



**UNIVERSITY OF DELAWARE**  
**CENTER FOR COMPOSITE MATERIALS**  
*INTERNATIONALLY RECOGNIZED EXCELLENCE*



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2005 RESEARCH REVIEWS

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# **Permeability characterization of dual scale porous media**

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## Outline

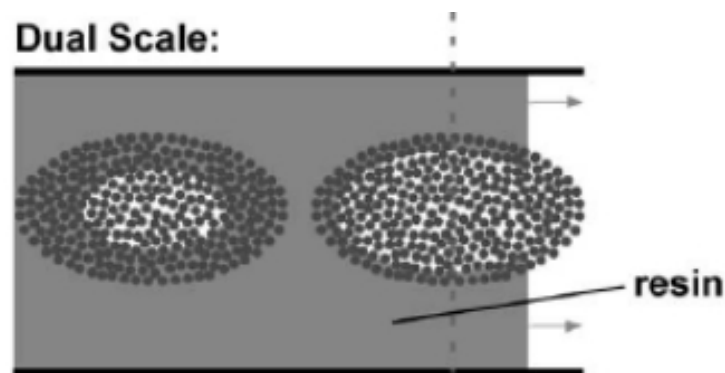
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- ◆ **Project goals**
- ◆ **Experimental setup**
- ◆ **Flow in porous media**
- ◆ **Liquid Injection Molding Simulation approach**
- ◆ **Motivation of project**
- ◆ **Experimental results**
- ◆ **Bulk permeability determination**
- ◆ **LIMS results**
- ◆ **Tow permeability determination**
- ◆ **Conclusions and future work**



## Project goals

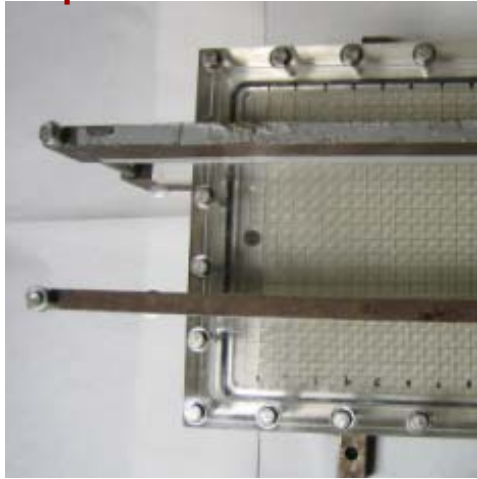
- ◆ **Quantify macro-scale and micro-scale permeability values of dual-scale fabrics used in composites manufacturing by performing only one experiment**
  - ✧ **Determine macro permeability directly from experimental data**
  - ✧ **Determine micro permeability from LIMS analysis**
  
- ◆ **Input determined permeability values into LIMS, so the true nature of flow can be ascertained during impregnation process**



