Presented at the COMSOL Conference 2010 Paris

LABORATORY OF BIOLOGICAL STRUCTURE MECHANICS

LaBS

www.labsmech.polimi.it

POLITECNICO DI MILANO



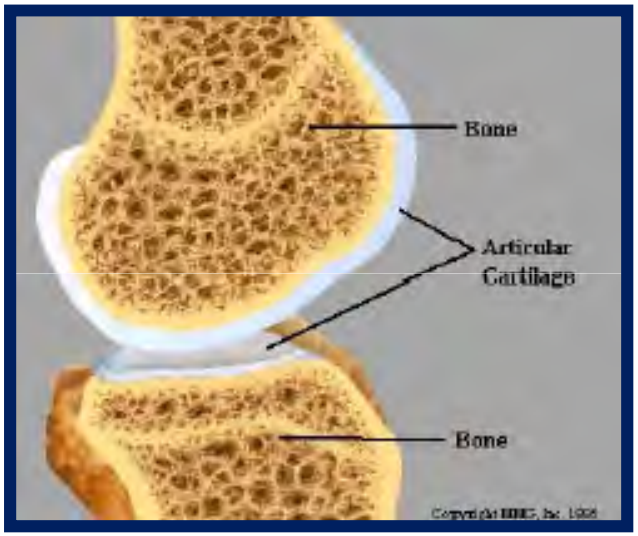


Finite Element Analysis of Permeation Tests on Articular Cartilage under Different Testing Conditions Using COMSOL Multiphysics.

