Introduction

Nowadays, composite industry constantly seeks for cost reduction. Liquid composite molding (LCM) promises to deliver the benchmarks set by out-of-autoclave processes; however, there are still some unanswered questions – e.g. reproducibility, mechanical property decreases and material handling issues to name a few. Usually in LCM, a process chain is established consisting of preforming, impregnation, curing and post processing. A preform can be defined as a textile structure assembled from several layers of fibrous materials such as fibers, yarns and fabrics. Due to the variability of preforming techniques, textile preforms not only vary in terms of fiber orientation and degree of entanglement but also in their geometry [1–3]. The topic of material handling can be put into context with preforming since most preforming techniques aim to increase the textile stability and subsequently the preform integrity. This processing step still lacks a suitable degree of automation. Many different mechanical approaches such as weaving, knitting, braiding and stitching [3] are currently under investigation to produce preforms.

Other promising methods include the usage of chemical binders which increase the stiffness of fabrics and consequently the geometrical stability. They also function as tackifiers that induce bonding between layers in a stack. Additionally, binders influence impregnation of preforms due to manipulated flow channels as well as the resulting viscosity of the matrix system. Their effects are also well documented and noticeable with respect to mechanical behavior [4–12]. For example, Wu et al. [4] documented the improvements of flexural strain and flexural strength for polymerized cyclic butylene terephthalate composites. Wang et al. [5] demonstrated the increasing tensile strength of the modified laminates through thermoplastic films placed in the interlaminar regions. Finally, Tanoglu and Seyhan [6] evaluated the ballistic performance of E-glass fiber reinforced polyester composites.

Most of fiber reinforced parts are manufactured from plane fabric structures. Usually weaving, plane braiding or stitching is utilized to produce these structures. These structures are cut and then processed with draping techniques into near net shaped structures which can be easily handled and impregnated. During draping the structure and geometry fixation are accomplished, while also accommodating for shearing and compaction processes that are inherent to this procedure [13]. Other methods that are summarized under direct preforming are 3D-weaving [14], 3D-knitting [15], automated dry fiber winding [16] and automated dry fiber placement [17, 18].
Selected fields of binder technology

Binder application

During filament production, the manufacturer applies a chemical cocktail known as 'sizing' onto the fibers as part of processing as this sizing inherits a better fiber-matrix bonding functionality. In a dry roving, the sizing acts as a 'stabilizer' holding the roving structure together and therefore can be seen as a binder [19]. In general, binders can be considered as additives for technical fabrics that provide adhesion between the textile structures. Currently, powder binders are the state of the art, existing either in thermoplastic or thermoset form. Other forms of binder can be found in mats of fibers, comingled yarns and exotic types, e.g. chemical stitching [20, 21].

In the category of powder binders typically epoxy resin based systems are used. These resins are usually applied without any curing agent and have a very high viscosity even at processing temperature. This gives them a thermoplastic character and enables good binder dissolution in the infiltration. For the application of the powder onto the fabrics, spreading technology is commonly used [22]. Subsequent to the application of the powder, it needs to be thermally activated which is usually achieved with IR-heaters or ovens. Alternatively, binders can be dissolved and applied through spraying in a solvent form. The wet fabric then needs to be dried for solvent evaporation.

Another category of binders is represented by mats of fibers made from thermoplastic filaments. They mostly consist of randomly orientated fibers at a low grammage (6–24 g/m²). These mats of fibers, which represent a semi-manufactured product, are usually inserted in the interlaminar open volume between technical layers. They are then activated through heat application in the preforming process in order to form a stiffened preform structure [23].

A similar process for binder application is the so-called hot melt application. In this process, a thermoplastic fiber yarn is directly applied to a technical textile. It is heated above melting point to stick, while the textile structure remains at a lower temperature. This way the hot melt freezes directly when applied to the fibrous material. This can lead to problems, particularly when applying high grammage of binder, i.e. as the time to freeze for the hot melt is comparatively short. Another disadvantage is the non-uniformity of the applied pattern and consequently the uneven binder distribution [24].

Another way of binder application is performed during yarn production, namely commingling. In this process, a thermoplastic fiber bundle or yarn is joined with a technical fiber bundle and rolled-up on a new spool for further processing. These commingled rovings are then used for classical weaving and braiding processes for textile production [23,25] (Figure 1).