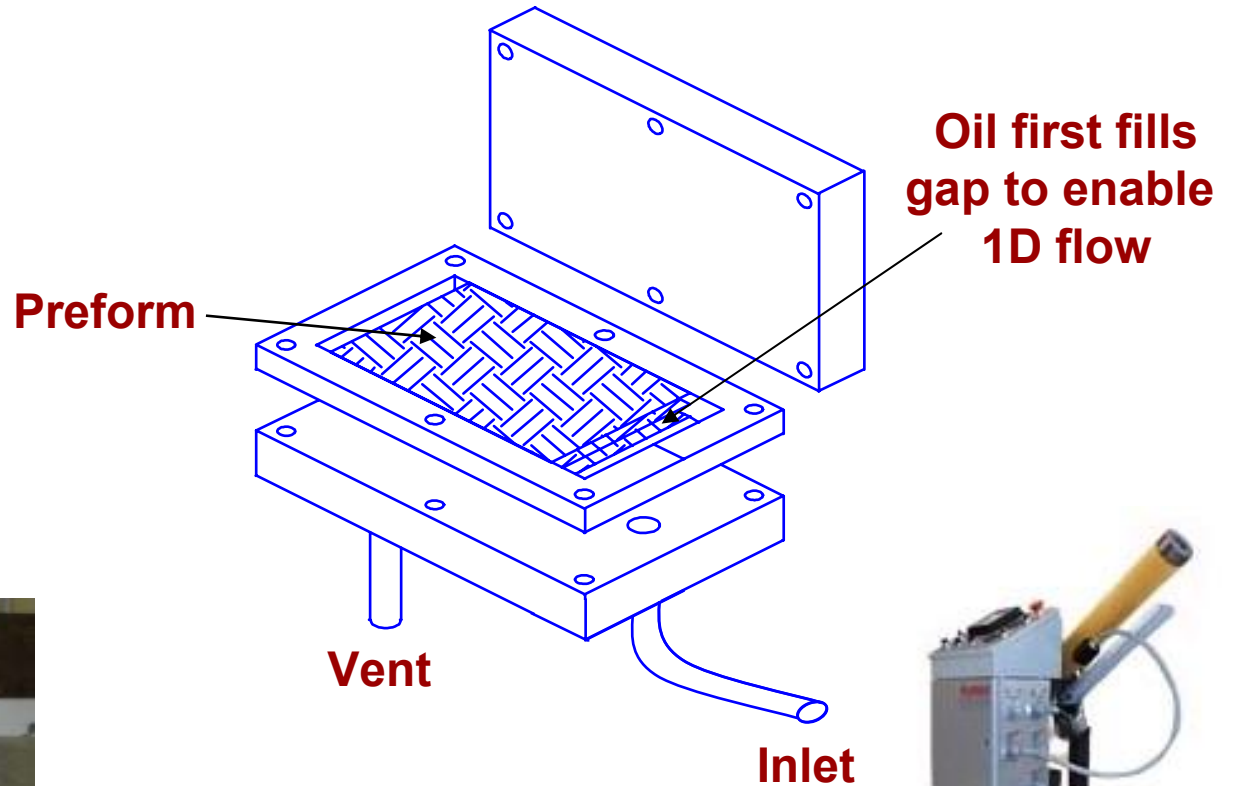
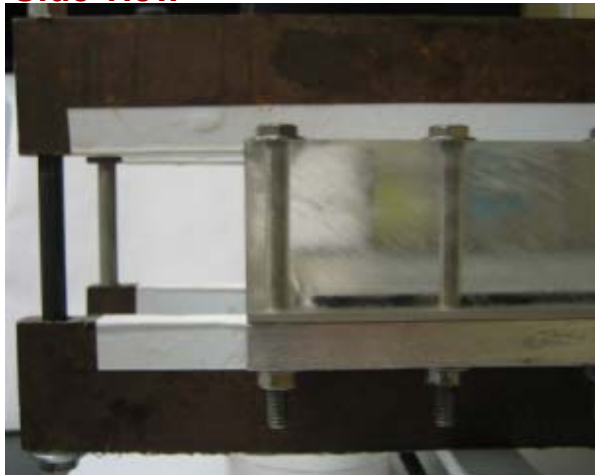


## Experimental setup

Top view



Side view



- Acrylic mold top
- Aluminum spacer
- Steel mold bottom
- Steel reinforcing bars

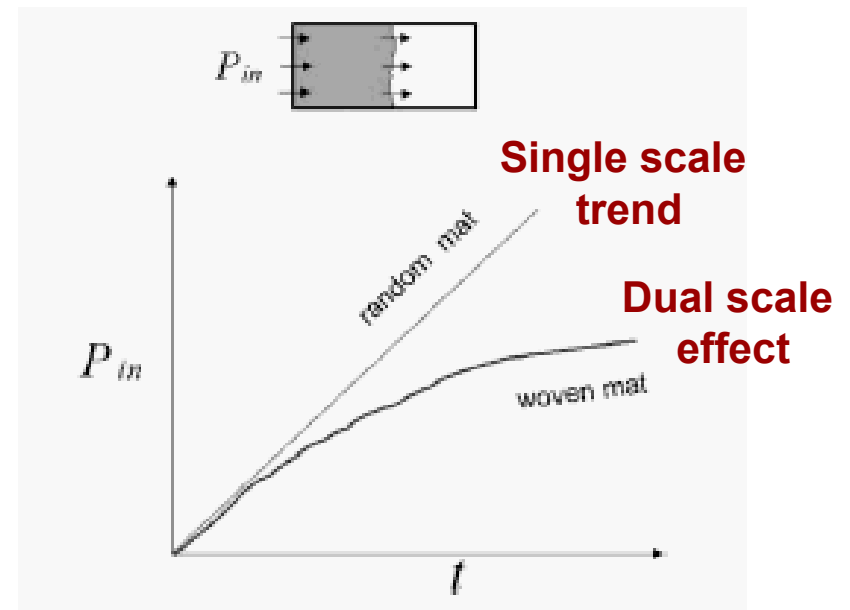
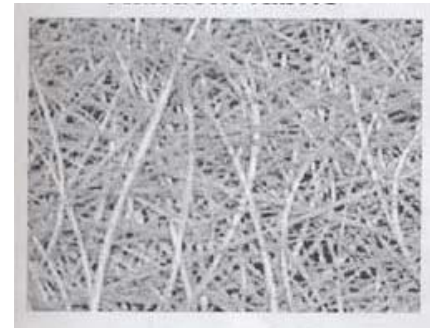




## Flow in porous media

### ◆ Flow in single scale porous media

- ✧ The pressure drop is *linear*
- ✧ Preform has *one permeability value* associated with it
- ✧ *No saturation length*
  - The flow front location and the fully saturated location are the same

