

The apparatus **10** comprises a nonionic hydrogel core **11** containing a soluble and ionizable salt, an anionic hydrogel **12**, a cationic hydrogel **13**, and a flexible conductor **14** through which an electric current is applied. Experimentation has revealed that nonionic gels do not contract or relax with changes in the ionic strength to the same degree as ionic gels. Thus, if a direct current is applied with polarity as shown, i.e. with the cationic hydrogel **13** serving as the anode and the anionic hydrogel **12** serving as the cathode, the cation held by the ionizable salt will move from the nonionic hydrogel core **11** into the anionic hydrogel **12** causing it to contract. Simultaneously, the anion held by ionizable salt in the nonionic hydrogel core **11** will move into the cationic hydrogel **13** causing it to also contract. By reversing the polarity of the current, both ions may be made to migrate back into the nonionic hydrogel core **11** causing both the anionic hydrogel **12** and the cationic hydrogel **13** to relax.

In this example, three layers are shown, but those having ordinary skill in the art will recognize that a composite comprising only two layers would produce the same effect. Referring now to FIG. **2**, such an embodiment is shown. The two-layer embodiment is made up of a nonionic hydrogel **11** containing a soluble, ionic salt, in intimate contact with an ionic hydrogel **13**, which may be either an anionic hydrogel or a cationic hydrogel. As was the case with respect to the embodiment of FIG. **1**, passing a current through conductor **14** will result in a contraction or relaxation response appropriate to the polarity of the electric current passed through it.

The hydrogels described with reference to FIGS. **1** and **2** are known in the art and may be prepared in accordance with known methods. For example, an anionic hydrogel suitable for use in this invention may be prepared according to the teachings of Kuhn et. al. in their article "Reversible Dilation and Contraction by Changing the State of Ionization of High-Polymer Acid Networks", *Nature*, vol. 165, no. 4196, pgs. 514-516 (April 1950), incorporated herein by reference. A cationic hydrogel suitable for use in the present invention may be prepared according to the teachings of S. Katayama and A. Ohate, *Macromolecules*, Vol. 18, p2782, (1985), incorporated herein by reference. A nonionic hydrogel suitable for use in the present invention may be polyacrylamide crosslinked with bisacrylamide, according to the procedure described in Tanaka et al., U.S. Pat. No. 5,100,933, incorporated herein by reference. The preferred embodiment of the present invention utilizes a nonionic hydrogel produced using a commercial grade of hydrophilic polyurethane foam due to the elasticity of such foams, though dense polyurethane may also be used to achieve similar results. Regardless of the nonionic hydrogel utilized, suitable soluble ionic salts for disposal within the nonionic hydrogel include sodium chloride, copper sulfate or aluminum sulfate. In embodiments utilizing such salts, an electric potential of about 2 volts per centimeter is suitable to create the desired mobilization. It should be noted, however, that the particular chemistries of the hydrogels and salts discussed herein are cited merely to illustrate particular embodiments of the invention and that other suitable hydrogels or salts will be readily apparent to those of ordinary skill in the chemical arts.

In order to control the effect described herein, the application of a direct current will result in a contraction or relaxation of the ionic gels. However, due to the ionic affinities of the hydrogels employed, the cessation of direct current will not stop the migration of ions and hence not offer proper control. This ionic control problem is inherent with the systems discussed in the Tanaka et. al., Adolf et. al.,

and Shahinpoor patents (U.S. Pat. Nos. 5,100,933; 5,250,167; and 5,389,222 respectively). To overcome this problem, some embodiments of the present invention utilize alternating current to prevent or retard the migration of ions. By cyclically reversing the direction of the current flowing through the apparatus, the ions may be made to migrate back and forth in a predetermined manner to achieve a desired near steady state condition. In addition, the application of a nonsymmetrical alternating waveform can be used to counter the natural tendency of the ionic salt to migrate to the ionic gels. Thus different waveforms may be developed to achieve the desired effect in polymer composites composed of different materials and having different ionic affinities.

Beyond the application of an alternating current control, an additional device for measuring the state of the composites may be attached to an electrical controller to control the voltage supplied to the composite. In some embodiments, this device is a calorimetric device adapted to monitor the concentration of salt in the gels based upon changes in gel color or turbidity. Such devices are common in the chemical arts and may be readily adapted to provide a suitable signal to an electrical controller.

The preferred embodiment, utilizes an imbedded electronic strain gauge to monitor the length of the gel system. These strain gauges, conventionally built into Wheatstone bridge circuits, respond to changes in length by changing the resistance through the gauge. Such a circuit **20** is shown in FIG. **3A**. Circuit **20** is disposed on one layer of the composite **10** such that the end connections **22** move in conjunction with contraction or relaxation of the composite **10**. Movement of the end connections **22** changes the resistance through the circuit **20** and is read by a voltmeter **24**. Voltmeter **24** may be further attached to an electrical controller to control the contractions or relaxations of the composite **10**. As shown in FIG. **3B**, in such an arrangement the electrical controller (not shown) would be programmed to a predetermined set point **30** and would monitor the voltage through the circuit **10**. If the voltage is greater than the set point **32** then the controller will maintain a first polarity **34**. If the voltage is less than the set point **36** then the controller will change reverse the polarity **38**.

While the invention contemplates practice in the form of sheets, the construction may also take the form of rods or fibers. Referring now to FIG. **4**, an embodiment utilizing a cylindrical rod is shown. In this embodiment, a conductive core **32** is coated with layers of a cationic hydrogel **13**, a nonionic hydrogel **11** and an anionic hydrogel **12** respectively and includes an exterior conductive coating **34** that acts as the cathode. Conductive core **32** is placed in electrical communication with conductive coating **34**. As was the case with respect to the embodiments of FIG. **1** and **2**, passing a current through conductor the conductors, here core **32** and coating **34**, results in a contraction or relaxation response appropriate to the polarity of the electric current. In some embodiments, core **32** is a flexible platinum wire that is wound to form an extension spring-like member, while other embodiments utilize cores made from different materials and having different configurations.

While the invention is described as being of a discrete number of layers, devices made from it may contain multiple sheets or bundles of fibers each of which are comprised of the functional layers described above. As shown in FIG. **5**, such an embodiment would include a plurality of composites **10** in common electrical connection to a power source **40** and with each composite **10** separated from one another by an electrically insulating layer **15** such that the passing of a