Flow in the presence of binder

The influence of binder on the flow behavior was addressed in the scientific literature over more than two decades, which is briefly reviewed in the following paragraphs.

Chen et al. [26] conducted binder wash-out experiments which were utilized to develop a model estimating the binder concentration at the end of filling in different regions. Concentrations varying from 1 to 5 wt. % were found in the wet preform resulting in a viscosity increase by a manifold of two. The model allowed for easy predictions of binder dissolution in resin, hence viscosity variations. Rohatgi and Lee [27] investigated the impact of two binder materials on the springback of preforms. The binders of interest were a precured bismaleimide thermoset resin as well as polymethylmethacrylate. They also dedicated part of their research toward resulting permeability changes. They concluded that due to the presence of binder a reduced macro flow occurs. Shih and Lee [28] chose a general approach examining two binders and their general impact on an LCM process chain. They concluded that due to the presence of binder a reduced macro flow occurs. Shih and Lee [28] chose a general approach examining two binders and their general impact on an LCM process chain. They concluded that due to the presence of binder a reduced macro flow occurs.
content. Furthermore, they pointed out that for better springback control, certain additives can act as intralamellar tackifiers. Estrada et al. [29] investigated the influence of binder content and its position in preforms on the permeability. A code called PERM was developed solving the in-plane flow through a unit cell for woven fabrics based on an analytical model. Wu et al. [4] studied the impact of binder content and preform hot pressing parameters. They tried to quantify the influence of these parameters on the preforms mechanical behavior, e.g. bending and peel strength as well as on the permeability. Wang et al. [5] introduced a novel technique called chemical stitching, where an injector inserts a so called chemical z-pin into the stack of fabric layers. Subsequently, it is cured to secure the geometrical integrity of the preform. This process is repeated at several points on the preform. The authors promote this method as minimal invasive to preserve the original permeability. Rimmel et al. [30] explored the possibilities for maximizing the out-of-plane permeability of preforms produced through Dry Fiber Placement. The system also possesses a functionality for online binder application which enabled them to vary the binder content on the placed rovings forming the preform. Sommerlot et al. [31] investigated the influence of additives, such as tougheners and tackifiers on resin flow, surface chemistry and permeability. Thereby, they focused on the influence of preforming conditions to adjust resin flow behavior. Schmidt et al. [51] concentrated on the solubility of epoxy binders after infusing and curing of composite glass fiber plates. The influence on the mechanical behavior was characterized and concluded that interface formations due to partial solubility decrease interlaminar bonding. Therefore, full solubility is preferable in order to maximize mechanical performance.

Nevertheless, a lot of open questions remain due to the complexity of the topic. The present study focused on the influence of test fluids as well as test conditions influencing the permeability measurement results.

**Experimental work**

In the present paper, an investigation was carried out in estimating the influence of certain experimental parameters on the permeability of bindered non-crimp fabrics (NCFs). Preforms of similar textile architecture were used in bindered and unbindered form. The influence of preforming parameters, permeability characterization test rigs as well as type and temperature of test fluids was examined.

Additional experiments were performed to enrich the findings of the achieved results during the permeability investigations: surface energy characterization of the test fluids as well as the binder, estimation of binder dissolution times, viscosity characterization of the test fluids and transverse compaction experiments.

**Preform configuration**

Each preform consisted of four layers of a 0°/90°-biaxial carbon NFC. Every layer of the unbinderd textiles showed an average grammage of 557 g/m² (including the sewing thread made from PES). The grammage of the bindered textile was 572 g/m² which encompasses both sewing thread and the powder binder (Epikote 05390). Two different types of preforms were stacked: one consisting of only unbindered textiles and another consisting of bindered textiles with a top layer of unbindered textile, as shown in Figure 2.

All stacked preforms were then compacted at varying levels in a hydraulic hot press. All preform samples were subjected to a pressure of approximately 0.8 MPa for a duration of 3 minutes. The temperature levels used during the hot-pressing process can be found in Table 1. The samples were then weighed to estimate the actual fiber volume fraction for the following permeability experiments.

