# COB-2023-1323
# INVESTIGATION OF THE INFLUENCE OF A HIGHLY PERMEABLE LAYER ON THE TRANSVERSE PERMEABILITY DETERMINATION OF RTM FIBROUS REINFORCEMENTS

**Gustavo Silva Pereira Junior**
Universidade Federal de Rio Grande, Campus Carreiros. Av. Itália, km 8, bairro Carreiros, Rio Grande, RS, Brasil. CEP: 96203-900.
**gustavopereira8991@gmail.com**

**Douglas Cardoso**
Universidade Federal de Rio Grande, Campus Carreiros. Av. Itália, km 8, bairro Carreiros, Rio Grande, RS, Brasil. CEP: 96203-900.
douglascardosoth@gmail.com

**Cristiano Peres Oliveira**
Av. Maria Anunciação Gomes Godoy, 1650 - Bagé, RS, 96460-000
cristiano.oliveira78@gmail.com

**Jeferson Avila Souza**
Universidade Federal de Rio Grande, Campus Carreiros. Av. Itália, km 8, bairro Carreiros, Rio Grande, RS, Brasil. CEP: 96203-900.
jasouza1974@gmail.com

***Abstract.*** *The transverse permeability of reinforcement materials is one of the variables that determines the rate of resin flow in the composite part injection process. A low transverse permeability can lead to incomplete resin impregnation and void formation in the composite part, resulting in reduced mechanical properties and potentially compromising the structural integrity of the part. The constant flow method (saturated) is a technique used to measure transverse permeability in the resin transfer molding (RTM) process. This method involves placing a thin, flat sample of the reinforcement material between two plates, and then applying a constant resin flow to one side of the sample. As the resin flows through the sample, it is collected on the other side and the flow pressure drop is measured. The transverse permeability of the reinforcement material can then be calculated based on the flow rate, pressure drop, resin viscosity and thickness of the sample using the Darcy's Law. Thus, when defining permeability in the transverse direction, it is important to ensure a rectilinear (1D) resin flow inside the mold cavity. Some studies have shown that the incorrect distribution of holes in the perforated plate may not produce the 1D flow behavior, resulting in large errors in transverse permeability calculations. The objective of present work is to numerically evaluate the possibility of eliminating these errors by including a highly permeable layer before the fibrous reinforcement region. For this purpose, a numerical study is presented on which fluid flow through the reinforcement fiber region and a highly permeable layer is modeled as a porous medium. A two fluid flow (air + resin) is modeled with the Volume of Fluid (VoF) method. GMSH software is used to create and discretize the geometry and OpenFOAM software is used to solve the flow problem, determining pressure drop and flow rate inside the mold. Results show that the highly permeable layer tends to decrease the error in determining the transverse permeability of the fibrous reinforcement in up to 20%.*

***Keywords:*** *transverse permeability , polymer composites , Resin Transfer Molding, numerical solution.*

## 1. INTRODUCTION

Composite materials have found widespread use in various fields, from transportation to sporting goods, as well as in energy, infrastructure, and architecture, where the demand for materials that are both rigid and lightweight is constantly growing. In recent years, liquid composite molding (LCM) technologies have significantly advanced, becoming an effective option for high-quality production compared to autoclave processing. ((MICHAUD, 2016)).

Basically, resin injection molding processes involve injecting a polymeric fluid into a pre-molded fiber reinforcement through a cavity with the desired final shape of the part. With the development of the technique, it was found that resin impregnation in the transverse direction of the part, instead of the in-plane direction, can significantly reduce injection time without the need for higher capacity injection equipment. However, resin injection in the

transverse direction requires prior estimation of the reinforcement's permeability to avoid the formation of voids and, consequently, defects in the produced part.

The essence of permeability as a determining factor for resin flow in fibrous reinforcements is reported in older references, where it is characterized as an indication of the relative ease with which the fluid passes through the pores, quantified in the three directions of a Cartesian plane of a laminate stack. Permeability can basically be differentiated into two types: planar and transverse (out-of-plane) ((RUDD et al., 1997)). The property was first identified by Darcy (BROWN, 2002) in 1856 based on observations of water flowing through a vertical column of sand, and a formula known as Darcy's law was defined

$$\vec{v} = \frac{\bar{K}}{\mu} \nabla P, \tag{1}$$

where $\vec{v}$ is the velocity vector [$m/s$], K is the permeability tensor [$m^2$], $\mu$ is the viscosity [$Pa.s$], and P is the pressure [$Pa$].

