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Polymers Functioning as Artificial Muscles

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Current research in the field of polymers has led to the development of synthetic muscles that function similar to biological muscles. Scientists have engineered polymers to contract up to one thousand times their original volume when exposed to changes in light, temperature, voltage, or pH. The ability to contract and relax makes these polymers ideal artificial muscles. Currently, artificial muscles are being applied in the field of robotics. NASA is in the process of developing a dust wiper for their planetary rovers that operates with an artificial muscle. A common goal that many scientists are working towards is the implementation of these synthetic muscles in humans to overcome muscular dystrophy and other muscle related handicaps.

The objective of this project was to synthesize a polymer gel and test its ability to contract and relax when placed in acidic and basic solutions. The subject of research and experimentation for this project was a poly-vinyl-alcohol/poly-acrylic acid (PVA-PAA) polymer gel. A gel is an intermediate between a liquid and a solid which consists of a polymer network and an interstitial fluid. A common property of polymer gels is the ability to undergo abrupt changes in volume by expanding and contracting. The reversible nature of these changes allows the polymer to experience a repetitive cycle of expansions and contractions to automate a human muscle.

The theory that governs the chemical reactions of the volume changes is based on three forces: polymer-polymer affinity, rubber elasticity, and hydrogen ion pressure. (Brock 1991) Polymer-polymer affinity involves the electrical attractions between the polymer (PVA-PAA) and the solvent (acid or base). An attractive force causes the polymer to absorb hydrogen ions or hydroxide ions in the solvent. Rubber elasticity is the tendency of the gel to shrink when placed under tension. Hydrogen ion pressure is a force caused by the movement of hydrogen ions within the gel. Hydrogen ions entering the gel cause it to swell up similar to a balloon's expansion when inflated.

An important characteristic of the polymer is the rate at which it changes volumes. Gel kinetics is a diffusion limited process because the rate at which hydrogen and hydroxide diffuse through the polymer is slower than the kinetics of the hydration and dehydration reactions. Contraction time t is equal to a contraction rate constant c times the square of the diameter d^2 , $t = c(d^2)$. The contraction rate constant is specific to the polymer. (Chiarelli 1988) The constant for PVA-PAA gel may range from 10^6 to 10^9 s/m². This large range shows the sensitivity to varying concentrations of PVA and PAA within the mixture.

An experiment was performed to test the strength and speed of PVA-PAA contractions and expansions when placed in acidic and basic solutions, respectively. The PVA-PAA gel was prepared by mixing together two 10% by weight solutions of PVA and PAA and drying it for two days on a sheet of glass in a desiccator. A problem occurred when the dried polymer could not be removed from the glass plate because the adhesion was too strong. A second batch was made with the same preparation procedure as the first batch; however, the polymer gel was divided into three parts to be dried on glass, plastic, and wax paper. As predicted, the polymer

could not be peeled off the glass. It would also not easily peel off of the wax paper. The plastic surface, however, did work well and the polymer was readily removed. This sample was soft, malleable, and clear.

Once dry, the polymer was placed in an oven at 100°C for 24 hours to catalyze the cross linkage of the polymer chains. The resulting polymer was stiff, brittle, and had turned brown. This unexpected result was most likely caused by a combination of over drying while in the desiccator and over baking while in the oven. The net outcome was a thin film that was too brittle to undergo the volume expansion experiments.

Tests on the contractive strength and speed of the PVA-PAA gel have yet to be performed. These experiments will be done when the preliminary steps of preparing, drying, and cross-linking the polymer are finalized. Future polymer gels will be prepared with a lower concentration of poly-vinyl-alcohol and poly-acrylic acid, 3% to 5% by weight, solution instead of the previous 10% solution. This is to reduce the brittleness of the dried polymer. Also, the polymer will be placed in the oven for a shorter time to prevent excessive dehydration and brittleness. Further experimentation will be done to find the optimum baking time and temperature for the cross-linking procedure.

Although the rate of contraction has not yet been tested, there is evidence to suggest that the rate is quick enough to be comparable to the contractive rate of human muscles. Using the contraction time equation previously defined and the contraction constants 10^6 and 10^9 s/m², the resulting times for a polymer of one centimeter in diameter would be 1.6 minutes and 27.7 hours respectively. Reducing the diameter of the polymer would decrease the time. A polymer with a one millimeter diameter would contract in one second. Further reduction of the polymer diameter would consequently cause volume reductions on the order of milliseconds. The mathematical theory does suggest that PVA-PAA can mimic the speed of biological muscle behavior.

References:

1. Brock, David L., "Review of Artificial Muscle based on Contractile Polymers," Massachusetts Institute of Technology Artificial Intelligence Laboratory, A.I. memo No. 1330, November, 1991.
2. Chiarelli, P. and de Rossi, D., "Determination of Mechanical Parameters related to the Kinetics of Swelling in an Electrically Activated Contractile Gel," *Progress in Colloid and Polymer Science*, Vol. 48, 1988.