G.Spatafora, F. Boschetti

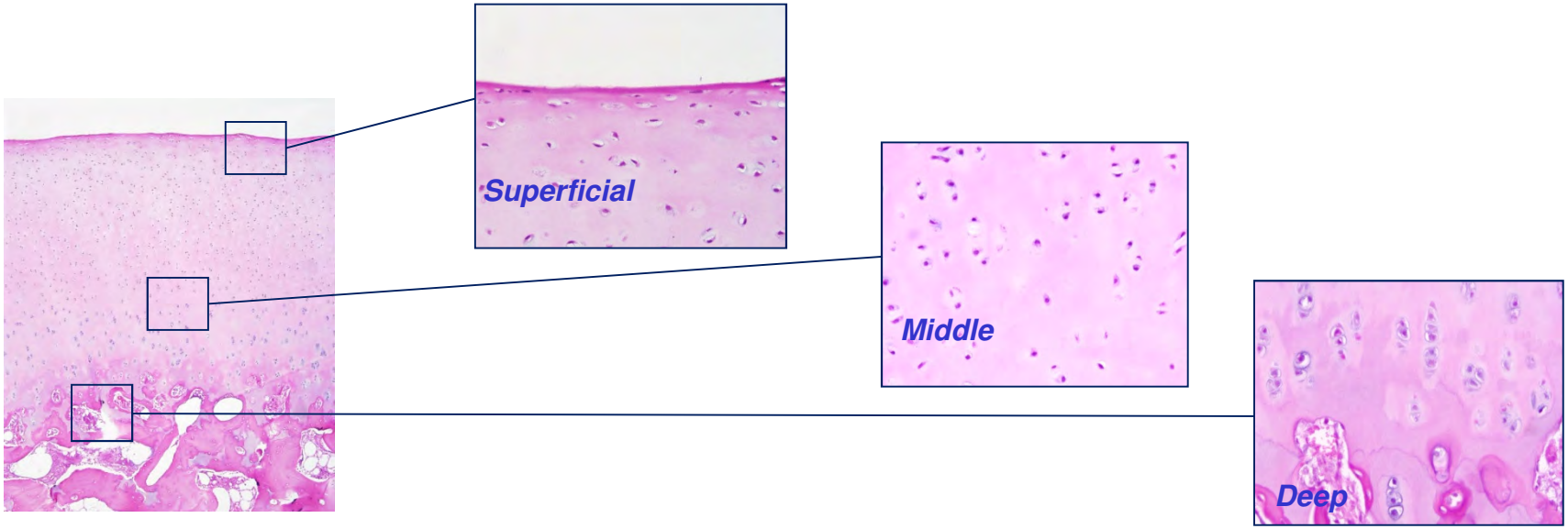
ARTICULAR CARTILAGE

- Articular cartilage is a composite material made of a solid porous matrix filled with water and fiber reinforced
- Functions are to withstand, transfer and distribute loads across diarthodial joints and to provide lubrication of articular surfaces
- Permeability is very important to determine the mechanical response of the tissue and is also related to metabolism because cartilage is avascular
- Permeability increases in the osteoarthritic joint → cartilage load support shifts from the interstitial water to the solid matrix



Articular Cartilage Structure

- **solid phase**
  - charged proteoglycan macromolecules → the compressive and tensile response
  - collagen fibers → the compressive and tensile response
- **interstitial fluid phase** → the flow-dependent transient response
- **ion phase**



POROELASTICITY, DARCY'S LAW AND BIPHASIC MODEL

1D models

- **Monophasic** (Sokoloff et al, 1966)
- **Biphasic** (Mow et al, 1980)
- **Triphasic** (Lai et al, 1991)

FE models

- **Poroelastic model** (Spilker et al, 1990)
- **Poroviscoelastic model** (Suh et al, 1998)
- **Fibril-reinforced model** (Soulhat et al, 1999)
- **Combined models** (Li et al, 2000 and 2004; Wilson et al. 2004; Huang et al., 2001)

***Initial Assumptions*:**

The tissue consists of an incompressible elastic, homogeneous and isotropic solid matrix, hydrated with an incompressible and inviscid fluid.

POROELASTICITY, DARCY'S LAW AND BIPHASIC MODEL

DARCY'S LAW

$$q = \phi v^f = -\frac{k}{\mu}\nabla p(x,t)$$

IN A COMPRESSION TEST:

$$\sigma_{total} = \sigma_{fluid} + \sigma_{solid}$$

$$\sigma_{fluid} = -\phi^f p I$$

$$\phi^f = \frac{V^f}{V^{total}}$$

$$\sigma_{solid} = -\phi^s p I + C\varepsilon = -\phi^s p I + \lambda_s tr(\varepsilon) I + 2\mu_s \varepsilon$$

$$\phi^s = 1 - \phi^f$$

POROELASTICITY, DARCY'S LAW AND BIPHASIC MODEL

In an isotropic biphasic model, the mechanical behaviur is described by:

- E – Young's modulus
- ν – Poisson's ratio
- H_A - Aggregate modulus
- K – Permeability
- Φ_f – fluid fraction