According to a recent review analyzing data from 1991 to 2017, there has been a notable surge in research dedicated to developing models that investigate flow patterns in LCM manufacturing processes. However, the growth in published studies examining the changes in permeability within pre-molded reinforcements has not exhibited the same level of increase ((BODAGHI et al., 2019)).

Several authors in the literature have expressed the need to standardize measurement procedures and quantify uncertainties regarding the techniques used to assess the permeability of fibrous reinforcements in the in-plane direction ((VERNET et al., 2014); (ARBTER et al., 2011)), as well as in the transverse direction (AKTAS et al., 2016; YONG et al., 2021).

The most commonly used method to determine transverse permeability involves subjecting a pre-molded reinforcement, placed between two perforated plates, to a fluid flow within a cylindrical cavity. The injection flow rate is kept constant, and the pressure drop inside the mold is measured during the experiment. Transverse permeability is then calculated using Darcy's law. The cylindrical cavity method was utilized by a significant number of participants in in the last benchmark of the three writings on the topic ((YONG et al., 2021)).

The techniques for measuring transverse permeability consist of replicating unidirectional flow within the fibrous reinforcement, which behaves as a porous medium. However, it is physically impossible to replicate this flow because it is necessary to support the fibrous reinforcement inside a cylinder, and for this purpose, two perforated plates are used, as shown in the work of ((OLIVEIRA, 2019)). The presence of these plates ends up hindering the adequate reproduction of flow in the transverse direction of the fibers.

There is an effort from both industry and the academic community to quantify the sources of uncertainty involved in the process. A recent study utilized numerical techniques to replicate the test, and the author demonstrated that by improving the distribution of holes in the perforated plate, the estimate of error can be significantly reduced. When the holes are more concentrated in the center of the plate, there is a strong influence on the flow patterns inside the fibrous preform ((PEREIRA; OLIVEIRA; AVILA SOUZA, 2022)).

Other works, such as the one by (YANG et al., 2022; (YANG et al., 2023), aim to use both numerical and experimental techniques to devise ways to minimize the influence of using different plates in determining the transverse permeability for the same specimen. To achieve this, the authors make use of discharge coefficients (YANG et al., 2022) and filling coefficients (YANG et al., 2023) as a means to quantify the efficiency of the molds.

Furthermore, another work found in the literature (SCHOLZ; GILLESPIE JR; HEIDER, 2007) describes a device that utilizes liquid or gas fluids to replicate a unidirection of the perforated plates by incorporating a highly permeable layer, which allows the streamline to organize unidirectionally before permeating the specimen. However, there is no comparison in the literature that quantifies the improvement in the results of determining transverse permeability in this particular device.

In order to assess the effectiveness of the highly permeable layer in organizing the fluid before permeating the specimen, the present study conducts a numerical analysis using two perforated plates with different hole distributions. The aim is to evaluate the performance of the highly permeable layer and compare it with results obtained without its presence. The geometry was developed using the software Gmsh, and the finite volume method was employed for the numerical solution using the openFoam software. The results suggest that it is possible to improve the accuracy of the measurements by up to 20% when the highly permeable layer is present before the resin permeates the fibrous reinforcement.

## 2. PROBLEM DESCRIPTION

Permeability of the reinforcement is determined through a saturated experiment in which flow velocity and pressure drop are measured. In the numerical experiment, the flow velocity is controlled while the pressure drop is calculated. Based on Darcy's Law, there is a linear correlation between pressure drop and flow velocity as in Eq (1). This equation adapted can be rewritten as

$$\bar{K} = \frac{\dot{\forall} \mu \Delta h}{A \Delta P},$$ (2)

where $\Delta h$ is the reinforced meidum height [m] and $\Delta p$ is the pressure drop across the cavity [Pa].

