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Aerogel- A Recent Innovation In Gel

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ABSTRACT

Aerogel is world's lightest material and drug delivery system. Aerogel having more than 15 entries in Guinness Book of the world's record is very low density solid state gel which is derived by replacing the dispersion phase of gel with gas. Aerogels are prepared by sol-gel process to extract liquid component of gel through super-critical drying. This allows the liquid removed without causing the solid matrix in gel to collapse due to capillary action. Aerogel possesses some properties like lowest density, lowest optical index of reflection, lowest electric constant and highest specific surface area. Materials used for preparation of aerogel include silica, metal oxides, organic and biological polymers, carbon nanotubes etc. Both hydrophilic and hydrophobic gels can be prepared. Solvents used for preparation of gel are explosive so, they are replaced by non inflammable liquid carbon dioxide. Applications of aerogel are very wide. Aerogels are used as a composite, as an absorbent, as a sensor, as a catalyst, as a thermal insulator, for improving dissolution properties of some drugs etc.

Keywords: Aerogel, Aerogelification, Thermal insulator

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INTRODUCTION

Aerogel, world's lightest solid material and drug delivery system, was first created by Steven Kistler in 1931. Kistler competed with Charles Learned to see if one of them could replace the liquid inside a jelly jar with gas without causing any shrinkage. Kistler won the bet and published his findings in 1931.¹ Pharmaceutical gels are well known as dense networks of fine particles dispersed in suitable media. Based on the types of dispersion phases, they are sub classified as hydro gels, alcogels and organogels which are dispersions of polymeric materials in water, alcohol and organic solvents respectively. Aerogel, having more than 15 entries in Guinness Book of World Record, is a very low-density solid-state gel which is derived by replacing the dispersion phase of a gel with gas. Aerogels can be made with a density only three times larger than that of air. Aerogel is a low-density solid-state material derived from gel in which the liquid component of the gel has been replaced with gas. Aerogels are produced by extracting the liquid component of a gel through super-critical drying. This allows the liquid to be slowly removed without causing the solid matrix in the gel to collapse due to capillary action, as would happen with conventional evaporation. The first aerogels were produced from silica gels. Kistler's later work involved aerogels based on alumina, chromia and tin oxide. Carbon aerogels were first developed in the early 1980s.(Figure.1)

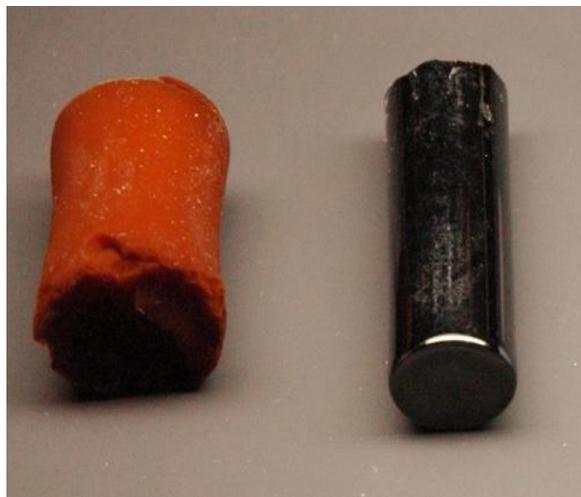


Figure. 1:A resorcinol-formaldehyde polymer aerogel (left) & an electrically-conductive carbon aero gel (right)

Aerogel is a concept of pulmonary drug delivery from a very light weight and highly transparent polymer material which is also known as “Frozen Smoke”, “Blue Smoke”, or “Solid Smoke”. These names suggest its hazy blue appearance as a solid. It has emerged out as one of the most promising means of drug delivery during the past few years.²⁻⁵

Technical Definition

An aerogel is an open-celled, mesoporous, solid foam that is composed of a network of interconnected nanostructures and that exhibits a porosity (non-solid volume) of no less than 50%.

The term “mesoporous” refers to a material that contains pores ranging from 2 to 50 nm in diameter. Generally speaking, most of the pores in an aerogel fall within this size range. In practice, most aerogels exhibit somewhere between 90 to 99.8% porosity and also contain a significant amount of micro porosity (pores less than 2 nm in diameter).