**Permeability setups**

For the current study, three different permeability characterization systems were used in different configurations, as shown in Table 2. Two of them covered the in-plane permeability measurements while the third one covered the out-of-plane permeability measurements. In general, this opens the possibility to fully determine the permeability tensor through the equations derived from Darcy’s law. The basis
for any kind of permeability estimation can be led back to following equation:
\[ \bar{v} = \frac{K}{\eta} \nabla p, \] (1)

describing the flow front velocity through a porous media \( \bar{v} \), dependent on the pressure difference \( \nabla p \) times the fraction of the permeability \( K \) divided by the viscosity \( \eta \).

The optical permeameter allows for very accurate flow front approximations due to the high density of measurement points. Hence, ellipse approximations and corresponding ellipse orientation angles show high accuracy [32]. However, the structural stiffness of the transparent upper mold is small compared to full metal molds, thereby resulting in small deformations during an experiment. These deformations can cause local porosity variations and as a result, changes in permeability (shown by Grössing [33]). In order to minimize these unwanted effects, low levels of compaction pressure are beneficial. This can be achieved either through low fiber volume content (FVC) with woven fabrics or medium FVC with materials that allow good fiber collocation during compaction, such as NCF materials.

The capacitive permeameter exhibits a full metal mold. Nevertheless, the comparably small number of eight capacitive linear sensors for flow front detection limits the accuracy of ellipse approximation as well as the orientation angle estimation, as shown by Fauster et al. [34]. These approximations form the basis for subsequent permeability calculation of \( k_1 \) and \( k_2 \) of non-uniform nature. The major advantage of the system over the optical permeameter lies in the possibilities due to its industrial design allowing for increasing the mold temperature as well as changing the test fluid from standard plant oil to real resin systems. In the following studies, different test fluids were employed as well as different levels of system temperature, which is defined as a single temperature for the pressure pot and the contained test fluid, the injection line as well as the mold.

Due to the observation of low degree of anisotropy (\( \alpha \approx 0.9 \)), differentiation between \( k_1 \) and \( k_3 \) is avoided and replaced with the quasi-isotropic representation \( k_m \). This is a well reported action when low anisotropies occur and is described in Equation (1) [35–37],

\[ k_m = \sqrt{k_1 k_2}. \] (2)

The out-of-plane permeameter, in order to estimate \( k_3 \), uses plant oil just as the optical permeameter. Moreover, all experiments were conducted at room temperature. The flow front advancement through the thickness of the material stacks is tracked by the change of time-of-flight utilizing an ultrasonic signal throughout the experiment [38]. While all in-plane experiments shared the same preform configuration as described in the former section, different preforms were necessary for the out-of-plane experiments. To estimate the out-of-plane permeability, constant injection pressure was applied. Due to the non-rigid nature of dry technical fabrics, there were turbulences and thus resulted in invalid data. Therefore, the need to reach a laminar flow can only be satisfied after a sufficient flow front advancement as was shown by Stöven [39]. He proposed to average values captured above a flow front height of 6 mm. This requirement indicates that preforms need to be thicker than this measure. On the other side, the ultrasonic signal can only penetrate a certain distance of dry preforms, limiting the maximum preform thickness. Moreover, a minimum FVC for sufficient signal transmission needs to be ensured. Depending on the type of textile architecture, the preferable value should be around 55% as reported by Becker et al. [40].

### Surface energy characterization

Characterization is carried out to understand the interactions between the test fluids and the binder material. For these purposes, contact angle (CA) measurements were carried out. CA of the samples

**Table 1. Preforming temperatures in the hot press.**

| Preform type    | 23 °C | 100 °C | 120 °C |
|-----------------|-------|--------|--------|
| Unbindered Preform | ✓     | ✓      | ✓      |
| Bindered Preform | ✓     | ✓      |        |

**Table 2. Overview of all test setups including the category of preform tested.**

| Permeability orientation | Preform type | Permeameter type | Test fluid | System temperature |
|--------------------------|--------------|------------------|------------|--------------------|
| In-plane permeability    | Unbindered Preform | Optical permeameter | Plant oil | ✓           |
|                          | Bindered Preform |                  |            | ✓           |
|                          | Unbindered Preform | Capacitive permeameter |         | ✓           |
|                          | Bindered Preform |                  |            | ✓           |
|                          | Unbindered Preform |                  |            | ✓           |
|                          | Bindered Preform |                  |            | ✓           |
| Out-of-plane permeability| Unbindered Preform | Ultrasonic permeameter | Plant oil | ✓           |
|                          | Bindered Preform |                  |            | ✓           |
were measured with a Drop Shape Analyzer (DSA 100, Krüss GmbH) at room temperature with a droplet volume of 2 µl. CA measurements were conducted with three different liquids, whereas each result was gained by averaging over five different droplet positions. The liquids used for the CA measurements and their respective surface tension values ($\gamma_l$) are listed in Table 3. The binder material EPIKOTE Resin 05390 came in powder form. Due to their powder form, DSA characterization was not possible hence specific plates were produced for testing. Additionally, tests were carried out with a Force Tensiometer (K100, Krüss GmbH) to compare the results between binder powder and its solid form. The Force Tensiometer helped to analyze the powder while considering capillary effects. Both methods showed similar results.

