SMART EFFICIENT LIGHTWEIGHT FACADE

INNOVATIVE MATERIAL GUIDE
VOL 1

SELF

Smart Efficient Lightweight Facade

Innovative Material Guide

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The purpose of the manual is to describe and demonstrate innovative materials for an efficient, lightweight and smartly working facade.
We explain their current state and their technological progress so the readers would grasp the knowledge and apply it to future design projects, contributing to the materials´ further development.

WHY Smart Efficient Lightweight Facade?

Smart

Today, with the advancement of technology, different materials can be chosen as part of a design pallette so it can be applied as compositional and visual surfaces by the architects. Logical trajectory of material development towards having selective and specialized performance lead to smart materials.

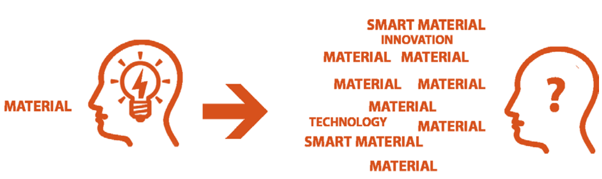
Smart materials are those that their properties can change in respect of external conditions such as light, temperature, pressure etc.

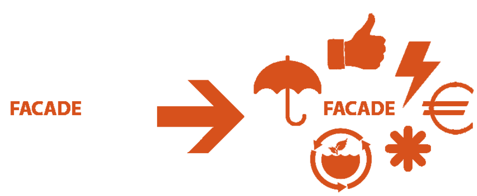
On the other hand, there are a lot of **innovative materials** that can offer interior comfort, even if they are not in the category of smart materials.

The manual focuses on materials that can be **used in a smart way** to achieve the desired interior conditions.

Efficient

Efficiency translated into design principles is referred to saving energy, mainly through passive strategies. Sealing the shell/facade of a building with the use of specific materials makes possible the elimination and/or control of the **transmission of energy** between inside and outside.





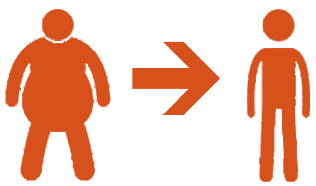
Lightweight

The amount of materials used, the transportation energy, the costs and the total envelop mass are significant parameters for the building industry.