In general aerogels are pretty fragile. Inorganic aerogels are friable and will snap when bent or in the case of very low density aerogels, when poked, cleaving with an irregular fracture. This said, depending on their density, aerogels can usually hold a gently applied load of up to 2,000 times their weight and sometimes more. But since aerogels are so low in density, it doesn't take much force to achieve a pressure concentration equivalent to 2,000 times the material's weight at a given point. The amount of pressure required to crush most aerogels with your fingers is about what it would take to crush a piece of Cap'n Crunch cereal.

Organic polymer aerogels are less fragile than inorganic aerogels and are more like green potting foam in consistency in that they are squish irreversibly. Carbon aerogels, which are derived from organic aerogels, have the consistency of activated charcoal and are very much not squishy.^{7,8}

There are several examples, however, of remarkably strong aerogels that can withstand tens of thousands of times their weight in applied force. A class of polymer-crosslinked inorganic aerogels called x-aerogels is such materials and can even be made flexible like rubber in addition to being mechanically robust (see Flavors of Aerogels). One type of x-aero gel made from vanadia (vanadium oxide) is extraordinarily strong in compression with the highest compressive strength to weight ratio of any known type of aerogel and rivals that of materials such as aerospace-grade carbon fiber composites! Regardless of composition, most types of aerogel can be made stronger simply by making them denser (between 0.1 and 0.5 g cm⁻³), however only at the expense of their light weight and ultralow thermal conductivity.

Special Properties of Aerogels

Many aerogels boast a combination of impressive materials properties that no other materials possess simultaneously. Specific formulations of aerogels hold records for the lowest bulk density of any known material (as low as 0.0011 g cm⁻³), the lowest mean free path of diffusion of any solid material, the highest specific surface area of any monolithic (non-powder) material (up to 3200 m² g⁻¹), the lowest dielectric constant of any solid material, and the slowest speed of

sound through any solid material. It is important to note that not all aerogels have record properties (in fact most don't, although they may have very good values for many properties).

By tailoring the production process, many of the properties of an aerogel can be adjusted. Bulk density is a good example of this, adjusted simply by making a more or less concentrated precursor gel. The thermal conductivity of an aerogel can be also be adjusted this way, since thermal conductivity is related to density. Typically, aerogels exhibit bulk densities ranging from 0.5 to 0.01 g cm⁻³ and surface areas ranging from 100 to 1000 m² g⁻¹, depending of course on the composition of the aerogel and the density of the precursor gel used to make the aerogel. Other properties such as transparency, color, mechanical strength, and susceptibility to water depend primarily on the composition of the aerogel.

For example, silica aerogels, which are the most widely researched type of aerogel (and the type people typically see in photographs), are usually transparent with a characteristic blue cast due to Rayleigh scattering of the short wavelengths of light off of nanoparticles that make up the aerogel's framework. Carbon aerogels, on the other hand, are totally opaque and black. Furthermore, iron oxide aerogels are just barely translucent and can be either rust-colored or yellow.

Records held by some specially-formulated **silica aerogels**:

- Lowest density solid (0.0011 g cm⁻³)
- Lowest optical index of refraction (1.002)
- Lowest thermal conductivity (0.016 W m⁻¹ K⁻¹)
- Lowest speed of sound through a material (70 m s⁻¹)
- Lowest dielectric constant from 3-40 GHz (1.008)
- Record held by a specially-formulated **carbon aerogel**:
- Highest specific surface area for a monolithic material (3200 m g⁻¹)

A more in-depth discussion of the properties of silica aerogel (Figure 2) and other historically underrepresented types of aerogel can be found in the Flavors of Aerogel section.^{7,10}



Figure. 2:A classic silica aerogel monolith

Superiority of Aerogel to Aerosol

Porous gels are prepared from a material which is soluble in pulmonary surfactant. The lower the density difference between the floating particle and the air, the higher are the chances the particle will stay afloat at a given level of air motion. Since the aerogel particles are highly porous (up to 95% filled with the air), they are much lighter than a solid particle and they have much better chances of remaining afloat reaching the innermost alveoli of the lungs and settling on the pulmonary surfactant rather than on the mucous membranes along the way. Since human lungs have an equivalent surface area of a tennis court, it is advisable to take advantage of as much of the surface of the lungs as possible for efficient drug delivery. The air suspension characteristics of the micron and submicron size aerogel particles are determined using a small chamber with a paddle fan.^{11,14}