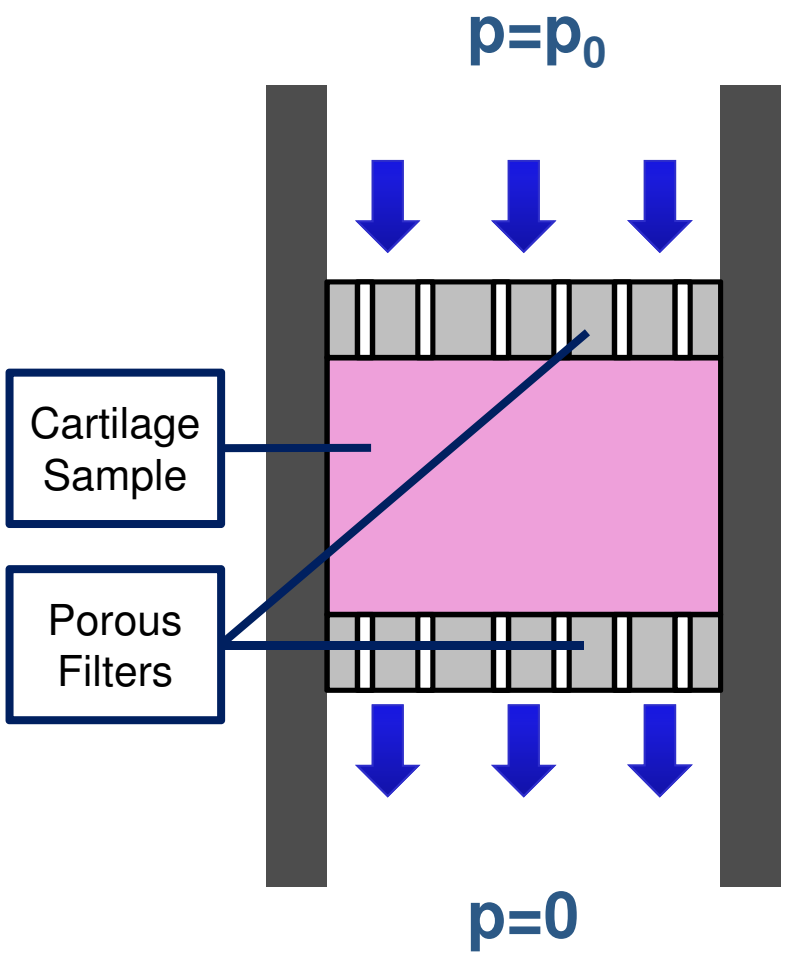
- They describe the mechanical behavior at the equilibrium;
- It describes the ease of flow through the porous matrix (∅ ~ 20-60 Å);
- It describes the transient response of the material;
- It is depth and strain dependent.

- Fluid fraction is the ratio of the fluid volume and the total volume:
  - There is a mutual relation between Young and aggregate modulus:
  - It describes the solid fraction (sometimes called *solidity*) and is:

$$\phi^f = \frac{V^f}{V_{total}}$$

$$H_A = \frac{E(1-\nu)}{\phi^s(1+\nu)(\phi^f - 2\nu)}$$

PERMEATION TEST



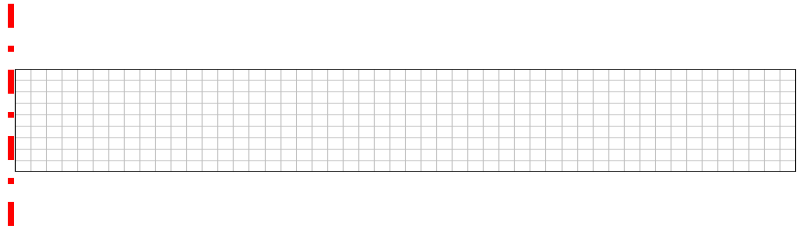
WHAT IS A PERMEATION TEST?

The permeation test gives a direct measurement of the apparent permeability k. The sample is supported by two rigid porous filters. A fluid pressure is applied on top of the sample, and flow through the sample is measured.

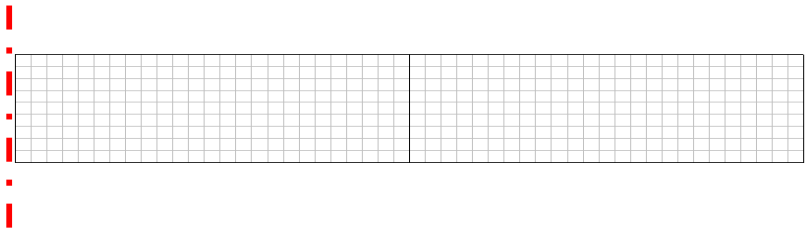
Other devices permit the imposition of flow and the measurement of the pressure.

- The low value of the permeability of articular cartilage introduces some measurement difficulties. The high hydraulic resistance of the sample induces the fluid to pass around the sample; it is not easy to guarantee the seal while maintaining a uniform deformation and to make measurements for low values of fluid pressure.
- The aim is to define a constraint that introduce a pattern of stress and strain similar to the ideal test of permeability and to calculate the local strain distribution by numerical simulations of permeation tests varying the sealing (glued sample or o-ring on top).