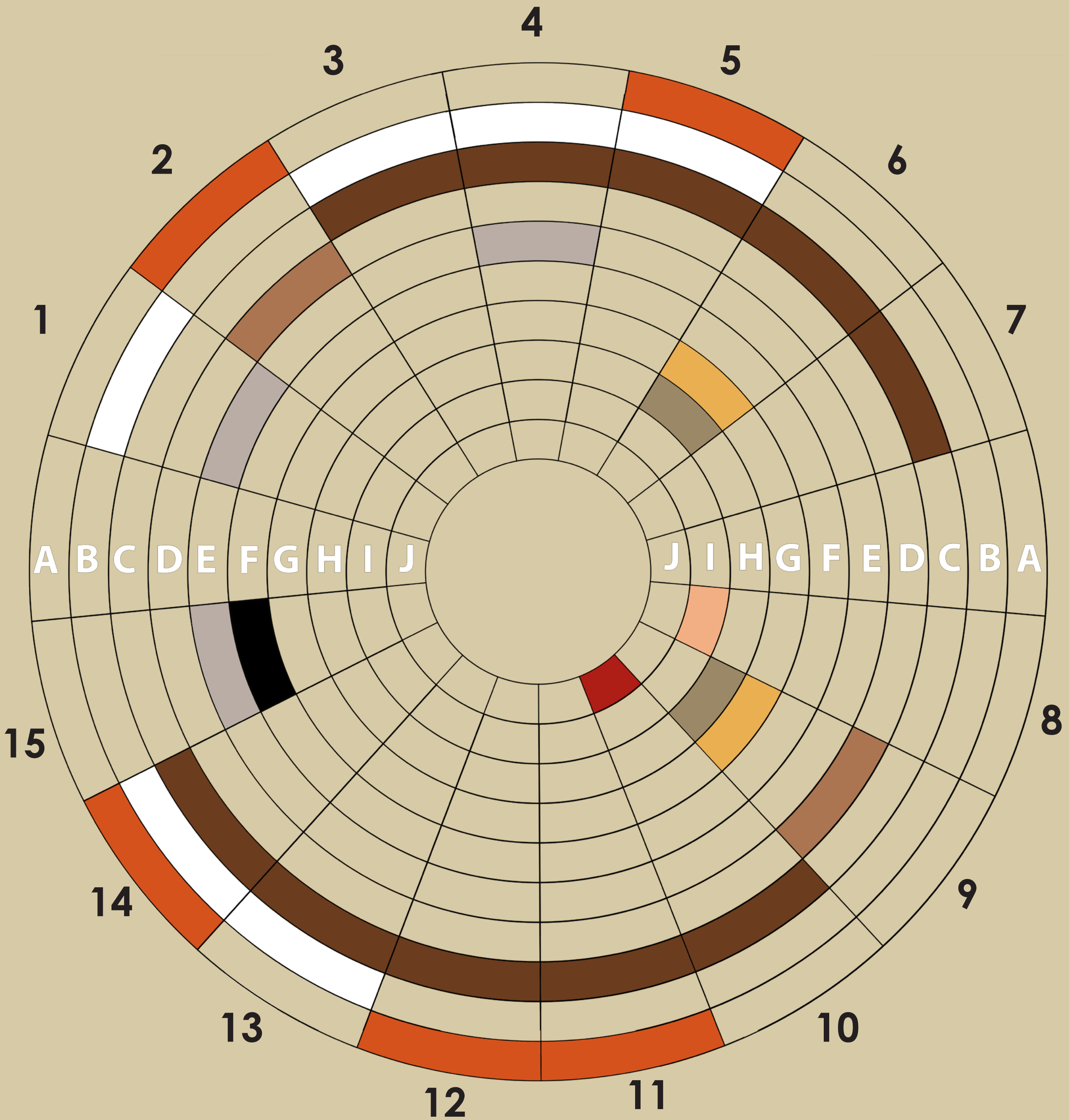
Lightweight constructions require less amount of materials, while burden the main structure with less loads. Designing and applying lightweight envelopes encourages the **sustainability** factor and at the same time promotes the total **architectural appearance** of the building.

Facade

The design of the façade is one of the controversial subjects in the design of a building. Whereas a lot of attention is given to the design of the main building and its structure/construction, the façade has major impact on the energy efficiency, the inside air quality and comfort of the residents as well as the interaction of the interior with the exterior space. Thus, it is extremely important to consider the principles of an efficient envelope while designing.



GUIDE



- A - Aesthetic appearance of building envelope
- B - Daylight provision
- C - Control of solar radiation transmission
- D - Energy generating
- E - Thermal insulation
- F - Acoustic insulation
- G - Monitoring structural performance
- H - Control of structural vibration
- I - Improving air quality
- J - Energy storage

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TECHNOLOGY READINESS LEVEL

System test, launch&operations	(8 - 9)
System development	(6 - 8)
Technology demonstration	(5 - 6)
Technology development	(3 - 5)
Research to prove feasibility	(2 - 3)
Basic technology research	(1 - 2)

* The estimations of Technology Readiness Level are based on personal research and material evaluation.
For more informations about TRL visit: http://en.wikipedia.org/wiki/Technology_readiness_level

ICONS

Lightweight

Low density e.g. about 10mg/cm^3

Thermal resistant

Prevention of heat transmission

Strong

No failure under load
No permanent deformation

UV resistant

Prevention of solar radiation transmission

Flexible

Ability to deform/bent under load

Water resistant

Prevention of water transmission

Durable

Long lifespan (more than 10 years)