The experimental setup and computational domain are depicted in Figure 1. Figure 1a provides an internal perspective of the mold cavity, allowing for the observation of the region situated between the perforated plates. The fibrous reinforcement is positioned between these plates, and the resin is compelled to flow through it in the transverse direction of the fibers. Figure 1b depicts the computational domain of the proposed problem, where the flow is simplified as a cylindrical cavity composed of the fibrous reinforcement and injection holes. At the bottom, there is a highly permeable layer with a height of 4 mm, and fibrous reinforcement specimens are simulated for five different heights. In the case where there is no permeable layer present, the height of the non-flow layer (NFL) is zero (figure 1c).
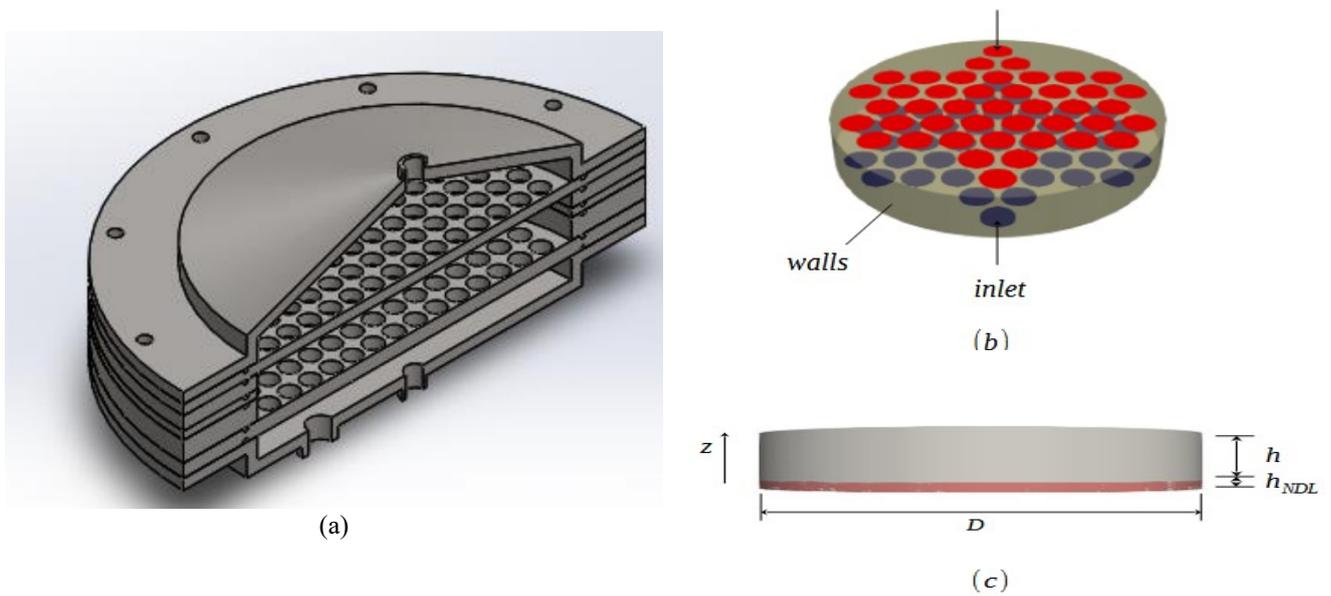


(a)

(b)

(c)

Figura 1: Cylindrical mold a) Cut section of the CAD (ESCHER, 2016), b) computational domain with NFL c) computational domain without NFL

At the start of the experiment, the mold is initially filled solely with air. The resin is introduced into the mold through the inlet holes, where it then permeates through the reinforcement before exiting the mold via the outlet holes (Figure 1). The two-fluid flow phenomenon is modeled using the Volume of Fluid (VOF) method, which was originally proposed by Hirt and Nichols in 1981(HIRT; NICHOLS, 1981). This modeling approach accounts for the presence of multiple phases, considering the flow of two or more immiscible fluids. The flow is assumed to be incompressible, with constant physical properties. Mathematically, the problem involves solving three simultaneous conservation equations, including the continuity equation.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0,$$ (3)

where $\rho$ the mixture density[kg/m³], t is the time [s], $\vec{v}$ is the velocity vectos [m/s]. A single momentum equation used to describe fluid velocity of both fluids

$$\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \bar{\tau} + \rho \vec{g} + \vec{F},$$ (4)

and an adjective transport equation for the resin volume fraction

$$\frac{\partial \rho f}{\partial t} + \nabla.(\rho f \vec{v}) = 0, \tag{5}$$

In Eqs. (4-5) $p$ is the pressure [Pa], $\bar{\tau}$ the stress tensor [Pa], $\vec{F}$ a field resistance [N/m³] and $f$ is the volume fraction..