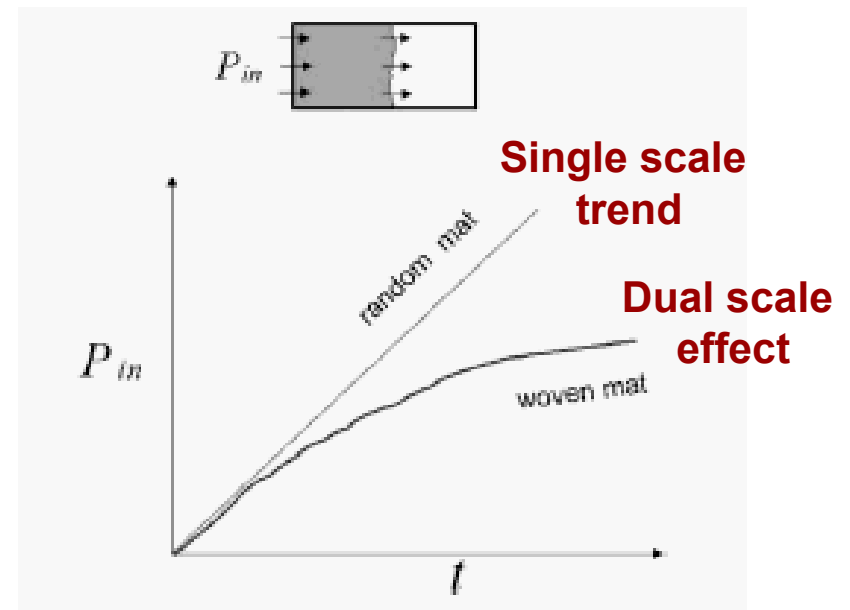
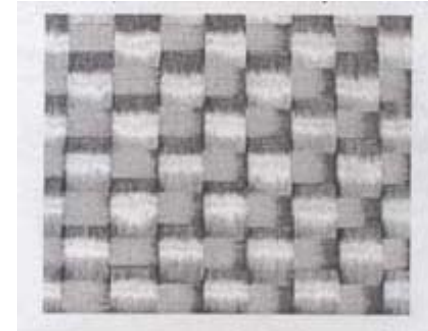




## Flow in porous media

### ◆ Flow in dual scale porous media

- ✧ The pressure drop is **nonlinear**, a droop is induced
- ✧ Preform has **two permeability values** associated with it
- ✧ **Saturation length**
  - The flow front location is ahead of the fully saturated location
- ✧ A fluid **sink** causing the droop
  - Fluid is impregnating the fiber tows





## Flow in porous media

### ◆ 1D constant flow rate injection

✧ Governed by Darcy's Law

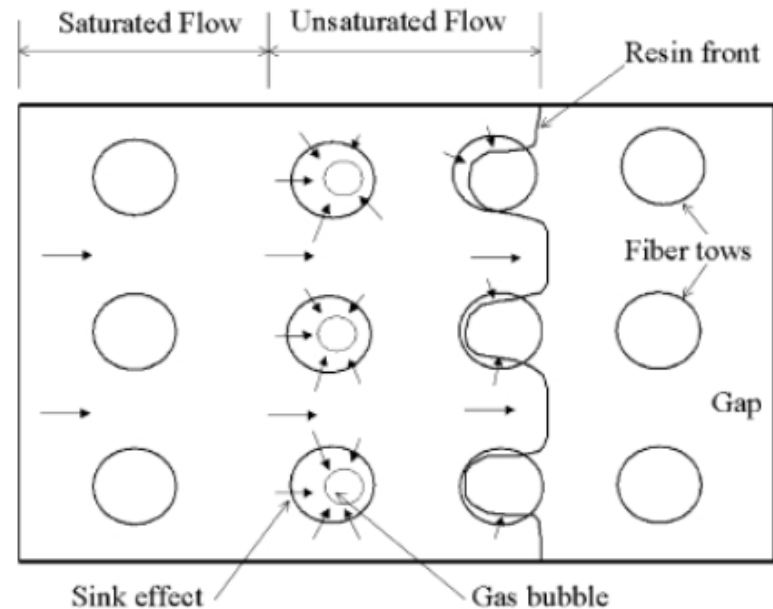
$$u_x = \frac{K}{\mu} \frac{dp}{dx} = \frac{Q}{A}$$