The surface energies of the tape materials were calculated using the Owens, Wendt, Rabel and Kaelble method [43–46]. Therefore, CAs of the binder plates with all three measuring liquids were determined. Once the angles and the surface energies of the measuring liquids are found, they can then be used as input parameters for Equation (3),

$$\gamma_\text{interfacial} = \frac{(1 + \cos(\Theta)) \cdot \gamma_l}{2 \cdot \sqrt{\gamma_p^2 + \gamma_p^2}}$$

On solving Equation (2), the results were plotted accordingly and a linear approximation was performed. Polar surface energy parts are calculated from the slope, while the dispersive parts are represented through the constant. The calculated surface energies ($\gamma$) of the binder material 05390 as well as the ones of the test fluids are given in Table 4. While the cumulative surface tension as well as the disperse part of both test liquids show reasonable comparability, there is a massive deviation in the polar region. This lack of polarity in plant oils is linked to the different chemical structures and the different polar surface tensions, as reported in the section ‘Surface energy characterization’.

Similar mixtures with RIMR135 resin were produced. They were then investigated in terms of time needed to fully dissolve the binder in the resin at different temperature levels. A double exponential relationship was revealed, as shown in Equation (4),

$$t [s] = 2.379e24 [s] \exp\left(-0.1489 [K^{-1}] \cdot T [K]\right) + 2.175e9 [s] \exp\left(-0.04483 [K^{-1}] \cdot T [K]\right).$$

This phenomenological relationship opens the possibility to estimate the theoretical time to fully dissolve the binder while in contact with resin. It can be used to estimate maximum experimental durations, limiting the dissolution to a certain degree. This also reveals that even moderate temperature levels during injection can lead to binder dissolution.

| Liquids          | Surface tension ($\gamma$) (mN/m) | Polar part ($\gamma_p$) (mN/m) | Disperse part ($\gamma_d$) (mN/m) |
|------------------|-----------------------------------|---------------------------------|----------------------------------|
| Water            | 72.8                              | 51.0                            | 21.8                             |
| Cyclohexan       | 35.4                              | 25.0                            | 25.0                             |
| Ethylene glycol  | 47.7                              | 16.8                            | 30.9                             |
| EPIKOTE Resin 05390 | 25.7                              | 4.9                            | 20.8                             |

Table 4. Surface energies for the binder material and literature values for the test fluids [47, 49].

| Liquids          | Surface tension ($\gamma$) (mN/m) | Polar part ($\gamma_p$) (mN/m) | Disperse part ($\gamma_d$) (mN/m) |
|------------------|-----------------------------------|---------------------------------|----------------------------------|
| Epoxy            | 45.0                              | 7.8                            | 37.2                             |
| Plant oil        | 33.6                              | 0                              | 33.6                             |
| EPIKOTE Resin 05390 | 25.7                              | 4.9                            | 20.8                             |

**Binder dissolution**

When impregnating a Bindered Prefrom during an LCM process, binder dissolution is an expected phenomenon. The resulting solution deviates in terms of chemo-rheological properties and is still considered a major unknown factor [26, 50, 51]. The powder binder and the test liquid RIMR135 are both based on bisphenol-A and mainly differ in terms of their molecular length; hence, the binder is frozen at room temperature, while the resin is still in liquid form. In contrary the test liquid plant oil does not share a common chemical structure with the binder material, hence qualitative binder dissolution tests were carried out.