MATERIALS USED FOR PREPARATION

The term aerogel does not refer to a particular substance, but rather to a geometry which a substance can take on—the same way a sculpture can be made out of clay, plastic, papier-mâché, etc., aerogels can be made of a wide variety of substances including:

- Silica
- Most of the transition metal oxides (for example, iron oxide)
- Most of the lanthanide and actinide metal oxides (Figure.3) (for example, praseodymium oxide)
- Several main group metal oxides (for example, tin oxide)
- Organic polymers (such as resorcinol-formaldehyde, phenol-formaldehyde, polyacrylates, polystyrenes, polyurethanes, and epoxies)
- Biological polymers (such as gelatin, pectin, and agar agar)
- Semiconductor nanostructures (such as cadmium selenide quantum dots)
- Carbon
- Carbon nanotubes
- Metals (such as copper and gold)

Aerogel composites, for example aero gels reinforced with polymer coatings or aero gels embedded with magnetic nanoparticles, are also routinely prepared.¹²⁻¹⁴

Method of Preparation

The Sol-Gel Process:

Sol-gel processing implies the synthesis of an inorganic network by a chemical reaction in

solution at low temperatures or the formation of an amorphous network in opposition to crystallization from the solution. The most obvious feature of this reaction is the transition from a colloidal solution (liquid) into a di- or multiphase gel (solid) that led to the expression “sol-gel process”. (Figure 4)

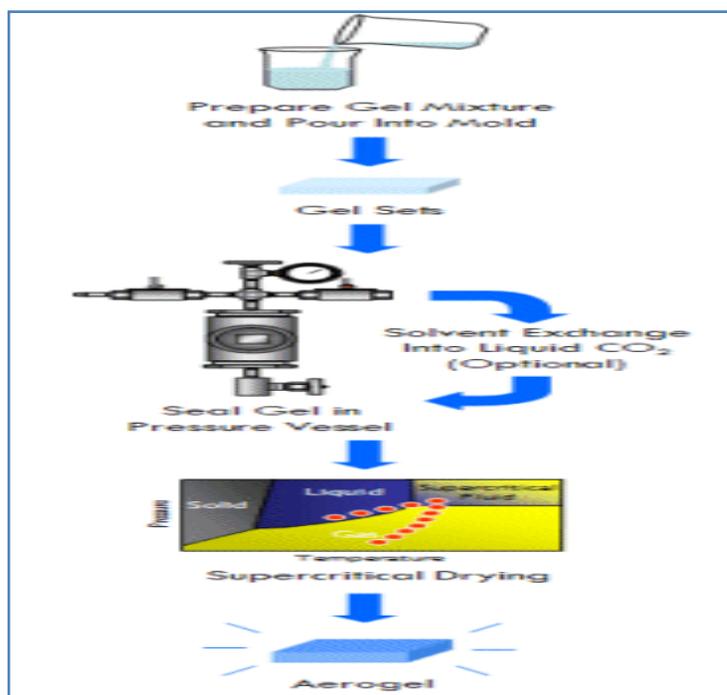


Figure. 4:Sol Gel Process

The formation of uniform suspensions of colloidal particles can be understood by calculation of the sedimentation rates assuming that the particles are spherical so that Stokes' law can be applied. More clearly, a sol is a colloidal suspension of the solid particles in a liquid in which the dispersed phase is small (1–1000 nm). Therefore, the gravitational force is negligible and short-range forces, such as van der waals attraction and surface charges, dominate interactions. The inertia of the dispersed phase is small enough such that it exhibits Brownian motion, a random walk driven by momentum imparted by collision with molecules of the suspending medium. Sol can be prepared by two techniques, condensation and dispersion of particles¹⁶ Condensation proceeds by nucleation growth of particles to the appropriate size, whereas dispersion involves the reduction of large particles down to the colloidal dimensions. The size and properties of the resulting particles depend on the relative rates of these two processes. Sol formation is favored when the rate of nucleation is high and the rate of crystal growth is low. Depending on the degree of cross linking and the growth process by which they are formed, the inorganic clusters can be either colloidal or polymeric in nature and can range from 10 to 200 °A in diameter. Generation of inorganic sols also requires controlled conditions, such that the resulting sol is