$$K = \frac{Q \mu \Delta L}{A \Delta p} = \frac{Q \mu v_{ff}}{A m}$$

where

$$v_{ff} : \text{flow front velocity} = \frac{Q}{A \phi}$$

$m$  : slope of  $P$  vs.  $t$  plot





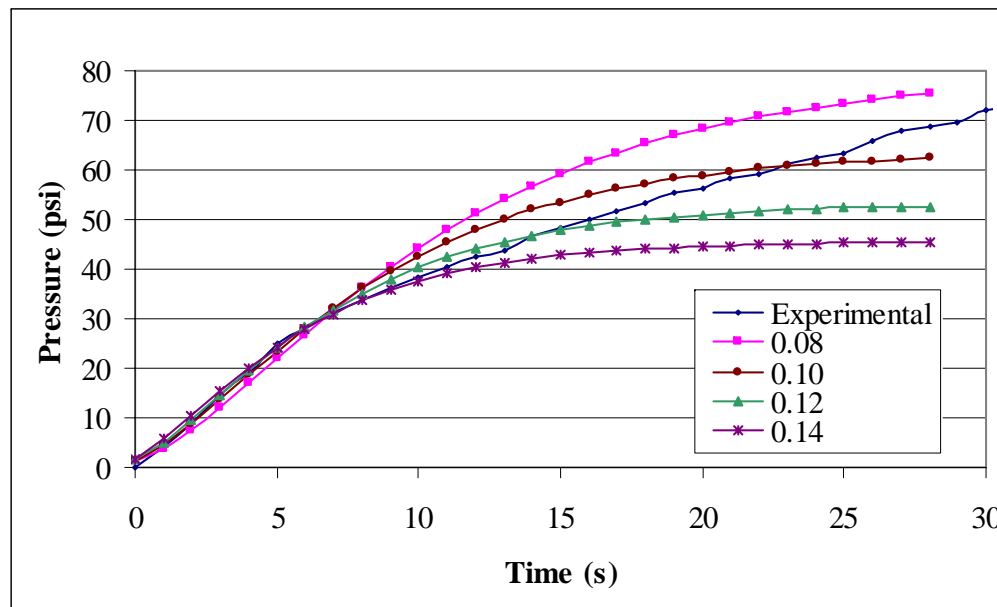
## Flow in porous media

### ◆ Assume constant sink

✧ An *analytical* solution can be obtained

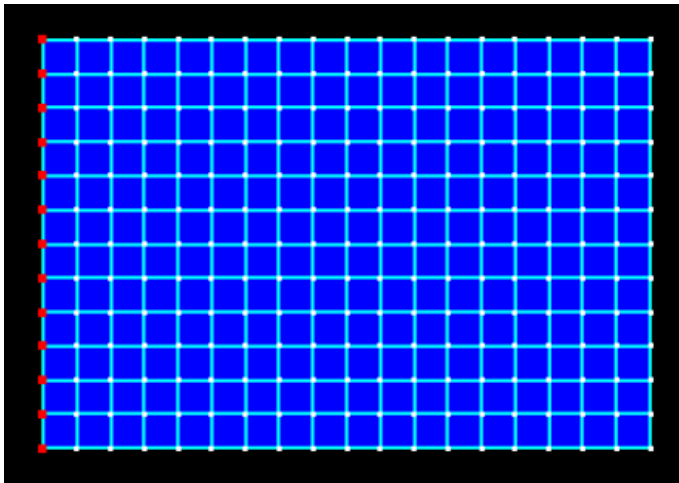
$$u_x = \frac{K}{\mu} \frac{dp}{dx} = Sx - \frac{Q}{A}$$

$$K = \frac{Q^2 \mu}{S A^2 P_{inj}} \left[ (1 - e^{-\frac{st}{\phi}}) - \frac{1}{2} (1 - e^{-\frac{st}{\phi}})^2 \right]$$

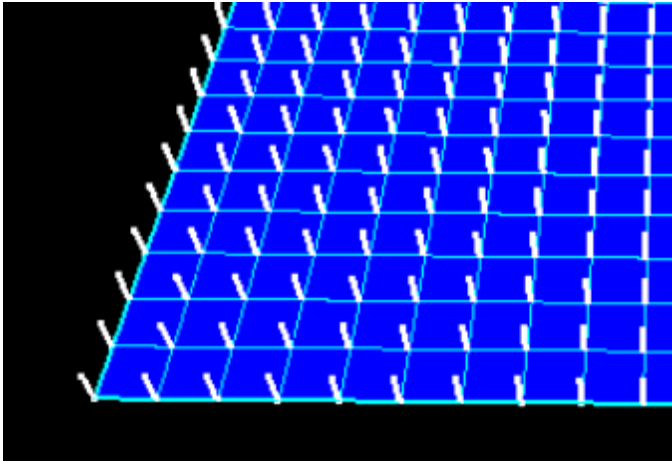




## LIMS approach



- ◆ Model mold with a standard 2D element mesh
- ◆ Impose 1D planar flow where  $Q = \text{a constant at boundary}$