Sound barrier

Prevention of sound transmission

Easy assembly

Installation and assembly without special requirements and equipments

Flammable

Easily burnt/fire spread

Recyclable

Reuse at the end of life with the same or different properties

Economic

Low cost for purchase, assembly, maintenance and operation

1.AEROGEL

Definition

"Aerogel is a **synthetic** porous **ultralight** material derived from a gel, in which the liquid component of the gel has been replaced with a gas. The result is a solid with extremely low density and low thermal conductivity." [1]

It was first created by Samuel Stephens Kistler in 1931, as a result of a bet with Charles Learned over who could replace the liquid in "jellies" with gas without causing shrinkage.

Aerogel is a silicon dioxide "gel" obtained through the "sol-gel" chemical technique and then dried in supercritical conditions. This allows the liquid to be slowly dried off without causing its matrix to collapse, as would happen with the conventional evaporation. The first aerogels were made out of silica gels. Kistler's later work involved aerogels based on alumina,chromia and tin dioxide. Carbon aerogels were first developed in the late 1980's.[1]
The result of the processes is a three-dimensional **amorphous solid matrix** made of SiO^2 particles with average diameter of 10 nm and open nanopores of 1 to 100nm (1nm = 1 millionth of a mm).
The obtained, extremely porous, structure is what gives rise to the **exceptional lightness** (its volume is 95-99% air, or other gas) and **insulation performance**, typical of the aerogel.

Remarks

Silica-based aerogels are not known to be carcinogenic or toxic. However, they are a **mechanical irritant** to the eyes, skin, respiratory tract, and digestive system. Small silica particles can potentially cause silicosis when inhaled. They also can induce dryness of the skin, eyes, and mucous membranes. Therefore, it is recommended that protective gear including respiratory protection, gloves and eye goggles be worn whenever handling aerogels. However, when aerogel is used it is usually **prefabricated** so the users **don't come in contact**. [2]

Silica aerogels appear to have **interesting optical properties.** The radiationwithin the range of visible light is highly transmittable, while the reflected light appears bluish and the transmitted light slightly yellow. The scattering of the light depends on the size of the so-called `scattering centers`-certain number of pores in the material. Different wavelengths of radiation will scatter with different magnitudes.

Special feature!

Aerogel is the **lightest solid ever conceived** by weighing approximately 3 times the air.

Properties

Aerogels exhibit properties and behaviours **closer** to those of a **gas** rather than to those of a solid. Aerogels are characterized by: [2]

- thermal insulation: good conductive insulators, good convective inhibitors, poor radiative insulators.
- friability: extremely durable, but at the same time extremely fragile. It can usually hold a load up to 1000 times its weight or even more, but if it's handled roughly or bent, it will collapse just like glass.
- transparent to translucent visual effect
- production costs that allow their use in a wide range of applications, due to the commercialization on a large scale.

Especially silica aerogels hold records for: 2

- Lowest density solid (0.0011 g cm^{-3})
- Lowest optical index of refraction (1.002)
- Lowest thermal conductivity (0.016 W/mK)
- 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

Innovation

A **heating treatment** to the aerogels can increase their transparency with 6% to a value of 76% due to the water desorption and the burning of the organic components. [9]

Table 1. Properties of aerogels.[2]

Bulk density	3-35 Kg/m^3
Internal surface area	600-1000 m^2/g
Thermal conductivity	0.013-0.0042 W/mK
Thermal tolerance	up to 500°C
Thermal expansion coefficient	2-4 x 10-6
Tensile Strength	16 kPa
Sound speed in the medium	100 m/s

Table 2. Relation between Ug-value and inclination of glazing.[4]

