Chapter 1

INTRODUCTION

1.1 Surface Properties of Hydrogels

Hydrogels can be either chemical gels or physical gels. In chemical hydrogels hydrophilic polymers are covalently bonded to one another. Such gels can be prepared by polymerizing monomers in the presence of crosslinking agents or by preparing chains with reactive groups and subsequently crosslinking these groups. In physical hydrogels, chains are held together non-covalently. Physical hydrogels include both synthetic hydrogels, such as polymers with hydrophobic end-groups that self-assemble by aggregation of these end-groups, and natural hydrogels, such as agarose and gelatin, which form gels via the formation of helix domains at low temperatures.

Despite the large volume fraction of water present in hydrogels, contact angles measured on hydrogel surfaces are often surprisingly high. On gelatin surfaces that were 15% polymer, for example, advancing contact angles of 75° were measured.[1] These high contact angles illustrate that the polymer component of the hydrogel dominates the gel/air interface. Contact angle measurements performed on hydrogel surfaces can also show very high hysteresis effects: while the advancing contact angle is high, the receding contact angle is low. On 15% gelatin, the receding contact angle is less than 10°[1]. This high hysteresis arises from the mobility of polymers in the gel; once covered with water polymers can reorient themselves to maximize contact of hydrophilic portions of the chain with the water in the drop.

In Chapter 2 thin films of a physical hydrogel are examined. These thin films of PEG end-capped with fluoralkyl groups (termed R_fPEG) illustrate the ability of polymers to change conformations in order to lower the surface energy of the gel/air interface. This change in polymer conformation at the interface is reflected in a change in wetting properties. R_fPEG films are prepared dry and then equilibrated at different levels of relative humidity (RH). Surprisingly, the contact angles of R_fPEG films are found to increase with increasing humidity, meaning the films become more hydrophobic as the water content of the air is increased. Furthermore, the transition that occurs between the low contact angle regime and the high contact angle regime is tied to changes in the crystallinity of the polymer. Contact angle hystersis is also extraordinarily high on these surfaces since they become wetting after contact with water.

In Chapters 3, 4, and 5 a second interfacial property of hydrogels is examined, hydrogel friction. The tribology of hard materials such as metals has been studied for centuries due to the industrial importance of these materials. Study of the tribology of polymers became important in the twentieth century, centering on the friction of elastomers and the friction of polytetrafluoroethane.[2, 3] The tribology of hydrogels, on the other hand, has only been studied by a handful of groups limited to the last few years. This interest in hydrogel tribology reflects their promise as biomedical materials where low friction is required.

One design goal for biomedical materials is development of coatings that are inherently lubricous: once they come into contact with water they do not require the application of extra lubricants.[3] Conventional lubricants have several drawbacks: tubes of lubricants are often reused, increasing the likelihood of cross contamination between patients. Also, once applied, conventional lubricants make it difficult for medical personnel to handle the now slippery surface. The ideal lubricious surface would have a high coefficient of friction when dry for good handling; when in contact with the bodily fluids of a patient, however, the surface would then swell and become lubricious.

To circumvent the toxicity issues of the synthetic hydrogels studied by other groups looking at gel friction, we focus on self-assembled carbohydrate hydrogels. Specifically, we use agarose as our base gel since it forms a strong gel at very low polymer concentrations. Unfortunately, the swelling of dry agarose alone is exceedingly slow. Due to the porous structure of agarose, however, a second polymer can be incorporated into the gel. When this polymer is a polyelectrolyte, the resulting semi-interpenetrating gel is able to swell from a dehydrated state. Unlike other groups, we purposely ensure that this second linear polymer is mobile in the gel so that it can diffuse out of the gel and make the surface self-lubricating. We show that hyaluronic acid (HA), a component of the synovial fluid, is an excellent lubricant for this purpose. Unfortunately, HA is very expensive, so much of the work developing this material is done with a second, cheaper anionic polymer, dextran sulfate. Besides development of a novel semi-interpenetrating hydrogel, we also modify the technique used to measure hydrogel friction. While other groups have measured friction under steady-state conditions, we use transient experiments to measure friction. These experiments are more indicative of real-world biomedical applications of lubricious gels where steady state sliding rarely occurs.

1.2 Hydrophilic Polymers in Solution

We envision that the agarose and HA semi-interpenetrating gels described above would be stored in a dry state. Many applications of HA, however, require that it is stored as a solution. In particular, concentrated solutions of HA are used during intraocular lens replacement to protect the delicate corneal epithelium, maintain the shape of the anterior chamber (the portion of the eye in which the lens is located) during lens removal, and give a lubricious environment to remove and implant lenses. Unfortunately, HA in these solutions (termed viscoelastics) is very unstable, the instability manifesting as highly variable mechanical properties that vex surgeons. Degradation of HA even persists when these viscoelastics are carefully stored in the cold. It would be very advantageous to develop viscoelastics in which the mechanical properties are less sensitive to the degradation of HA and have less stringent storage requirements. HA cannot be eliminated from the formulation because of its positive effects on wound healing.[4]

In Chapter 6 the viscosity of mixtures of HA and other hydrophilic polymers are examined to screen for polymers that are able to enhance the viscosity of HA. A variety of different polymers (synthetic and organic) of differing charge (anionic, cationic, and neutral) and differing abilities to hydrogen bond (hydrogen bond acceptors and hydrogen bond accepters and donors) are examined. The commonality of the polymers that enhance HA viscosity is lack of flexibility: the four polymers for which we observe viscosity enhancement have a persistence length larger than that of HA. Based on increased light scattering it is believed that heightened concentration fluctuations occur when HA is mixed with these more rigid polymers. It is hypothesized that depletion interactions induced by the high molecular weight HA cause aggregation of the more rigid polymers.

Finally, the four appendixes examine the possibility that self-assembly of hydrophilic polymers functionalized with hydrophobic end groups might be controlled with light. Several hydrophobic small molecules have been shown to possess photo-responsive solubility.[5] In molecules like azobenzene, this change in solubility is due to a *trans* to *cis* isomerization upon UV light exposure that increases the dipole moment of the molecule. In malachite green, UV light exposure causes the molecule to change from a neutral form to a charged form. The literature reports on the ability of these molecules to change the solubility, viscosity, and the swelling of water soluble polymers on which they are attached.[6-8] While these observations suggest that photoresponsive hydrophobes might control the equilibrium aggregation state of polymer chains, it has not yet been proven. Both PEG functionalized with azobenzenes and poly(N,N-dimethylacrylamide) functionalized with a vinyl derivative of malachite green are synthesized and studied in an attempt to make polymers that undergo photoresponsive aggregation in solution. Also, PEG copolymers bearing azobenzenes are used to functionalize gold surfaces in an attempt to fabricate materials with photoresponsive wetting properties.

1.3 References

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