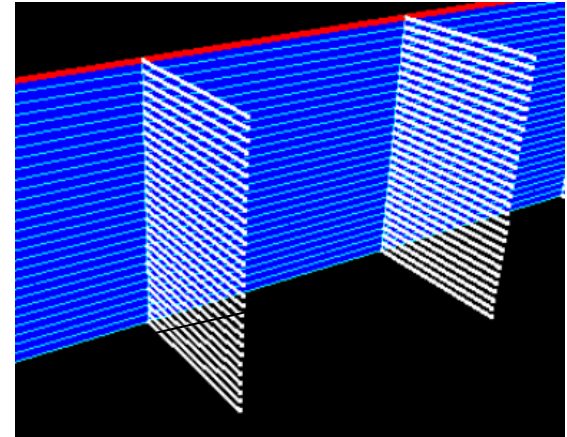


- ◆ Implement saturation program
  - ✧ 1D elements attached to each node to model  $K(\text{tow})$
  - ✧ Enables interactions between macro and micro flow



## Project motivation

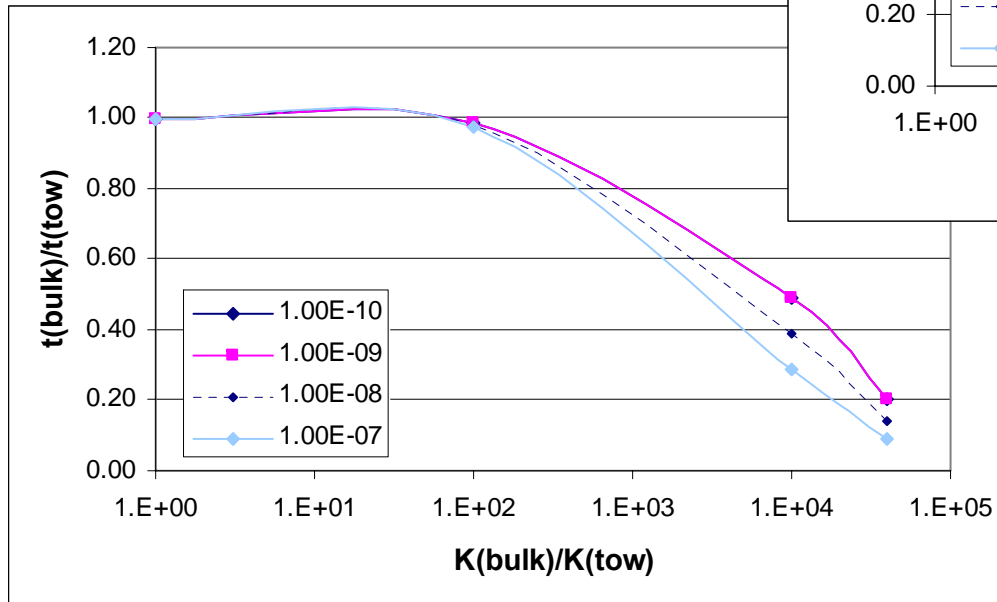
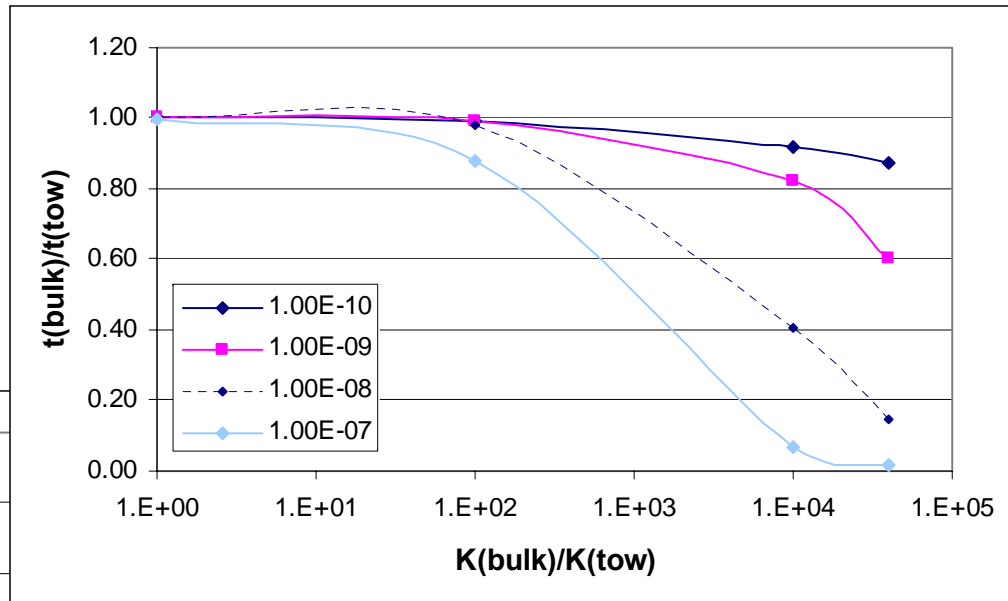
- ◆ Saturation of tows can be properly predicted along with the macroscopic resin flow front in RTM and VARTM processes
  