In a first stage, either the RIMR135 or the plant oil was heated to a target temperature. Subsequently, a mixture comprising of binder with either RIMR135 or plant oil was produced. The amount of binder was adjusted according to the ratio expected to be present during the permeability experiments; consequently, 2.56 g of binder were put into 50 ml of test fluid. The mixture was then constantly stirred with a magnetic stirrer. The stirring device was then stopped after equidistant time intervals to perform a qualitative optical inspection whether the binder already fully dissolved. The liquid was inspected for solid powder particles and density cords. If none of these were found full dissolution of the binder has taken place. The binder showed no tendencies of dissolution in the plant oil, neither at room temperature nor at higher temperature levels (up to 160 °C). This phenomenon is linked to the different chemical structures and the different polar surface tensions, as reported in the section ‘Surface energy characterization’.

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dissolution and can cause inhomogeneous binder distribution in the final composite part. Moreover, it is necessary to investigate the rheological impact of the binder on the test fluid viscosity.

**Viscosity characterization of test liquids**

An Anton Paar Physica MCR501 rheometer was used to analyze the viscosity behavior of the test liquids which were then utilized in the permeability measurements. A plate-plate experimental setup was chosen with a 50 mm plate in diameter and a gap of 0.5 mm resulting in approximately 1 ml of required liquid for each experiment.

The liquids of interest for this specific test were neat epoxy resin RIMR135 (without any hardener) and a plant oil consisting of a mix from rapeseed and sunflower oil. A frequency sweep starting from 1 to 500 rad/s was performed for RIMR135 to estimate the frequency dependency of the test liquid. High correlation between shear frequency and viscosity was observed, hence according to Mustafa [29], this is due to the dilatant behavior of epoxy resins. Since plant oils in general depict Newtonian flow behavior [52–54], no frequency sweep was performed.

As one can see in Figure 3, the viscosity development of RIMR135 and its mixture show a double exponential behavior, whereas the plant oil demonstrates exponential behavior for the viscosity over temperature graph. Besides the shift between neat resin and resin-binder mixture, there is also a difference in the slope compared to the plant oil.

Additionally, other mixtures of RIMR135 with distinct levels of binder content were produced and tested in terms of their viscosity. In general, the amount of binder content in the resin leads to a parallel shift towards higher viscosity levels. It is believed that the higher molecular weight of the binder causes this effect.

**Compaction behavior**

All preforms from Table 1 were investigated with respect to their transverse compaction behavior. They were tested with an UTS 250 tensile test machine from Hegewald & Peschke Meß- und Prüftechnik GmbH utilizing a preform compaction setup [55]. The compaction test setup allowed accurate control of displacement between the two acting faces. The preforms were compacted until a gap of 2.5 mm was attained (corresponding to a target fiber volume fraction of approximately 50%) and

![Figure 3. Viscosity development of both test liquids used in the permeability experiments including a distinct mixture of resin and binder.](image)

![Figure 4. Maximum compaction pressure required to achieve the target fiber volume fraction.](image)
correlating with the adjusted cavity height inside the in-plane permeability experiments. The maximum compaction pressure as well as the stress relaxation were determined and are shown in Figure 4.

As one can see, there is no significant difference between the 100°C and 120°C hot pressed preforms in terms of their average maximum compaction pressure. A reasonable explanation could be that there was adequate pressing time of 3 minutes during the preforming stage, as binder temperature was set above its melting point. This time span seemed to allow sufficient flow among the binder within the textile.

Moreover, it appears that the binder inhibited fiber collocation resulting in higher maximum compaction forces when comparing to Unbindered Preforms. During the hot-pressing stage, the melted binder particles penetrate the fiber interspaces below and above them. When the preform is then demolded and cooled down to room temperature, those penetrated areas show a high degree of fixation. Therefore, most of the fiber collocation during compaction is limited to the filaments which are not in contact with binder (see Figure 2).

When looking at the sample which was pressed at room temperature, a greater maximum compaction force was observed as well as a higher level of statistical uncertainty. The absence of interlayer bonding due to pressing below the binder melt point is explaining this. Hence, the binder particles cannot penetrate the interspaces, but rather absorb elastic energy which increases the maximum force. The significant increase in deviation could be explained through the higher probability of nesting effects. Due to the lack of interlayer fixation, any kind of preform handling can result in textile layer shifts. This increases the possibility of undoing previously achieved filament order between two interfaces.