The reinforcement region is formulated as as porous medium and its resistance to flow movement is accounted in momentum equation with a Darcy's law adaptation by defining

$$\vec{F} = \frac{\mu}{K} \vec{v}, \tag{6}$$

The physical properties of the mixture (density and viscosity) are calculated as a function of the resin volume fraction, such as

$$\rho = f \rho_{resin} + (1-f) \rho_{air}, \tag{7}$$

$$\mu = f \mu_{resin} + (1-f) \mu_{air}, \tag{8}$$

The boundary conditions are show in table 1.

| Local | Boundary conditions |
|-------|---------------------|
| inlet | prescribed volumetric flow rate |
| outlet | total pressure equal to zero |
| walls | no slip |

Table 1: Boundary conditions

Five different heights of fibrous reinforcement were simulated for each of the two perforated plates with different configurations (Figure 2). The construction of the plates aimed to compare a situation with a homogeneous distribution of holes (Figure 2a) and a situation with a poor distribution (Figure 2b). Furthermore, two scenarios were analyzed (Figure 1): one where there is a highly permeable layer present, as shown in Figure 1b (referred to as the NFL layer), and another where the fluid encounters the specimen immediately upon injection (Figure 1c).
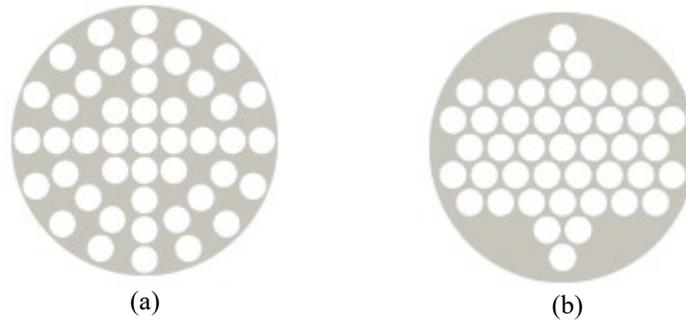


(a)                                    (b)

Figura 2: perforated plates with (a) homogeneity in the distribution of holes
and (b) plate with holes more concentrated on center.

The openFoam software, specifically the interFoam solver, was used to solve the problem. For each layer (reinforced medium and NFL), a permeability value was determined, with the fibrous reinforcement having an approximate permeability of 2.52e-12 and the NFL having an infinite permeability. The Gmsh software was utilized for the discretization of the geometries. Furthermore, a mesh independence test was conducted, indicating that the independent mesh consists of approximately 200,000 hexahedra.

Table 2 presents the parameters used in the simulation.

Table 2: Properties of simulation

| Property | Value |
|---|---|
| Flow rate [m³/s] | prescribed velocity |
| Mold height (reinforcement) [mm] | 3.8 – 6.35 – 9.35 – 15.88 – 22.23 |
| Mold NFL [mm] | 0.00 – 4.00 |
| Mold diameter [m] | 0.15 |
| Resin density [kg/m³] | 920 |
| Resin viscosity [Pa.s] | 0.993 |
| Reinforcement in-plane permeability[m²] | $2.519 x 10^{-11}$ |
| Reinforcement transverse permeability [m²] | $2.519 x 10^{-12}$ |
| NFL permeability | infinite |

## 3. RESULTS

First, the heights of fibrous reinforcement were simulated without the highly permeable layer. The pressure drop inside the mold was determined, and the transverse permeability was calculated using Darcy's law (Eq. 2). The reinforcement permeability results are shown in Table 3.

Table 3: Results Permeability results without the use of a highly permeable layer.

| h [mm] | $K_{zz,theo.}[m^2]$ | Perfil A | | Perfil B | |
|---|---|---|---|---|---|
| | | $K_{zz,num}[m^2]$ | Error [%] | $K_{zz,num}[m^2]$ | Error [%] |
| **3,80E-03** | 2,52E-12 | 1,65E-12 | 34,68 | 1,51E-12 | 40,10 |
| **6,35E-03** | 2,52E-12 | 1,89E-12 | 25,14 | 1,66E-12 | 33,97 |
| **9,53E-03** | 2,52E-12 | 2,12E-12 | 15,83 | 1,85E-12 | 26,52 |
| **1,59E-02** | 2,52E-12 | 2,26E-12 | 10,36 | 2,01E-12 | 20,38 |
| **2,22E-02** | 2,52E-12 | 2,32E-12 | 7,87 | 2,11E-12 | 16,24 |

Through the results presented in Table 1, it is evident that both the hole distribution and the height of the fibrous reinforcement influence the pressure drop inside the cavity and, consequently, lead to an error in determining the transverse permeability of the tests. Comparing the two plates at the same height, it can be observed that only by improving the hole distribution in the perforated plate, it is possible to improve the permeability estimate of the medium by up to 8%. When analyzing the same plate at different heights, it is noted that specimens with shorter heights tend to have larger errors in determining permeability. Therefore, in order to obtain precise results, it is necessary to use plates with better hole distribution and heights that allow fluid to permeate all the spaces inside the cavity.