- ◆ Model cross-section
- ◆ Inputs
  - ✧ **2D elements**
    - Bulk permeability  $8E-10m^2$
    - Transverse permeability  $1E-12m^2$
  - ✧ **1D elements**
    - Tow permeability  $2E-14m^2$  to  $8E-10m^2$
    - Distribution media permeability  $1E-08m^2$
- ◆ Vary resistance at the vent





## Project motivation

As you move away from the vent, curves begin to collapse onto one another.  
Resistance plays less of a role, but K<sub>tow</sub> value clearly impacts fill time.



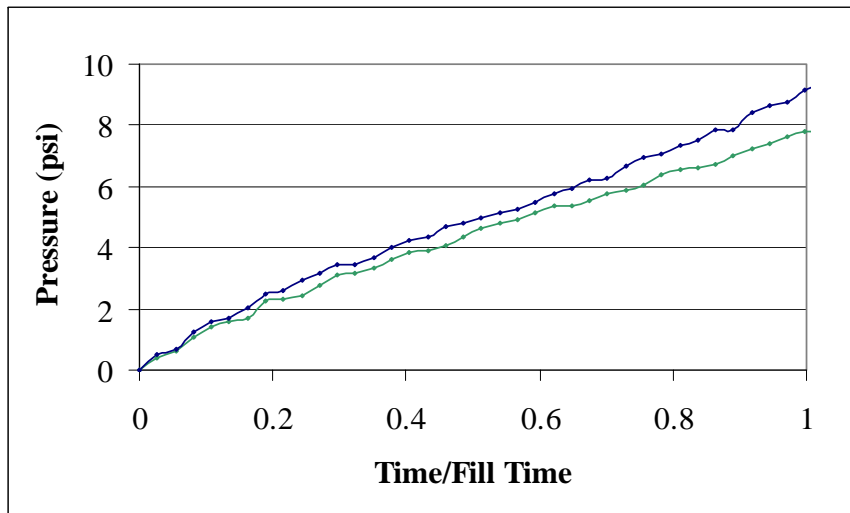
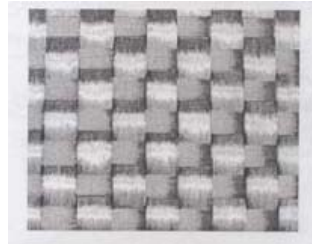
As tows become less permeable, the time to fill the tows increases.  
As the resistance at the vent increases, the time to fill the tows decreases.



## Experimental results

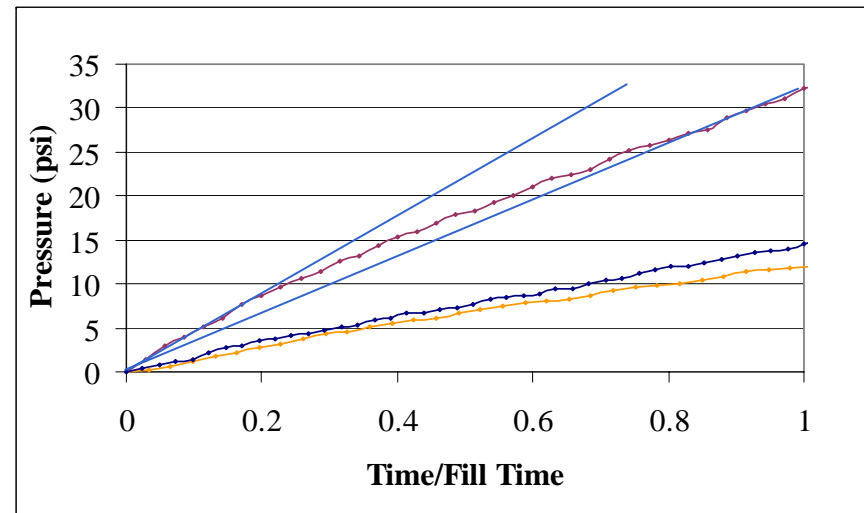
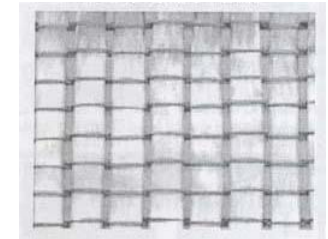
### ◆ Pressure vs. normalized time

- Plain weave E-glass
- $Q = 170$  cc/min
- $V_f = 41\%$



### ◆ Pressure vs. normalized time

- Biaxial stitched E-glass
- $Q = 170$  cc/min
- $V_f = 47\% \text{ \& } 39\%$



Darcy's law valid in both linear regions of data

- ◇ At beginning:  $K_{tow}$  is so small, no tows are filled (unsaturated)
- ◇ At end:  $K_{tow}$  is so large, all tows are filled immediately (saturated)



