Effect of Poisson's Ratio on the Intrinsic Mechanical Properties of Poly (Vinyl Alcohol) Hydrogels: Preliminary Results

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Statement of Purpose: Physically cross-linked poly vinyl alcohol (PVA) hydrogels have been extensively studied as porous viscoelastic materials for a synthetic cartilage replacement. These physically cross-linked networks can be modified by changing the weight percent PVA, degree of hydrolysis, molecular weight of PVA, freeze/thaw rate, and number of freeze/thaw cycles to generate a range of mechanical properties[1,2]. Wang and coworkers reported the modularity of PVA mechanical strength by varying weight percent PVA and number of freeze thaw cycles to obtain an elastic modulus ranging from 0.001 MPa to 2.117 MPa[2]. Typically, the mechanical properties of PVA hydrogels are described by reporting the elastic modulus or Young's modulus. More descriptive methods for determining the intrinsic mechanical properties for porous viscoelastic materials are described by Mow and Armstrong[3,4,5]. With more relevant mechanical properties, PVA hydrogels may be able to approximate the intrinsic properties of articular cartilage. The aim of this work was to evaluate how physically cross-linked PVA hydrogels may be improved by further understanding their mechanical properties.

Methods: Samples were synthesized using Mowiol® 28-99 at a 30 wt. % PVA solution in deionized water. The PVA was dissolved by stirring at 90 ˚C for 2 to 3 hours. PVA hydrogels were cast into a mold, yielding a cylinder with a diameter of 16 mm and height of 17 mm. Three freeze-thaw cycles were performed by placing the samples in a –20 ˚C freezer for 3 hours, then placing them at room temperature for 3 hours. Unconfined compression testing was conducted between two smooth aluminum plates at a strain rate of 100%/min in water at 37 °C. Each sample was strained to 20% (axial) followed by stress relaxation for a time (t) of 1800 seconds (s). The samples were imaged at 0% (t=0 s) and 20% (t=12.0 s) strain to determine the overall transverse strain. Motic Images Plus 2.0 software was used to measure the sample width from the images. Five specimens were tested with unconfined compression. The Young's modulus was determined from the unconfined compression test by measuring the slope of the linear region in the stress-strain curve. The Poisson's ratio was calculated by dividing the transverse strain by the axial strain. The aggregate and shear modulus were calculated by previously described methods for isotropic linear elastic materials[5]. The stress relaxation response for one sample was plotted for applied load intensity {stress at t [s(t)] over equilibrium relaxed stress, [s_{eq}]} versus normalized time (strain rate * time), as depicted in Figure 1.

Results: The results for the Young's modulus, Poisson's ratio, aggregate modulus, and shear modulus in the PVA hydrogels and previously cited properties of articular cartilage are outlined in Table I. The Young's modulus is within the range of previously reported values for articular cartilage. The Poison's ratio for the PVA hydrogels is outside the range typically observed in articular cartilage. Due to the high Poisson's ratio, the aggregate modulus was on the high end of typically reported values, and the shear modulus was lower than reported values. The shear modulus for the PVA hydrogel agrees with previous work by Stammen[6].

Table I: Intrinsic Mechanical Properties of PVA Hydrogels Subjected to Unconfined Compression

Properties	PVA Hydrogels Results	Articular Cartilage Properties[5]
Young's Modulus, MPa	0.398 ± 0.023	0.3 – 1.0
Poisson's Ratio (Optical)	0.432 ± 0.028	0 – 0.4
Aggregate Modulus, MPa	1.305 ± 0.468	0.35 – 1.0
Shear Modulus, MPa	0.139 ± 0.008	0.23

Figure 1 describes the stress relaxation response for the PVA hydrogels. The response for a material with a Poisson's ratio near 0.45 was predicted by Armstrong for biphasic materials[4]. A material with a Poisson's ratio nearing 0.5 was described to have minimal changes in volume upon compressing with little fluid exudation[4,5].
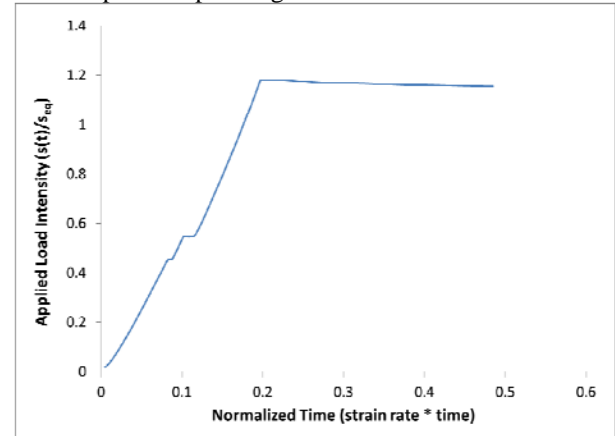

Figure 1: PVA Hydrogel Stress Relaxation Response under Normalized Time and Load

Conclusions: The intrinsic mechanical properties of a 30% PVA hydrogel were determined by measurements in unconfined compression and stress relaxation response. The Poisson's ratio and stress relaxation response describe a highly elastic material with minimal fluid exudation upon compression. PVA hydrogels with increased fluid exudation may better mimic articular cartilage mechanical properties.

References:
1. Baker, M. I. et al., *J. Biomed. Mater. Res. Part B App. Biomater.*, 100, 1451-57 (2012).
2. Wang, B. H. et al., *Spine.* 34, 2745–53 (2009).
3. Mow, V. C. et al., *J. Biomech. Eng. 102,* 73–84 (1980).
4. Armstrong, C. G. et al., *J. Biomech. Eng.* 106, 165-73 (1984).
5. Mow, V. and Huiskes, R. Basic Orthopaedic Biomechanics and Mechano-Biology, 2005.
6. Stammen, J. A. et al., *Biomater.* 22, 799-806 (2001).