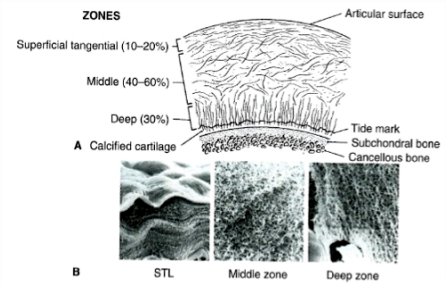
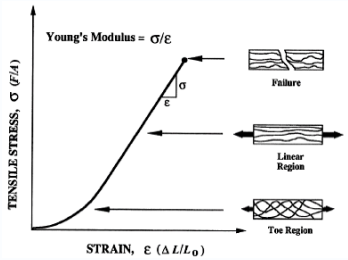
ME 482 Experimental Tissue Mechanics
Professor A. Wagoner Johnson

9/7/16 (continued topic from 9/2)

Cartilage Tensile & Compressive Properties





Nordin and frenkel

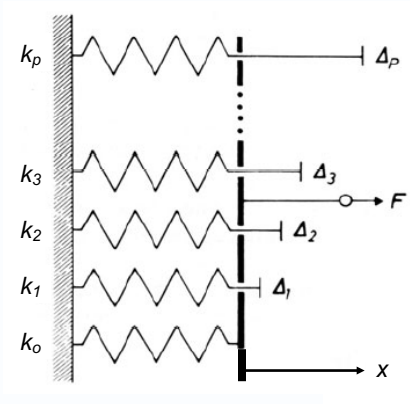
Recommended reading (general for AC):
Please see the 3rd slide

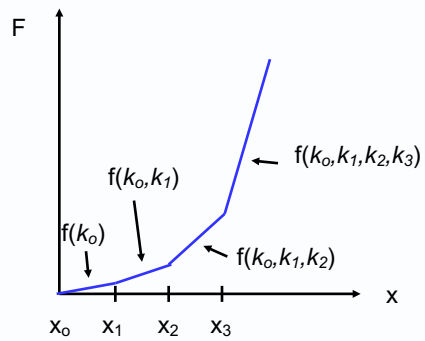
Today – Cartilage (continued from 9/2)

- Mechanical behavior in tension
- Mechanical behavior in compression

- Assign HW 2 due 9/9

The toe region with non linear stiffness can be described using the fiber recruitment model





$$F = \sum_{i=0}^{p} k_i (x - x_i)$$

After x_p, no more fibers recruited

A HW assignment will be posted on Piazza on the fiber recruitment model this afternoon. It is due 9/9 in class.

In the assignment you will use MatLab or Excel to generate force-displacement and stress-strain curves for a given sets of fibers with particular properties (e.g. fiber stiffness, number of fibers, etc).

This is a nice exercise to help connect something physical, that you can easily envision (pulling fibers), with a simple mathematical model (fiber recruitment model).

The exercise will help you to understand how these factors (number of fibers, stiffness, how straight they are) contribute to the shape of the curve, and how to write a simple code based on a this model to generate the curves.

HOMEWORK 2: Fiber Recruitment Model

Due in class Friday, 9/9

3 HR STUDENTS (a-e) *4 HOURS DO ALL (a-f)*

The fiber recruitment model was introduced in class when we discussed tensile properties of cartilage. It is also applicable to tissues like tendon and ligament.

Use the fiber recruitment model to create force (F) versus displacement (x) curves for cartilage (or ligament) under tensile loading. The sample consists of 10 fibers. Assume that each fiber has a stiffness of k = 25 N/mm and that one new fiber is recruited every 0.2 mm. This problem can be solved most efficiently by using Excel or MATLAB to write the code and then modifying it as needed for the cases below. *(Note some parts of the homework must be completed by 4 hr students, but not 3hr students. These are indicated.)*

a. Plot the load-displacement curves up to 5 mm. At what displacement does the curve become linear? Does this value change if 15 fibers are available for recruitment? If so, what is the value for 15 fibers?

b. Describe how the load-displacement curve changes and show the plot if 5 fibers are again recruited, but now the first 5 fibers that are recruited have stiffness of k = 25 N/mm as in (a) and the last 5 fibers have stiffness of k' = 100 N/mm. Assume that all fibers are recruited at a rate of 1 fiber per 0.2 mm as in (a).

10

Constant Strain-Rate tensile tests (Equil. tensile tests)
Fiber alignment with tensile axis

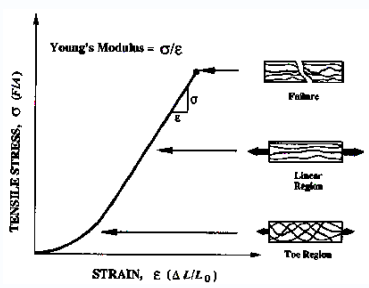
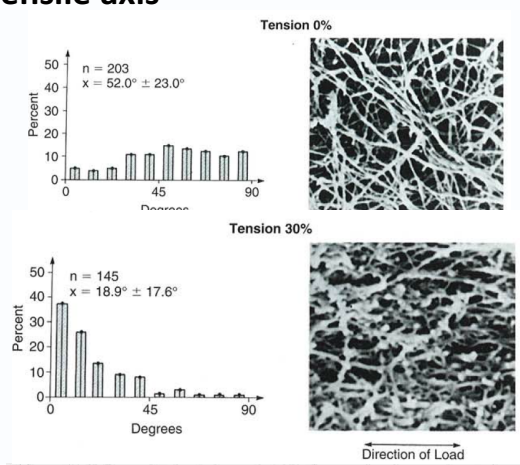


FIGURE 5-13. Typical stress–strain curve for articular cartilage in a uniaxial and uniform strain rate experiment. The toe region is marked by an increasing slope, whereas the linear region appears to be a straight line with a slope of σ/ε (354).