stable with respect to agglomeration and precipitation. Several factors, such as polarity of the solvent, ionic strength of the reaction medium and temperature, can be used to manipulate the formation of the sol. Gelation is the process whereby a free flowing sol is converted into a 3D solid network enclosing the solvent medium. A gel is a semisolid rich in liquid. It is interesting to note that liquid does not allow the solid network to collapse, and the solid network does not allow the liquid to flow out. The point of gelation is typically identified by an abrupt rise in viscosity and an elastic response to stress. For preparation of aerogels, the gelation is most conveniently induced through a change in the pH of the reaction solution. The mechanical state of the gel depends very much upon the number of cross-links in the network. It is obvious that the greater the degree of cross-linking, the more rigid the structure formed.^{6,17}

Chemistry of Sol-Gel Process.

There are several parameters which influence the hydrolysis and condensation reactions (sol-gel process), including the activity of the metal alkoxide, the water/alkoxide ratio, solution pH, temperature, nature of the solvent and additive used. Another consideration is that catalysts are frequently added to control the rate and the extent of hydrolysis and condensation reactions. By varying these processing parameters, materials with different microstructures and surface chemistry can be obtained. Further processing of the “sol” enables the fabrication ceramic materials in different forms. Thin films can be produced on a piece of substrate by spin coating or dip-coating. When the “sol” is cast into a mold, a wet “gel” will form. With further drying and heat-treatment, the “gel” is converted into dense ceramic or glass particles. If the liquid in a wet “gel” is removed under supercritical conditions, a highly porous and extremely low-density material called an “aerogel” is obtained. The evidence of silicate hydrolysis and condensation to form polysilicate gel and particles is seen in many natural systems like opals and agates¹⁸. The first metal alkoxide was prepared from SiCl_4 and alcohol by Ebelmen, who found that the compound gelled on exposure to the atmosphere and $\text{Si}(\text{OC}_2\text{H}_5)_4$ can therefore be regarded as the first “Precursor” for glassy materials¹⁹

Precursors for Sol-Gel Processing

The precursor is nothing but the starting materials for the sol-gel process.

- (1) Precursors should be soluble in the reaction media.
- (2) They should be reactive enough to participate in the gel forming process²⁰.

Some salts, oxides, hydroxides, complexes, alkoxides, acylates, and amines are used as precursors if soluble in proper solvents^{21,22}. Alkoxides are the most common sol-gel precursor, since they are commonly available. Bradley et al. Journal of Nanomaterials have well explained

the basic chemistry of the precursor²³. It is very difficult to predict the type of precursor to be used for a given purpose. The reactivity of precursor does not depend only on its chemical nature but also on the applied reaction condition²⁴. Compared to the precursors of other element, the network forming power of Silicon is more to build up a gel¹⁸. That is why other expensive alkoxide precursors can be substituted by cheaper ones like silicon alkoxide such as TEOS, TMOS, and water-soluble precursor such as Na₂SiO₃ for sol-gel processing. Hydrophobic aerogels obtained from the precursor without surface chemical modification are called hydrophobic precursors and that of hydrophilic are called hydrophilic precursor.

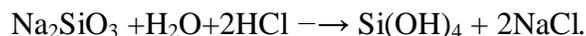


Figure.3: Transition metal oxide aerogels including an iron oxide aerogel

REACTION MECHANISM

For Silicon Alkoxide: Silicate gels are synthesized by hydrolyzing monomeric tetra functional and tri-functional silicon alkoxide precursors employing a mineral acid (e.g. HCl, C₂O₄H₄) or a base (e.g., NH₃, NH₄OH) as a catalyst.^{25,26}

Water Soluble Silicates and Minerals: Sodium silicate (Na₂SiO₃) has been and probably will always be the cheapest source of relatively pure silicic acid from which silica gel can be made. Sodium silicate reacts with water to give silicic acid and then the silicic acid polymerizes and forms silica gel as shown in the following reactions:



Further, there are some reports available on preparation of silica gels using aluminosilicates, calcium silicates, wollastonite, and so forth²⁷⁻²⁹.