Next, both plates were simulated at the same heights, but now with the presence of a permeable layer that organizes the fluid trajectory to create flow lines orthogonal to the plane of the fibrous reinforcement. This allows for the measurement of pressure drop from the unidirectional flow in the Z direction only. The results are presented in Table 4.

The results from Table 4 show the permeability results as a function of height for the different perforated plates with the presence of the permeable layer. It is noticeable that there is an improvement in the results compared to those shown in Table 3. A similar behavior is observed regarding the increase in the height of the fibrous reinforcement. As the height of the specimen increases, there is a decrease in the error in determining the transverse permeability. Additionally, the hole configuration still contributes to an increase in the permeability error.

Table 4: Transverse permeability results with NFL.

| h [mm] | $K_{zz,theo.}[m^2]$ | Perforated plate A with NFL | | Perforated plate B with NFL | |
|--------|--------|--------|--------|--------|--------|
| | | $K_{zz,num}[m^2]$ | Error [%] | $K_{zz,num}[m^2]$ | Error [%] |
| **3,80E-03** | 2,52E-12 | 2,27E-12 | 9,86 | 1,88E-12 | 25,38 |
| **6,35E-03** | 2,52E-12 | 2,32E-12 | 7,93 | 2,00E-12 | 20,56 |
| **9,53E-03** | 2,52E-12 | 2,35E-12 | 6,82 | 2,16E-12 | 14,29 |
| **1,59E-02** | 2,52E-12 | 2,38E-12 | 5,50 | 2,25E-12 | 10,74 |
| **2,22E-02** | 2,52E-12 | 2,41E-12 | 4,34 | 2,31E-12 | 8,40 |

In Figure 3, a graph is presented, organizing the error as a function of mold height for the different plates. The orange and blue colors represent perforated plates A and B without the presence of the permeable layer, respectively, while the yellow and green colors represent plates A and B, respectively, with the presence of the permeable layer. It is evident that using a permeable layer before the flow permeates the fibrous reinforcement improves the accuracy of the test by up to 20%, as shown in plate A at a height of 3.8 mm. This demonstrates that perforated plates with NFL have a positive impact on determining transverse permeability in tests.
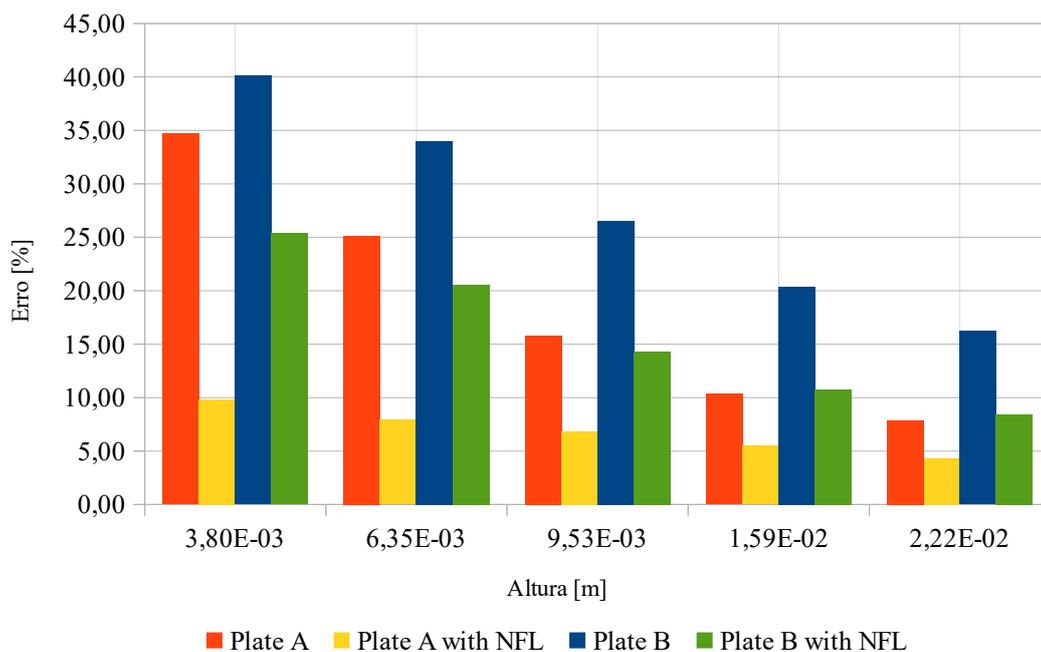


Figure 3: Comparison of the results.