Nordin and Frenkel



Collagen fibril alignment is clearly demonstrated by the scanning electron micrographs (×10,000) (*right*) of cartilage blocks under 0% stretch (A) and 30% stretch (B). The histograms (*left*), calculated from the micrographs, represent the percent of collagen fibers oriented in the direction of the applied tension. At 0% stretch the fibers have a random orientation; however, at 30% they are aligned in the direction of the applied tension. *Reprinted with permission from Wada, T., & Akizuki, S. (1987). An ultrastructural study of solid matrix in articular cartilage under uniaxial tensile stress.* J Jpn Orthop Assn, 61 FIG. 3-14

Equilibrium tensile tests via the stress relaxation experiment give tensile properties of the ***solid matrix***

- **Must eliminate fluid flow as a contributor to behavior
- **Test at 'equilibrium' (static tests – low strain rates)
  Example rate is 0.5 cm/min
- **Incremental experiments that allow **stress relaxation** in between deformation increments
- Equilibrium tensile modulus from linear region of up to ~15% strain, <1 MPa to 30 MPa
- Consider that there are variations due to species, age, joint, location in joint, depth, orientation relative to split lines, composition, state of degeneration

Tensile Modulus variations

Mow & Huiskes

What are some general conclusions we can make about tensile modulus? How do you rationalize your answer? What is the evidence?

TABLE 5-5A. EQUILIBRIUM TENSILE MODULUS (MPa) OF NORMAL HUMAN, BOVINE, AND CANINE ARTICULAR CARTILAGE: INHOMOGENEOUS VARIATIONS THROUGH THE DEPTH OF THE CARTILAGE LAYER[a]

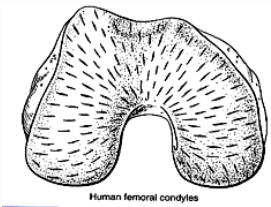
	Bovine		Canine		Human	
	Glenoid	Humerus	Femoral Groove	Femoral Condyle	Femoral Groove	Femoral Condyle
Surface	5.9 (2.4)	13.4 (4.6)	27.4 (8.4)	23.3 (8.5)	13.9 (2.4)	7.8 (1.7)
Middle	0.9 (0.5)	2.7 (1.6)			3.4 (1.4)	4.0 (1.1)
Deep	0.2 (0.2)	1.7 (0.8)			1.0 (0.5)	

[a]All sample harvested in a direction parallel to the local split-line direction. Data are expressed as mean (SD). From Akizuki et al. (7) and Setton et al. (464), with permission. Data on bovine articular cartilage from Ebara et al. (105), with permission.

TABLE 5-5B. EQUILIBRIUM TENSILE MODULUS (MPa) OF NORMAL, FIBRILLATED, AND OSTEOARTHRITIC HUMAN ARTICULAR CARTILAGE: INHOMOGENEOUS VARIATIONS THROUGH THE DEPTH OF THE CARTILAGE LAYER[a]

	Normal	Fibrillated	Osteoarthritic
Surface	7.79 (1.37)	7.15 (1.89)	1.36 (0.09)
Subsurface	4.85 (1.37)	7.47 (0.65)	0.85 (0.81)
Middle	4.00 (1.05)	4.90 (1.03)	2.11 (0.30)

[a]All samples were harvested from the femoral condyle in an orientation parallel to the local split-line direction. Data are expressed mean (SD), from Akizuki et al. (7), with permission.



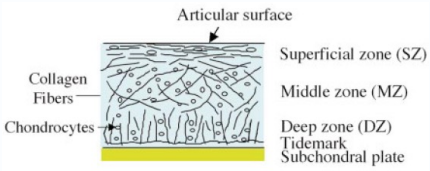
Human femoral condyles

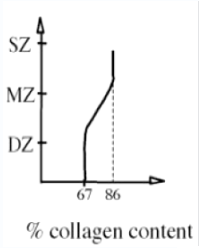
FIG. 3-5

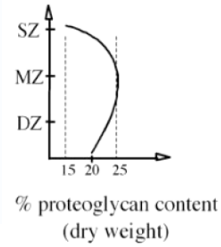
Split lines

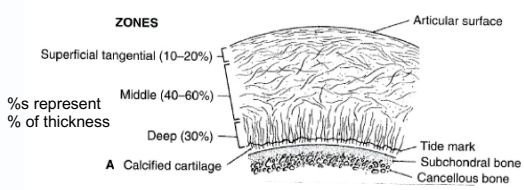
From the table, make some conclusions and/or observations about the tensile modulus of AC. Reasonable exam question:

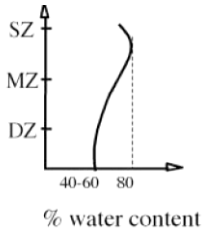
State the observation/conclusion from the table and then rationalize it in 1-2 statements. e.g. more fibers than, less fibers than, more aligned than etc. You would be expected to know and use the information below.