It is evident that the structure of sol-gel glasses evolves sequentially as the product of successive hydrolysis and condensation reactions (and reverse reactions, i.e., esterification and alcoholic or hydrolytic depolymerization)¹⁵. Thus, knowledge of mechanisms and kinetics of these reactions will provide insight into the gels and gel-derived glasses. The hydrolysis reaction is catalyzed by

the addition of an acid or a base ^[29]. In fact, the final form of hydrolyzed silica depends on the pH of the solution. At low pH levels (highly acidic), the silica particle tends to form a linear chain with low crosslink density. This leads to a soft gel, which is reversible and can be redispersed in solution. As the pH value increases, the number of cross-links between the polymer chains also increases. At high pH (highly basic), the polymers become more branched and the number of cross-links increases. At low pH, hydrolysis occurs by electrophilic attack on the oxygen atom of the alkoxide group, whereas at higher pH, hydrolysis and polymerization occur by nucleophilic attack on the Si ion (Si^{4+}). Atoms, ions, or groups which have a strong affinity for electrons are termed electrophiles, while positive ions are termed nucleophiles. In general, all electrophiles are oxidizing agents and all nucleophiles are reducing agents. It is generally found that the process of gelation proceeds with smaller segments dissolving and redepositing onto the larger chains so that the smaller molecules decrease in number but assist the larger molecules to grow until they form fractal aggregates. This process is called Ostwald ripening ³⁰.

Preparation of hydrophobic aerogel:

1 liter of soda water glass solution (with 7% w/w of SiO_2 and Na_2O) +0.5 liter of an acidic ion exchange resin (Styrene divinyl benzene copolymer having sulphonic acid groups) until the pH of aqueous solution is 2.3. Ion exchange resin was filtered off and aq. Solution was adjusted to pH 5 by 1M NaOH. Resulting gel is aged at 85°C for further 3 hrs. and water is subsequently replaced by acetone using 3 liters of acetone.

Acetone containing gel was then silylated with trimethylchlorosilane (5% of trimethyl chlorosilane per gram of dry gel). the gel was dried in air. (3 hrs. at 40°C, then 2 hrs at 50°C & 12 hrs at 150°C). The transparent aerogel thus obtained had a density of 0.15g/cm³, its specific surface area was 480 m²/g and it was permanently hydrophobic.¹⁴

Preparation of hydrophilic aerogel:

Permanent hydrophobic aerogel as prepared above was paralyzed for 1 hr at 600 °C in a gentle stream of air by means of a tube furnace.

The transparent aerogel was obtained had density of 0.18 g/cm³, surface area 450 m²/g and was hydrophilic.¹⁴

Supercritical Drying

In general, supercritical drying is used when liquid needs to be removed from a sample that would be damaged by evaporative or other drying techniques. Biological specimens, for example, are often preserved through supercritical drying.

Supercritical drying is a clever technique by which we can pull the rug out from under capillary action. As mentioned earlier, capillary action induced by liquid evaporating from a gel's pores causes the gel to shrink. So what if there was some way to avoid capillary forces to begin with? This is where supercritical drying comes in.

All pure substances (that won't decompose) have what's called a critical point—a specific and characteristic pressure and temperature at which the distinction between liquid and gas disappears. For most substances, the critical point lies at a fairly high pressure (>70 atmospheres) and temperature (>400°F). At the critical point, the liquid and vapor phases of a substance merge into a single phase that exhibits the behavior of a gas (in that it expands to fill the volume of its container and can be compressed) but simultaneously possesses the density and thermal conductivity of a liquid. This phase is called a supercritical fluid.

