Permeability experiments using 3D printed fracture network sample

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Literature Review

- Try to make the Berea sandstone sample with the 3D printing technology, and compare with the porosity result between CT images and mercury porosimetry.
- The comparison revealed that 3D printed sample’s porosity and pore-throat diameter are less 2% and 56μm than the nature rock sample.

Ishutov et al., 2017
Try to design the fracture network and make it by 3D printing technology.

Compare the permeability result between calculation and experiment, and find that the results are in the same order.

Anna Suzuki et al., 2017
Purpose

- Test that if the 3D printing technology can print the fracture network successfully or not.
- Try to measure the permeability with the increasing confining pressure.
Introduction

Methodology

Preliminary Result

Summary

Future Work

Workflow

Design

3D Printing

Experiment

Simulation

- Fracture parameters
- OpenSCAD

- SLA technology

- YOKO2 system

- Fortran Code
Sample Design

- Fracture Center: randomly choose
- Radius: 3 mm
- Aperture: 0.2 mm
- Orientation:
  - strike: 5°, 15°, 25°, ..., 355°
  - dip: 5°, 15°, 25°, ..., 85°
- Fracture number: 9*36 = 324
OpenSCAD

- Design the 3D model by coding.

STL file
OpenSCAD

- Concept of the 3D model design.
OpenSCAD

Concept of the 3D model design.

- 25 mm
- 22 mm
- 40 mm
OpenSCAD

- Concept of the 3D model design.

Prevent the leakage from the side of the sample
OpenSCAD

- The model of my experiment:

![Model of experiment]
3D printing technology

- There are two kinds of 3D printing technology that are commonly used.

- **FDM (Fused Deposition Modeling)**
- **SLA (Stereolithography)**
3D printing technology

- **FDM (Fused Deposition Modeling)**
- Resolution: 0.5 mm
- Price: cheap
- Material: ABS, PLA
3D printing technology

- **Resolution**: 0.2 mm
- **Price**: expensive
- **Material**: photopolymer resin

**SLA**
(Stereolithography)
3D printing technology

- Radius: 3 mm
- Aperture: 0.2 mm

<table>
<thead>
<tr>
<th></th>
<th>FDM</th>
<th>SLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>0.5 mm</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Price</td>
<td>Cheap</td>
<td>Expensive</td>
</tr>
<tr>
<td>Material</td>
<td>ABS, PLA</td>
<td>photopolymer resin</td>
</tr>
</tbody>
</table>
YOKO2 System

Air Pressure

Confining Pressure

\[ k = \frac{2Q \mu_g L}{A_s} \cdot \frac{P_u}{(P_u^2 - P_d^2)} \]

- \( k \): air permeability (m²)
- \( \mu_g \): air viscosity (Pa*s) = \(1.96 \times 10^{-6}\)
- \( L \): sample length (m)
- \( A_s \): sample cross section area (m²)
- \( P_u \): pressure at the top of sample (MPa)
- \( P_d \): pressure at the bottom of the sample (MPa) = 0.1
Experiment Result

- Confining pressure: 1 → 3 MPa → 5 MPa (oil leakage)
- Air pressure < 0.1 MPa

<table>
<thead>
<tr>
<th>Confining Pressure (MPa)</th>
<th>Air Permeability (m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.83E-12</td>
</tr>
<tr>
<td>3</td>
<td>2.05E-12</td>
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</tbody>
</table>
Simulation Result

- **Setting:**
  - Diameter: 0.006 (m)
  - Aperture: 0.0002 (m)
  - Volume density: $2.13 \times 10^7$ (fracture number/m$^3$)
  - JRC: 1
  - JCS: 100 (MPa)

<table>
<thead>
<tr>
<th>confining pressure (MPa)</th>
<th>hydraulic conductivity (m/s)</th>
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<tbody>
<tr>
<td>1</td>
<td>3.32E-14</td>
</tr>
<tr>
<td>3</td>
<td>3.48E-14</td>
</tr>
</tbody>
</table>
Summary

- The 3D printed fracture network sample can be used to conduct the permeability test at low confining pressure.
- The reason of the difference between experiment result and simulation result still need to be figured out.
Future Work