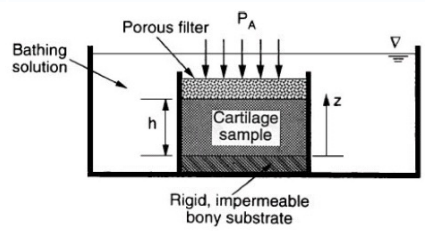
Mow and Guo, Annu Rev Biomed Eng, 2002, 4:175-209

General conclusions about tensile modulus of AC

1. Tensile modulus from SZ measured parallel to split lines is > MZ and DZ
   - SZ has high collagen content
   - SZ fibers are aligned parallel to the surface of the cartilage *and* aligned relative to the split lines.
2. Tensile modulus of normal cartilage > fibrillated > osteoarthritic
   - Morphological disruption from normal to fibrillated to osteoarthritic. This means there is a disruption of the collagen organization and the composition of the cartilage has changed (more on this later…)
3. Tensile modulus of samples aligned parallel to split lines **>** than perpendicular
   - Resistance to tensile load greater along fiber direction because the load is in the direction of the fibers (i.e. fibers are taking the load).
4. We might speculate that the canine SZ has more dense collagen aligned with the split lines compared to human since the modulus is higher. But we cannot make a definitive conclusion across species with the information that we have.

Confined compression experiments for equilibrium compressive properties of the solid matrix – "aggregate modulus," H_A

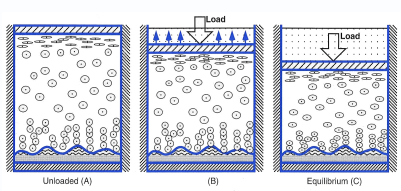
- Ideally frictionless
- Cylindrical sample height, h
- Confined, impermeable ring
- Porous-permeable filter
- Uniaxial applied load (multi-axial stress/strain state due to constraints imposed by wall)
- Rapid initial fluid exudation until equilibrium reached
- Dimensions recovered through
  - Elasticity of solid matrix
  - Fluid imbibition and redistribution in interstices

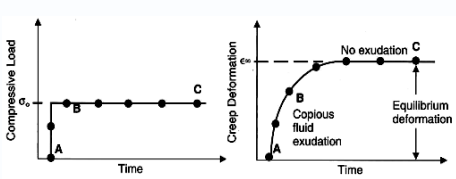


Mow & Guo, Ann Rev Biomed Eng '02

Compressive modulus of solid matrix, called the Aggregate modulus, H_A, can be determined 2 ways

1. Creep experiments

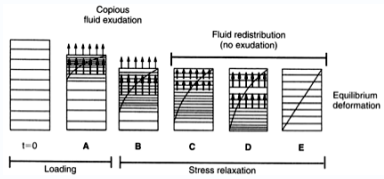


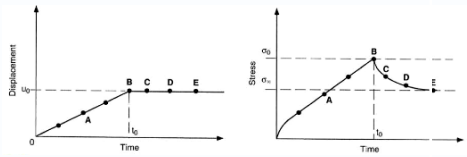


Nordin & Frenkel

Compressive modulus of solid matrix, called the Aggregate modulus, H_A, can be determined 2 ways

2. Stress relaxation experiments





- dislacement rate is cst and = U_o/t_o
- Deformation to Uo, hold
- Stress increases to σ_o
- Then decays until equilibrium is reached
- Initial fluid exudation vs fluid redistribution
  - Forced exudation with large frictional fluid drag through matrix – need high stress to achieve forced compaction
  - After exudation, compressive stress decays as solid redistributes in matrix
  - Stops when stress generated in solid reaches the stress generated by modulus of the matrix

- Physiologically
  - High stress levels difficult to maintain
  - Stress relaxes, attenuates stress

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Values for Equilibrium Aggregate Modulus for Cartilage – *you should have a general sense of this* (i.e. on the order of 0.5-1 MPa)

TABLE 5-9. EQUILIBRIUM AGGREGATE MODULUS (MPa) OF LATERAL CONDYLE AND PATELLAR GROOVE CARTILAGE AND MENISCUS

	Human[a]	Bovine[b]	Canine[c]	Monkey[d]	Rabbit[e]
Lateral condyle	0.70	0.89	0.60	0.78	0.54
Patellar groove	0.53	0.47	0.55	0.52	0.51
Meniscus	NA[f]	0.41	NA	NA	NA

[a]Young normal.
[b]18 months to 2 years old.
[c]Mature beagles and greyhounds.
[d]Mature cynomologus monkeys.
[e]Mature New Zealand White rabbits.
[f]Not available. Data shown were obtained from indentation creep tests.

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