Say we have a sealed container containing a liquid below its critical point inside and equipped with a pressure gauge on top. In fact, a certain amount of liquid will evaporate in the container until the vapor pressure of the liquid is reached in the container, after which no more liquid will evaporate and the gauge will read a corresponding stable pressure. Now if we heat this container, we will notice the pressure in the container increases, since the vapor pressure of a liquid increases with increasing temperature. As the critical point draws near, the pressure in the container squeezes molecules in the vapor close enough together that the vapor becomes almost as dense as a liquid. At the same time, the temperature in the container gets high enough that the kinetic energy of the molecules in the liquid overwhelms the attractive forces that hold them together as a liquid. In short, as the pressure and temperature in the container get closer to the critical point, the liquid phase becomes more gas-like and the vapor phase more liquid-like. Finally, the critical point is reached and the meniscus dividing the two phases blurs away, resulting in a single supercritical phase. As this occurs, the surface tension in the fluid gradually drops to zero, and thus the ability of the fluid to exert capillary stress does too.

Aerogelification

In the case of making aerogels, a gel is placed in a pressure vessel under a volume of the same liquid held within its pores (let's say ethanol for example). The pressure vessel is then slowly heated to the liquid's critical temperature. As this happens, the vapor pressure of the liquid increases, causing increase in the pressure in the vessel and approach the critical pressure of the liquid. The critical point is then surpassed, gently transforming the liquid in the gel (as well as the liquid and vapor surrounding the gel) into a supercritical fluid. Once this happens, the ability of the fluid in the gel to exert capillary stress on the gel's solid framework structure of the gel

has decreased to zero.

With supercritical fluid now present throughout the entire vessel and permeating the pores of the gel, the fluid in the gel can be removed. This is done by partially depressurizing the vessel, but not so much as to cause the pressure in the vessel to drop below the critical pressure. The temperature of the vessel must also remain above the critical temperature during this step. The goal is to remove enough fluid from the vessel while the fluid is still supercritical so that when the vessel is fully depressurized /cooled down and drops below the fluid's critical point, there will simply not be enough substance left in the vessel left for liquid to recondense. This might require several cycles of heating (and thus pressurizing) followed by depressurization (again all done above the critical point). Once enough fluid has been removed from the vessel, the vessel is slowly depressurized and cooled back to ambient conditions. As this happens, the fluid in the vessel passes back through the critical point, but since much of the fluid has been removed and the temperature is still elevated as the vessel depressurizes, the fluid reverts to a gas phase instead of a liquid phase. What was liquid in the gel has been converted into a gas without capillary stress every arising and an aerogel is left behind. (Figure.5)

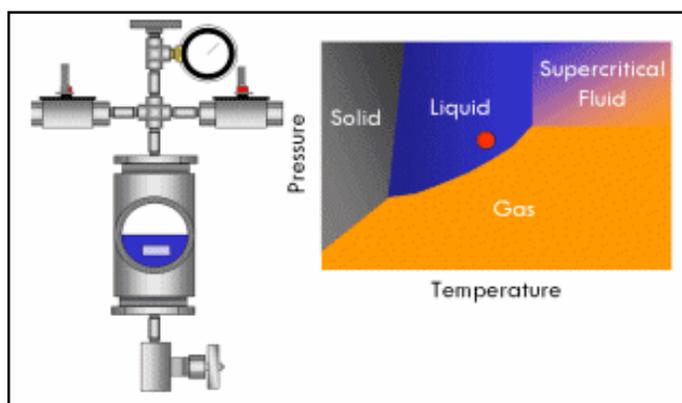


Figure.5:Aerogelification

It is important to note, however, that most of the liquids used in the preparation of gels are organic solvents such as methanol, ethanol, acetone, acetonitrile and such liquids are potentially dangerous at the temperatures and pressures required to make them supercritical. To make the aerogelification process less dangerous, the liquid component of a gel can be exchanged with a non-flammable solvent that mixes well with organic solvents—liquid carbon dioxide.^{26,29}

APPLICATIONS

Aerogel as a Composite.

As silicon alkoxide precursor is reactive enough to form gel networks with other metal oxides, several studies were carried out to synthesized silica aerogel composites for various applications.

