94	2.37	1.47	1.14	1.0	1.33
Crimp in warp [%]	0.89	0.85	0.42	1.04	0.51	0.39	0.26	0.5	0.38	0.33	0.44	0.67	0.44	0.43	0.57	0.57	0.57	0.4	0.5

Table 2: Measured crimp data of 19 woven textiles

The crimp in warp direction is in the range of 0.26 % - 1.04 % and the crimp in weft direction is in the range of 0.54 % - 2.37 %. If the textile is built up with the same yarn density and linear density in warp and weft, the difference in crimp only results from the warp yarn tension during production. Higher warp yarn tension results in a higher weft yarn crimp. The higher weft yarn tension leads to a higher permeability in warp direction compared to the permeability in weft direction. In Figure 12 the K1- and K2-permeability data of four textiles that have each equal yarn density and linear density in warp and weft are plotted.

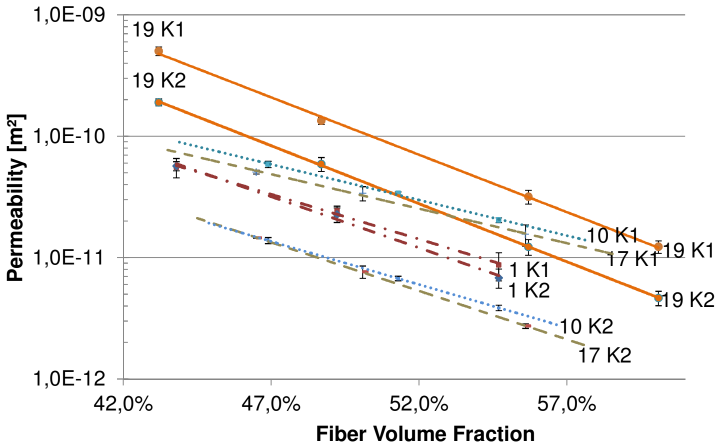

Figure 8: K1- and K2-permeability plotted versus fiber volume fraction of all textiles that have each equal yarn density and linear density (No. 1, 10, 17, and 19)

Even though all textiles have each the same yarn density and linear density in warp and weft only textile No. 1 shows isotropic flow behavior (K1=K2; circular flow front). For textile No. 10 and 17, in comparison, the K1-permeability is higher than the K2-permeability by a factor of 9.
The correlation between the anisotropy data of the textiles and their relation of weft to warp crimp becomes apparent in Figure 13. Plotted are the anisotropy data (K2/K1) of all twill weave textiles (No. 7, 10, 13, 14, 17 and 18). Figure 9 allows drawing the conclusion: the higher the warp yarn tension (less crimp) the higher the permeability in warp direction.

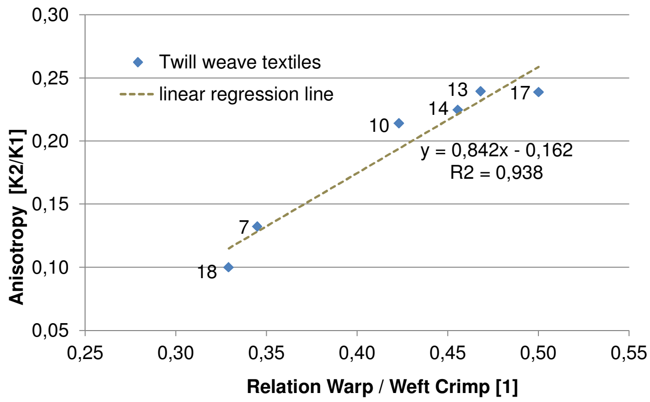

Figure 9: Anisotropy data (at 50 % Vf) of twill weave textiles No. 7, 13, 10, 14, 17, and 18 plotted versus the relation of warp to weft yarn crimp

4 Conclusion

In the empirical part of this study, 19 woven glass fiber textiles covering a specific variety of weave, linear density, yarn density, and crimp were selected in order to determine their effects on in-plane and out-of-plane permeability. In total close to 400 in-plane and out-of-plane permeability measurements have been conducted. An Openness Curve has been found to separate close (dense) woven textiles from open woven textiles.
The results can be summarized as follows:

- The K1, K2 and K3 permeability increases with increasing single filament diameter
- The K2 and K3 permeability of plain weave textiles is higher in comparison to twill weave textiles.
- The slope of the in-plane and out-of-plane permeability-fiber volume fraction curve can be predicted if the linear density and the yarn density are known. The denser a textile is the more the permeability decreases with increasing fiber volume fraction.
- The crimp has a big influence on the permeability. The anisotropy of woven textiles can be predicted by the relation of warp to weft yarn crimp.

Figure 15 summarizes the findings of this study.

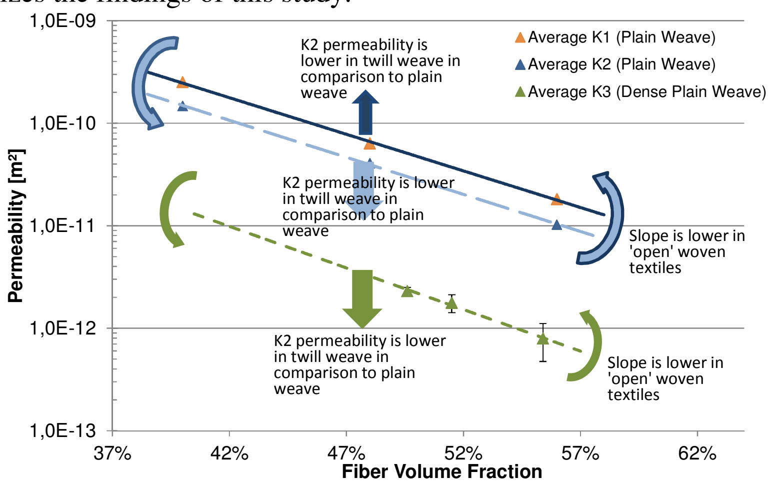

Figure 15: Overview of the main influences of textile parameters on the permeability of woven textiles based on an averaged plain weave curve

With the knowledge of these interrelations specifically designed woven textiles can be defined to allow a very fast injection process. At the same fiber volume fraction textiles differed in their K1 and K2 permeabililty by up to a factor of 27.

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