**Permeability results and discussion**

In this section, a summary of the most important results of the permeability measurements are presented. Therefore, several compositions of preform permeability data are compared. Moreover, the illustrated results include pictograms highlighting the unique test conditions of the experiments shown in the compositions. All permeability values are displayed as mean permeability $k_{mn}$ based on the assumption of low anisotropy. Moreover, all permeability values were calculated from corresponding viscosities of the utilized test fluid and system temperature.

Firstly, a preliminary test series including both in-plane permeameters are presented in Figure 5. Primary objective for the test series was to investigate the influence of small changes in cavity height, by inserting 5 μm transparent polymer films into the optical permeameter's cavity. Thus, the cavity height was reduced from 2.59 to 2.54 mm and 2.49 mm, correlating with the porosities from Figure 5. As one can see, a reduction of 10 μm in cavity height (correlating with about 2% porosity) induces a significant drop in permeability. In comparison, the cavity height of the capacitive permeameter was adjusted to 2.48 mm which corresponds to 48.65% of porosity. Hence, the permeability is lower than the ones estimated in the optical permeameter. This is especially important when considering the following experimental results.

In Figure 6, a composition of all Unbindered Preforms, tested with both permeameters, different test fluids and different temperatures are shown. When comparing the preforms tested at room temperature with oil in both permeameters, the phenomenon described in Figure 5 appears. Therefore, the results are not fully comparable due to their difference in porosity.

When considering the preforms tested in the capacitive permeameter, different influences affect the results. Firstly, there seems to be a minor increase of permeability when increasing the system temperature (from room temperature to 75°C with oil); however, this effect is not significant when judged from the standard deviation. Secondly, this effect
also appears when switching the test fluid (from oil to resin at 75 °C), thus confirming the suspicion of influences on permeability due to changing surface energy of the test fluid. This hypothesis is supported by literature, e.g. Korosi and Kovats [56] who investigated the influence of temperature on the surface energy of organic liquids as well as Dimitrovova and Advani [48] as well as Luo et al. [57] who studied the influence of the surface energy on the unsaturated flow in LCM processes. They acknowledged that there is an influence of the test fluid’s contact angle on the permeability.

As can be seen, Figure 7 compares the Unbindered Preforms with Bindered Preforms, hot pressed at varying temperatures. The Unbindered Preforms showed a permeability of around 50% greater than the Bindered Preforms. Besides this obvious difference, the preforming temperature did not seem to have a significant impact on the permeability nor on the orientation angle and anisotropy. Consequently, all experimental data concerning the Bindered Preforms measured in the optical permeameter were treated as one population, thus reducing the standard deviation by tripling the sample size. A possible explanation is the fiber architecture of NCFs, which allow for easy fiber collocation and therefore leave more open flow channels in the roving, as well as in the interspaces compared to woven
fabrics. This category of fabric has lots of undulations which induce low local porosity and high reacting pressures during compaction in the cavity at comparable porosities.

The results of the through thickness experiments are displayed in Figure 8. It appears that the influence of binder on the through-thickness permeability ($k_3$) is significantly higher compared to the in-plane permeability experiments. For the preforms which were pressed at room temperature, a drop of around 70% was observed. The preforms pressed at 120°C seemed to have a higher permeability while the standard deviation showed an increase as well. This effect could result from the binder behavior during hot pressing, when binder liquefies, viscosity drops and capillary effects induce flow from the interlaminar region toward the intralaminar region. Hence, macro structures open again and allow for better flow. The increased standard deviation on the other side might be caused by the fixation induced by hot pressing, preventing in-plane layer movement or nesting.

When analyzing in-plane permeability data of Bindered Preforms, one would expect a certain pattern of behavior as shown in Figure 9. From this figure, it is considered that the Unbindered Preforms would form a base line in the permeability over temperature relationship. The offset between the Unbindered Preforms and the Bindered Preforms at room temperature would already contain a mix of overlapping effects, such as porosity reduction caused by the binder, influence of wetting behavior between binder and test fluid, different compaction behavior of the preform inside the mold due to the relatively rigid condition of the binder and other unknown effects. Furthermore, it was expected to observe a decrease of permeability with increasing system temperatures due to softening of the binder. At even higher system temperatures, binder dissolution could lead to increasing permeability.