## 4. CONCLUSIONS

In the present study, a numerical analysis of procedures for determining the transverse permeability of fibrous reinforcements was conducted. Two different perforated plates were simulated at 5 different heights considering two situations: a) the use of a permeable plate for better fluid distribution, and b) without their presence.

The results show that both the height of the reinforcement and the distribution of holes in the plate strongly influence the process. For smaller heights, there is a considerable error that does not occur when the test specimen is larger than a height of 15.88 mm. Additionally, it can be concluded that plates with better hole distribution also exhibit lower errors. The presence of permeable plates proved to be effective in reducing the error, potentially increasing the accuracy of transverse permeability by up to 20% in some cases. This is because the presence of permeable plates organizes the flow before it permeates the fibrous reinforcement.

## 5. REFERENCES

ARBTER, R. et al. Experimental determination of the permeability of textiles: A benchmark exercise. Composites Part A: Applied Science and Manufacturing, v. 42, n. 9, p. 1157–1168, set. 2011.

BODAGHI, M. et al. On the variability of permeability induced by reinforcement distortions and dual scale flow in liquid composite moulding: A review. Composites Part A: Applied Science and Manufacturing, v. 120, p. 188–210, maio 2019.

ESCHER, M. PROJETO MECÂNICO DE UM EQUIPAMENTO PARA MEDIÇÃO DA PERMEABILIDADE TRANSVERSAL DE PROFORMAS FIBROSAS. 2016.

HIRT, C. W.; NICHOLS, B. D. Volume of fluid (VOF) method for the dynamics of free boundaries. Journal of Computational Physics, v. 39, n. 1, p. 201–225, jan. 1981.

MICHAUD, V. A Review of Non-saturated Resin Flow in Liquid Composite Moulding processes. Transport in Porous Media, v. 115, n. 3, p. 581–601, dez. 2016.

OLIVEIRA, C. P. DETERMINAÇÃO NUMÉRICO-EXPERIMENTAL DA PERMEABILIDADE TRANSVERSAL DE COMPOSTOS HÍBRIDOS UTILIZADOS EM PROCESSOS DE MOLDAGEM LÍQUIDA. , 1 dez. 2019.

PEREIRA, G.; OLIVEIRA, C.; AVILA SOUZA, J. Investigation of the perforated plates influence on the experiment for the transverse permeability determination of RTM reinforcements. Procceedings of the 19th Brazilian Congress of Thermal Sciences and Engineering. Anais... Em: 19TH BRAZILIAN CONGRESS OF THERMAL SCIENCES AND ENGINEERING. ABCM, 2022. Disponível em: <http://abcm.org.br/anais-de-eventos/CIT22/0358>. Acesso em: 27 maio. 2023

RUDD, C. D. et al. Liquid Moulding Technologies: Resin Transfer Moulding, Structural Reaction Injection Moulding and Related Processing Techniques. [s.l.] Elsevier, 1997.

SCHOLZ, S.; GILLESPIE JR, J. W.; HEIDER, D. Measurement of transverse permeability using gaseous and liquid flow. Measurement of transverse permeability using gaseous and liquid flow, p. 2034–2040, 3 maio 2007.

VERNET, N. et al. Experimental determination of the permeability of engineering textiles: Benchmark II. Composites Part A: Applied Science and Manufacturing, v. 61, p. 172–184, jun. 2014.

YANG, B. et al. On the design of test molds based on unidirectional saturated flows to measure transverse permeability in liquid composite molding. Polymer Composites, v. 43, n. 4, p. 2234–2251, abr. 2022.

YANG, B. et al. Performance evaluation of unidirectional molds used for measuring saturated transverse permeability of engineering textiles. Composites Part A: Applied Science and Manufacturing, v. 169, p. 107524, jun. 2023.

YONG, A. X. H. et al. Out-of-plane permeability measurement for reinforcement textiles: A benchmark exercise. Composites Part A: Applied Science and Manufacturing, v. 148, p. 106480, set. 2021.

## 6. ACKNOWLEDGE

## 7. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.