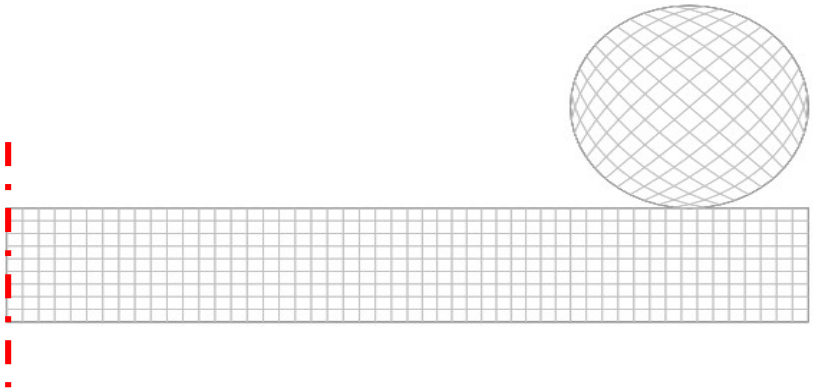
1. Ideal test (no seal)



2. Glue test

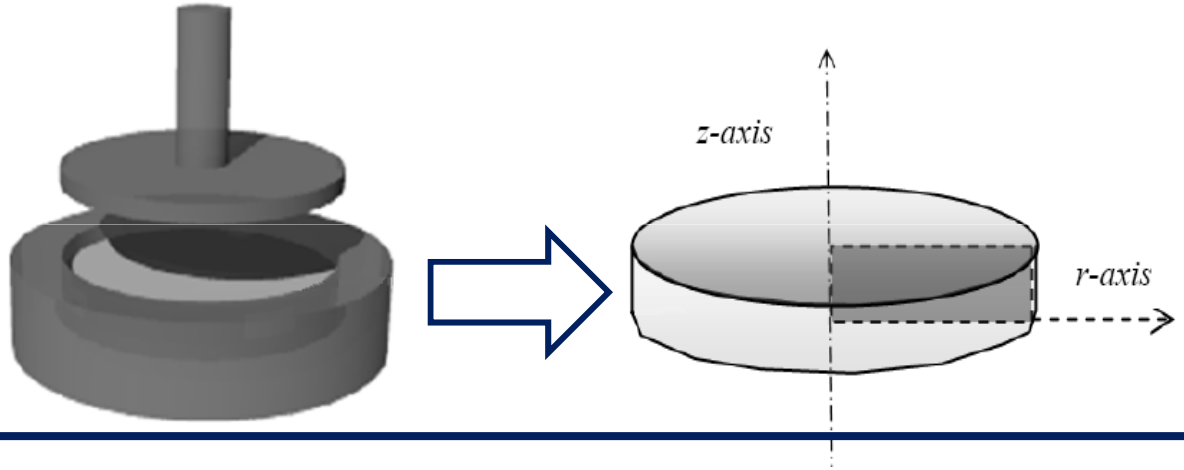


3. O-Ring test



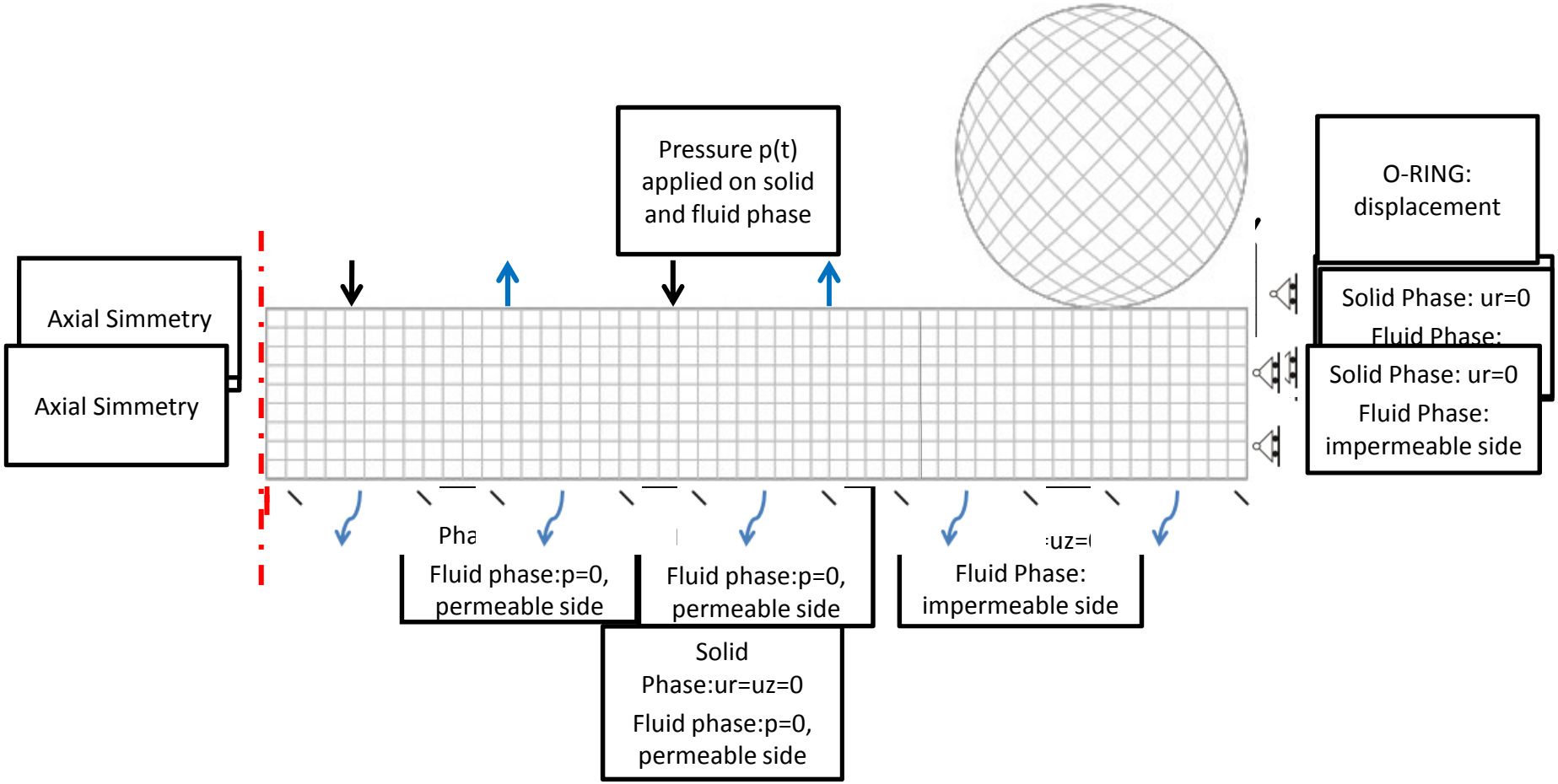
COMSOL MULTHIPHYSICS: GEOMETRY AND MESH

- The geometry used in COMSOL Multiphysics is 2D with axial symmetry
- We considered a diameter of 12mm and a thickness of 1mm.