## Bulk permeability determination

- ◆ **Directly determine unsaturated permeability**
  - ✧ Use initial slope data from **P vs. t** plot
- ◆ **Indirectly determine bulk permeability**
  - ✧ Convert to permeability value through established ratio

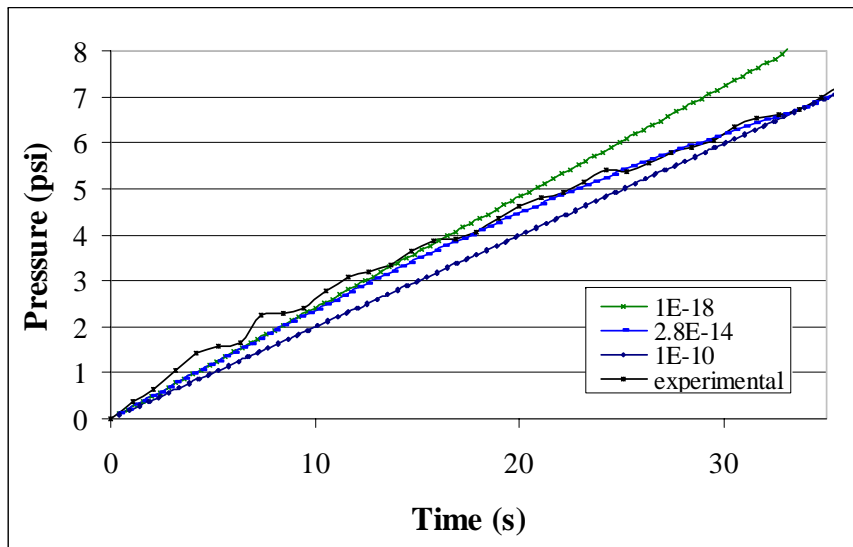
type	Vf (%)	slope (psi/s)	K <sub>unsat</sub> (m <sup>2</sup> )	K <sub>bulk</sub> (m <sup>2</sup> )	K <sub>bulk</sub> /K <sub>unsat</sub>
woven	41	0.2490	1.10E-09	1.34E-09	1.21
woven	41	0.3030	9.11E-10	1.10E-09	1.21
stitched	39	0.4457	6.03E-10	7.18E-10	1.19
stitched	39	0.4418	6.08E-10	7.24E-10	1.19
stitched	47	1.2400	2.49E-10	3.21E-10	1.29