- Print the same designed sample to conduct the permeability test to verify the repeatability of the 3D printed fracture network.
- Try to design the anisotropic samples to conduct the permeability test and compare with the simulation result.
Thank you
Fracture Center

program center
implicit none
integer :: i
real :: lx,ux,ly,uy,lz,uz,lenx,leny,izen,t,h,k
real :: x(210),y(210),z(210)
lx=-11.0
ux=11.0
lenx=ux-lx

ly=0.0
uy=40.0
lenz=uz-lz

call random_number()

do i=1,210
  call random_number(t)
x(i)=lx*lenx*t

  ly=-(((11)**2-(x(i)**2)**2)*(0.5))
  uy=((11)**2-(x(i)**2)**2)*(0.5)
  leny=uy-ly
  call random_number(h)
y(i)=ly*leny*h

  call random_number(k)
z(i)=lz*izen*k

do end

open(2, file='center.txt')
write(*,'(F0.2,F0.2,F0.2)') x(i), y(i), z(i)
write(2,'(F0.2,F0.2,F0.2)') x(i), y(i), z(i)
end do
end

\[ x^2 + y^2 = (11)^2 \]

lx : x lower boundary
ux : x upper boundary
ly : y lower boundary
uy : y upper boundary
lz : z lower boundary
uz : z upper boundary
Software - OpenScad

• Design the 3D model by coding.

• Code:
  ➢ Translate
  ➢ Cylinder
  ➢ Rotate
  ➢ Difference

```plaintext
translate([46.0991, -1.06581E-14, -50])
cylinder(r=56.4493, h=1, center=true);
```

```plaintext
$fn=100;

difference(){
  // sample
  translate([0, 0, -50])
  cylinder(r=50, h=100, center=true);

  //
  translate([46.0991, -0.0000000000000106581, -50])
  rotate([0, 1, 0], [1, 28, 63516, 0])
  cylinder(r=56.4493, h=1, center=true);

  //
  translate([-8.95509, -6.87169, -41.7223])
  rotate([3, 1, 0], [4.331453, 0])
  cylinder(r=60.4206, h=1, center=true);

  //
  translate([-8.0129, -25.5026, -76.5577])
  rotate([3, 1, 0], [-1.962605999, 0])
  cylinder(r=31.728, h=1, center=true);

  //
  translate([-34.2155, 34.7545, -50])
  rotate([7, 1, 0], [-2.26030893, 0])
  cylinder(r=31.728, h=1, center=true);

  //
  translate([-7.10543, -7.10543, -15, -50])
  rotate([7, 1, 0], [-1.492558328, 0])
  cylinder(r=62.8975, h=1, center=true);
```
STL file

- STL file describes only the surface geometry of three-dimensional objects by triangles.
- There are two types in STL file:
  1. **Text (ASCII)**
  2. Binary code

```plaintext
solid OpenSCAD_Model
  facet normal 0.0350001 -0.0022718 0.999385
  outer loop
    vertex 48.5116 1.66129 6.37547
    vertex 47.6361 -1.91765 6.39799
    vertex 48.6349 -1.88277 6.36309
  endloop
endfacet
facet normal 0.0350002 -0.00227184 0.999385
  outer loop
    vertex 47.6361 -1.91765 6.39799
    vertex 48.5116 1.66129 6.37547
    vertex 47.5128 1.62641 6.41037
  endloop
endfacet
```

**Normal vector of the triangle**

**The vertexes of the triangle**
Simulation VS Experiment

\[ K = k \frac{\rho \cdot g}{\mu} \]

- \( K \): hydraulic conductivity (m/s)
- \( k \): intrinsic permeability (m\(^2\))
- \( \rho \): fluid density (kg/m\(^3\))
- \( g \): acceleration of gravity (m/s\(^2\))
- \( \mu \): viscosity coefficient (kg/(s*m))

\[ \rightarrow K = k \cdot 10^{3 \cdot 10^{-3}} = k \cdot 10^7 \text{ for the water at } 20^\circ C \]

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