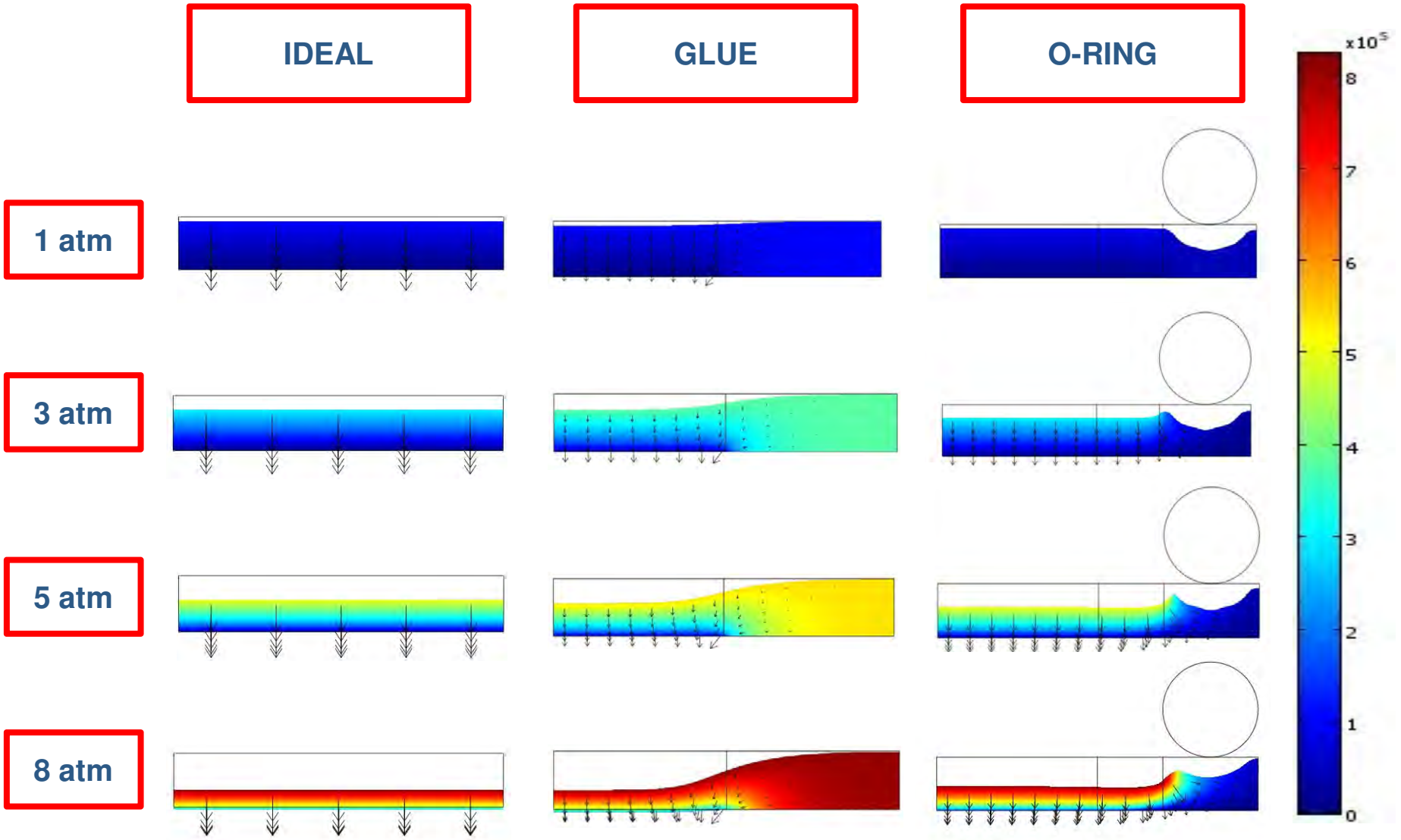


- We used a mapped mesh, recommended for simple geometries free of holes.
- The Finite Elements (FE) are Lagrangian-quadratic: COMSOL Multiphysics uses these elements by default.