$$K_{unsat} = \frac{Q^2 \mu}{A^2 \phi m}$$

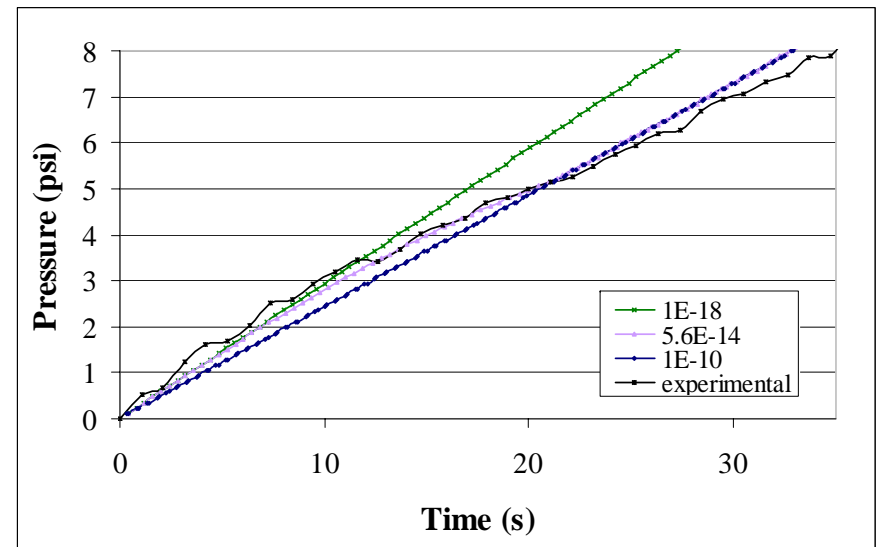


## LIMS pressure results

### ◆ Plain weave E-glass



$$\frac{K_{sat}}{K_{tow}} = \frac{1.34E-9}{2.8E-14} = 4.79E4$$

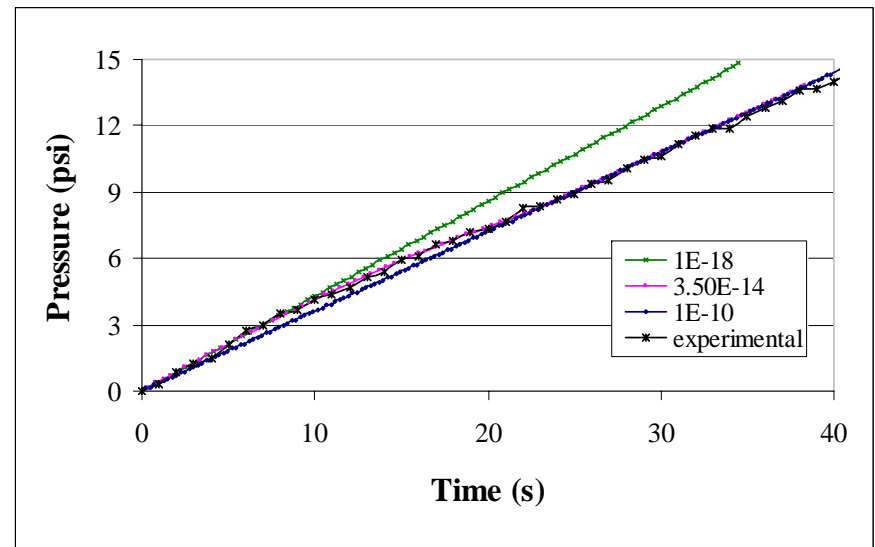
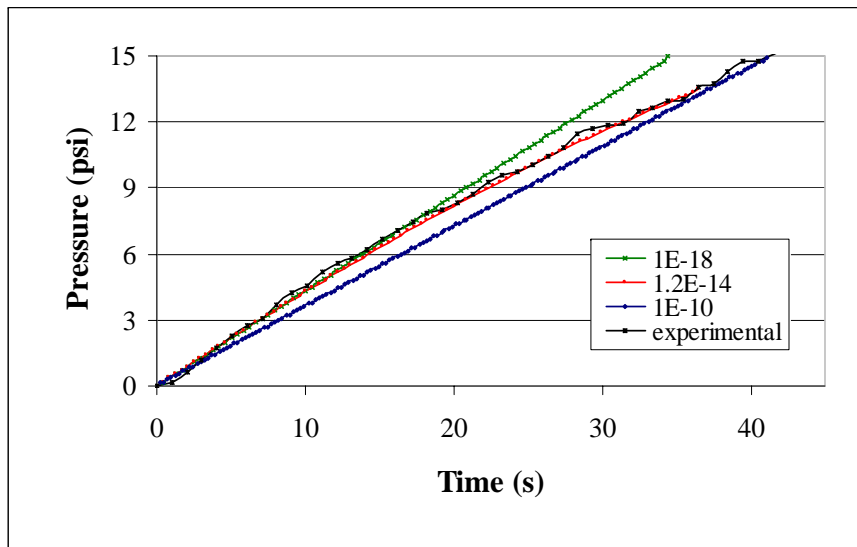


$$\frac{K_{sat}}{K_{tow}} = \frac{1.10E-9}{5.6E-14} = 1.96E4$$



## LIMS pressure results

### ◆ Biaxial stitched E-glass



$$\frac{K_{sat}}{K_{tow}} = \frac{7.18E-10}{1.2E-14} = 5.98E4$$

$$\frac{K_{sat}}{K_{tow}} = \frac{7.24E-10}{3.5E-14} = 2.07E4$$



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## **Tow permeability determination**

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- ◆ **Correlate simulation data to experimental data**
  - ✧ **Keep  $K(\text{bulk})$  value constant, vary  $K(\text{tow})$  values**
  - ✧ **Minimize error of  $K(\text{tow})$**
  
  - ✧ **Vary  $K(\text{bulk})$  values, vary  $K(\text{tow})$  values**
  - ✧ **Simultaneously minimize the error of  $K(\text{tow})$  and  $K(\text{bulk})$**
  
  - ✧ **Both methods require a great deal of simulation-generated data**
  - ✧ **Investigate a closed-form or series solution**



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## **Conclusions and future work**

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- ◆ **One experiment can quantify both the macro/bulk and the micro/tow permeability values of E-glass fabrics**
  - ◆ **Difference of four orders of magnitude from macro to micro values**
  - ◆ **Orders of magnitude are consistent, but there is still no concrete correlation between the ratio of  $K(\text{sat})/K(\text{tow})$**
  - ◆ **The two permeability values can be implemented into LIMS to more accurately model the flow**
    - ✧ **The implementation of 1D elements allows for the interactions between the macro and micro flow**
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- ◆ **Establish the best method to determine  $K(\text{tow})$**
- ◆ **Evaluate which error analysis technique is best**
- ◆ **Evaluate fabrics with large tows**
- ◆ **Make composite parts to evaluate how cross section, i.e.: the size of the tows, correlates to the permeability values**
- ◆ **Compare VARTM simulation results with experiments**