For the Bindered Preforms, it was expected to find decreasing permeability values at increased system temperature until the binder undergoes full ‘melting’. In fact, it is more of a continuous softening due to the lack of crystallization in uncured epoxy resins, accordingly no melting point. Thus, the binder would slowly flow under the influence of the compaction pressure inside the mold and would fill up the interlaminar spaces while remaining at high viscosity. Attaining higher temperature, the
viscosity drastically reduces and capillary effects can then take place, thereby sucking the binder into the intralamellar spaces. Moreover, the dissolubility of the binder increases significantly hence resulting in increasing permeability.

Following data compilation of experiments, Figure 10 shows the evaluated permeability values for all Bindered Preforms. They are grouped into experiments conducted with oil and experiments conducted with epoxy resin as test fluid. The comparison of experiments conducted with oil highlighted the previously described influence of cavity height and hence the porosity differences due to the choice of permeameter. The difference between permeability mean values of Bindered Preforms using oil was around 8% while the Unbindered Preforms showed a difference of 14%. Perhaps there is an added influence of changed surface energy due to the increased system temperatures and is mixed into the results, thereby reducing the effect. Furthermore, the difference in mean values between oil and resin at equal system temperature is significant. This indicates a severe influence of the test liquid on the permeability measurement.

When considering all Bindered Preforms and presuming the comparability of experiments conducted with oil and resin, permeability increases up to a certain point with the system temperature. Beyond that point, a significant drop in permeability was observed. This observation stands in absolute contrast with the initial working hypothesis. Therefore, the bar is greyed and should not be treated as reliable data.

Nonetheless, a reasonable explanation could be found in binder dissolubility and viscosity development. The nature of these effects could drive and influence the observed phenomenon. Considering the double exponential function (Equation (3)), one can describe the dissolubility time of the nominal binder content in a Bindered Preform. It also becomes apparent that small changes of temperature have very high impact, due to the double exponential nature of full dissolubility over temperature. Therefore, more binder would dissolve during an experiment and alter the viscosity of the test fluid (see Figure 3). Moreover, this could lead to binder washout near the injection point, reducing the overall binder content in this region. On the contrary, this would mean that the region near the flow front accumulates binder during an experiment. Merging those thoughts, it becomes unclear whether the estimated permeability values must instead be considered as apparent values, due to the influence of dissolved binder on viscosity and the changes in porosity distribution in the preform within an experiment. To fully understand this phenomenon, further studies are carried out.

**Conclusions and outlook**

Prior work has documented various possibilities of binder usage in composite manufacturing. Today, many different binder types, as well as application methods are used to accomplish maximum preform fixation, fiber orientation integrity and easy preform handling. These innovations come at the price of higher complexity of LCM processing due to the influence of binders. In the present paper, several characterization methods were employed, intended to paint a full picture of the flow situation during an LCM process in the presence of binder. For these purposes, two test fluids were investigated in terms of their interaction with the binder and subsequently used for permeability experiments. Significantly different behavior between the test fluids was discovered. For one, the surface energy differed significantly compared to actual epoxy resin. Consequently, the dissolubility of the binder in the test fluid was not given at all. The permeability experiments were conducted at normal laboratory conditions (room temperature, oil) as well as manufacturing-oriented conditions (increased system temperature, resin) ensuring maximum correlation with real production processes. They revealed and confirmed the suspicion of surface energy influencing the flow in porous media. Another interesting finding was that there was noteworthy permeability behavior at high temperatures when using resin as test fluid. A permeability increase followed up by a major decrease over system temperature was observed. It is highly probable that the dissolution of the binder governs this behavior. Nonetheless, this discovery needs further investigation to understand the mechanisms driving this phenomenon. Further work analyzing the binder distribution after injection is currently carried out. Therefore, a newly developed methodology is employed. It explores the possibility of estimating binder concentrations through viscosity measurements. Therefore, a data base consisting of viscosity values in correlation with binder-resin mixtures is generated. After a permeability experiment, the impregnated preform area is segmented into concentric parts and cut. The resin in those preform segments is then released through a pressing and filtering technique. Subsequently, the filtered resin is tested in terms of viscosity and the accumulated dissolved binder is determined. Due to the segmentation, a local binder dissolution distribution can be generated. If this experiment is repeated and stopped at different times also a time series can be generated. This
information could then be used to develop a model describing the binder washout during injection. Consequently, the correlation between binder washout and viscosity development could be implemented into simulation solvers increasing the predictability.

**Disclosure statement**

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