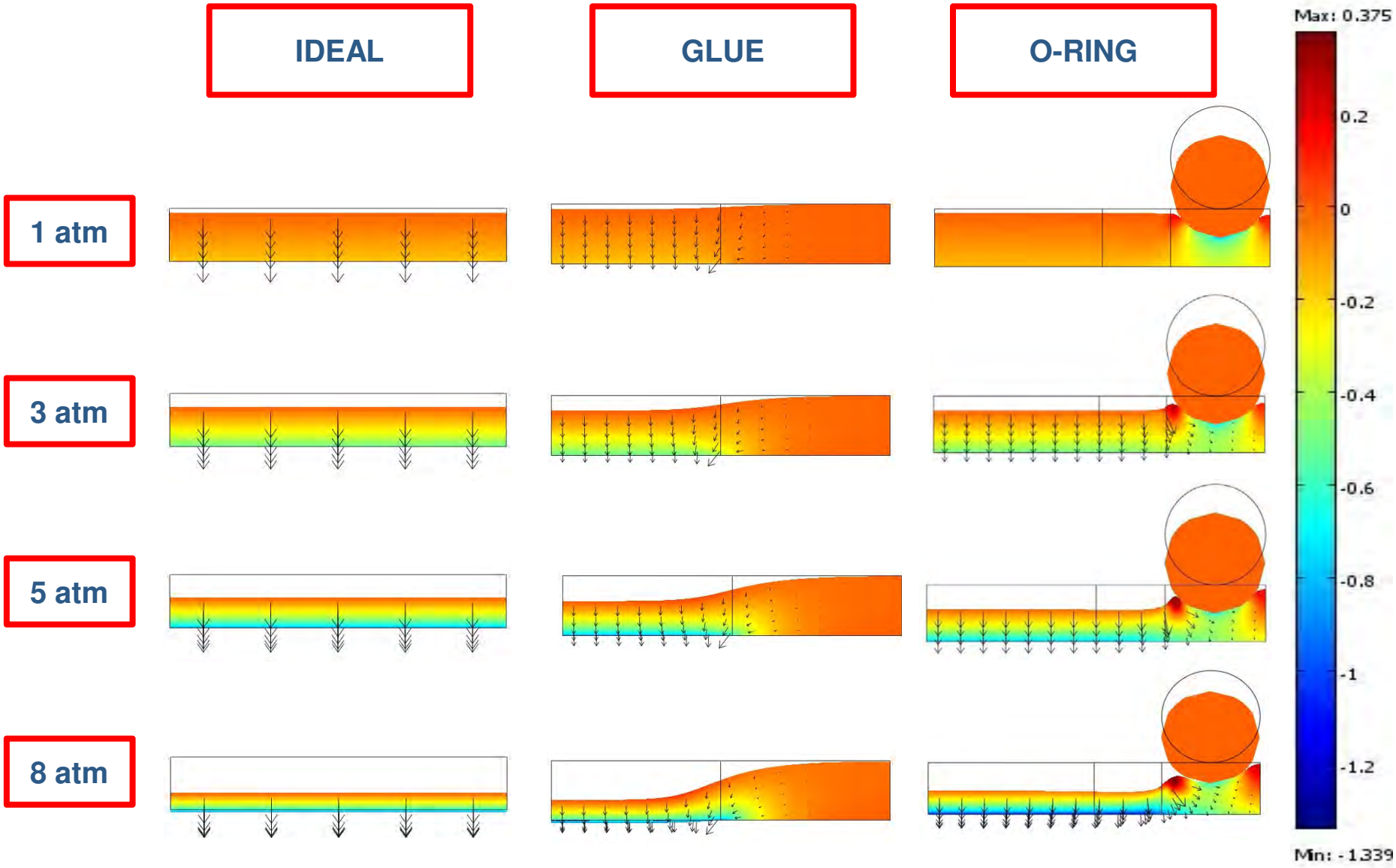
COMSOL MULTIPHYSICS: BCs



COMSOL MULTIPHYSICS: PRESSURE RESULTS



COMSOL MULTIPHYSICS: STRAIN RESULTS



CONCLUSIONS

- The model allows calculation of local strains and deformed shape. The former is essential for the evaluation of permeability from direct tests, the latter is useful to understand whether the imposed constrain alters dramatically the sample geometry

- Simulations revealed a uniform deformed shape in the central area for all the configuration tested.

  The o-ring configuration is the preferred choice to guarantee seal to avoid experimental difficulties related to using glue.

- The experimental set-up designed on the basis of the numerical results will allow to determine the permeability of articular cartilage as a function of strain.

POLITECNICO DI MILANO

LABORATORY OF BIOLOGICAL STRUCTURE MECHANICS

LaBS

www.labsmech.polimi.it





THANKS FOR ATTENTION

SAMPLES