Structural and magnetic properties of silica aerogel-iron oxide nanocomposites were studied by Casas *et al.*^{16, 17}

Aerogel as an Absorbent.

Synthesis of flexible and super hydrophobic aerogels and their use in absorption of organic solvents and oils were studied by A. Venkateshwara Rao *et al.* They investigated the absorption and desorption capacity of super hydrophobic silica aerogels using eleven solvents and three oils.^{21, 22}

Aerogel as a Sensor.

Aerogels have high overall porosity, good pore accessibility, and high surface active sites. They are therefore potential candidates for use as sensors. A study by Wang *et al.*²³ on silica nanoparticle aerogel thin films showed that their electrical resistance markedly decreases with increasing humidity. They are highly sensitive to 40%RH and greater and operate with a 3.3% hysteresis, which is attributed to their pore structure. Xerogels of the same material, on the other hand, show very low sensitivity (Figure 6).

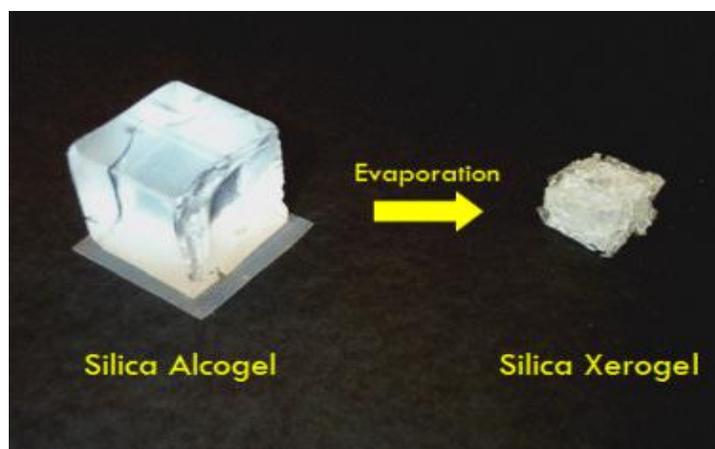


Figure.6:Xerogel

Surface modified aerogels are less affected by humidity as compared to hydrophilic aerogels and can be used as anticorrosive, hydrophobic agents²⁴ Wub and Chen-yang studied aerogels for biosensor applications. In this study, mesoporous aerogels were prepared at room temperature by sol-gel polymerization with an ionic liquid as the solvent and pore-forming agent. The as prepared aerogel was characterized by different instruments (a) Before absorption (b) Immediately after absorption, $t = 0$ min (c) At $t = 20$ min (d) At $t = 30$ min. (e) After desorption, $t = 40$ min. The as-prepared aerogel was further arrayed onto slides and successfully recognized a short human gene ATP5O by an immobilized oligonucleotide probe on the aerogel surface. The large capturing capacity of the porous structure was also demonstrated by comparing with a

planar surface at high target concentrations. The results indicate that the as prepared aerogel can function as a recognition substrate for nucleotide acids. This report proposes a preparation technique to synthesize mesoporous aerogel using the sol gel process and utilize the aerogel's high surface area and large internal porous volume for molecular recognition of nucleotide acids.²⁵

Aerogel as Material with Low-Dielectric Constant.

SiO₂ aerogel thin films have received a significant attention in IC applications because of their unique properties such as their ultralow dielectric constants, high porosity, and high thermal stability. Park et al. investigated silica aerogel thin films for interlayer dielectrics, and the dielectric constant was measured to be approximately 1.9. They produced ultra low dielectric constant aerogel films for intermetal dielectric (IMD) materials. The SiO₂ aerogel films having a thickness of 9500 Å, a high porosity of 79.5%, and a low dielectric constant of 2.0 were obtained by a new ambient drying process using n-heptane as a drying solvent.²⁵⁻²⁹

Aerogel as Catalysts.

The high surface area of aerogels leads to many applications, such as a chemical absorber for cleaning up spills. This feature also gives it a great potential as a catalyst or a catalyst carrier. Aerogels aid in heterogeneous catalysis, when the reactants are either in gas or liquid phase. They are characterized by very high surface area per unit mass, high porosity which makes them a very attractive option for catalysis. Some of the reactions catalyzed by aerogels are listed below.

Some examples of aerogels in catalysis

- 1) Synthesis of nitrile from hydrocarbons using nitric oxide (NO)³⁰.
- 2) Isobutene can be converted into methacrylonitrile by reacting it with NO on zinc oxide aerogel³¹.

Aerogel as a Storage Media.

The high porosity and very large surface area of silica aerogels can also be utilized for applications as gas filters, absorbing media for desiccation and waste containment, encapsulation media, and hydrogen fuel storage³¹. Partially sintered aerogels can resist the tensions of a gas/liquid interface because their texture is strengthened during sintering. They can therefore be used for the storage, thickening, or transport of liquids, for example, rocket fuels. In the latter case, the low weight of aerogels is particularly advantageous. Aerogel can be used in drug delivery systems due to their biocompatibility.³³ Carbon aerogels are used in the construction of small electrochemical double-layer super capacitors. Due to the high surface area of the aerogel,

these capacitors can be 1/2000th to 1/5000th the size of similarly rated electrolytic capacitors. Aerogel supercapacitors can have very low impedance compared to normal supercapacitors and can absorb or produce very high-peak currents. At present, such capacitors are polarity-sensitive and need to be wired in series if a working voltage of greater than about 2.75V is needed.³⁴

Aerogel as a Template.

Hupp et al. used silica aerogel films for dye sensitized solar cells. High surface area mesoporous aerogel films were prepared on conductive glass substrates. Atomic layer deposition was employed to coat the aerogel template conformally with various thicknesses of TiO₂ with sub nanometer precision. The TiO₂-coated aerogel membranes were incorporated as photo anodes in dye-sensitized solar cells. The charge diffusion length was found to increase with increasing thickness of TiO₂ leading to increasing current and efficiency.³⁵

Aerogel as a Thermal Insulator.

Apart from high porosity and low-density one of the most fascinating properties of aerogels is their very low thermal conductivity. Aerogels possess a very small thermal conductivity, 1–10% that of a solid, additionally, they consist of very small particles linked in a 3-dimensional network with many “dead-ends”. Therefore, thermal transport through the solid portion of an aerogel occurs through a very tortuous path and is not particularly effective. The space not occupied by solids in an aerogel is normally filled with air (or another gas) unless the material is sealed under vacuum. These gases can also transport thermal energy through the aerogel. The pores of aerogel are open and allow the passage of gas (albeit with difficulty) through the material.

In Housing, Refrigerators, Skylights and Windows:

Silica aerogels can be synthesized using low cost precursors at ambient pressure which makes aerogels suitable for commercialization. Aerogels transmit heat only one hundredth as well as normal density glass. The first residential use of aerogels is as an insulator in the Georgia Institute of Technology’s Solar Decathlon House, where it is used as an insulator in the semitransparent roof.

In Clothing, Apparel and Blankets.

Commercial manufacture of aerogel “blankets” began around the year 2000. An aerogel blanket is a composite of silica aerogel and fibrous reinforcement that turns the brittle aerogel into a durable and flexible material.

In Space.

NASA used aerogels to trap space dust particles aboard the Stardust spacecraft. The particles

vaporize on impact with solids and pass through gases, but can be trapped in aerogels. NASA also used aerogel for thermal insulation of the Mars Rover and space suits. The US Navy is evaluating aerogel undergarments as passive thermal protection for divers.³⁶⁻³⁸

CONCLUSION

The unique optical, thermal, acoustic and mechanical properties of aerogels originate from the combination of a solid network and nanosized pores filled with air. The choice of the precursors and the optimization of sol-gel parameters determine the physical properties of the final aerogel product. Drying of the aerogels is carried out with supercritical or ambient pressure drying methods, depending upon the commercial aerogel application. An extensive chemical modification provides a new space for studying the property of aerogels. Ambient pressure drying techniques will probably make industrial preparation much cheaper and will thus make aerogels more competitive. The most important area for the application of aerogels is in all kinds of thermal insulation. Also, SiO₂ aerogels have some physical and ecological advantages (nontoxic, nonflammable, easy to dispose of) compared with most of other materials in the market.

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