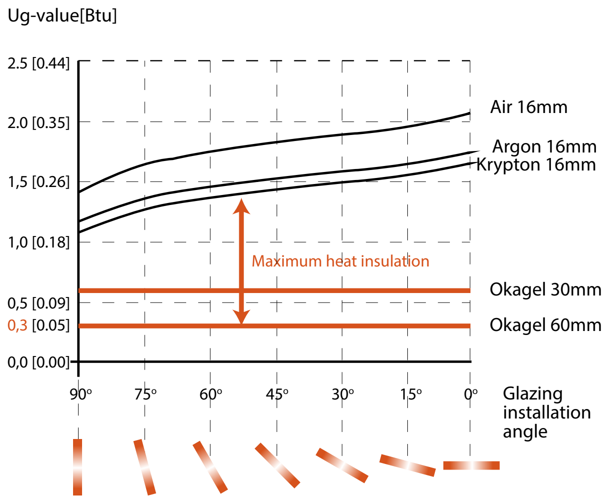
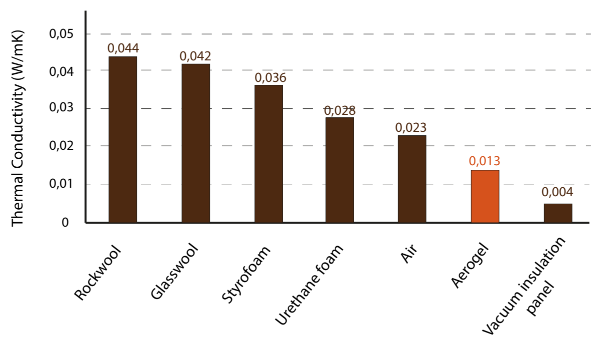


Table 3. Thermal conductivity of aerogel and other conventional insulation materials.[4]



Applications

Aerogels are applied in a variety ofindustrial as well as architectural examples: [1,3]

- Renovation and thermally insulation of old and historic buildings and structures to meet the energy standards, due to the outstanding properties of Fixit 222 Aerogel high-performance insulating plaster. It is **equally suitable for indoor and outdoor use**. In new buildings the high-performance plaster can also be used on highly insulating brickwork. Depending on the bricks used, a 3 to 5 cm layer of Fixit 222 is sufficient to achieve Minergie-standard insulating levels.
- In granular form to add insulation to skylights. Georgia Institute of Technology's 2007 Solar Decathlon House project used an aerogel as an insulator in the semi-transparent roof.
- A chemical adsorber for cleaning up spills.
- Commercial manufacture of aerogel 'blankets' began around the year 2000, combining silica aerogel and fibrous reinforcement that turns the brittle aerogel into a durable, flexible material. The mechanical and thermal properties of the product may be varied based upon the choice of reinforcing fibers, the aerogel matrix and opacification additives included in the composite.
- NASA used aerogel for thermal insulation of the Mars Rover and space suits.
- Highly insulated openings at the British Research Station "Halley VI" in Antarctica. (U value = 0.3 W/mK)

Further readings

- www.cabot/corp.com/Aerogel

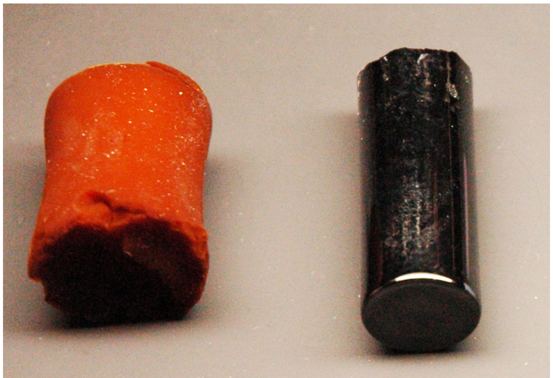


Fig 1

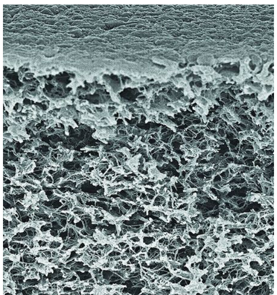


Fig 2

Fig 3

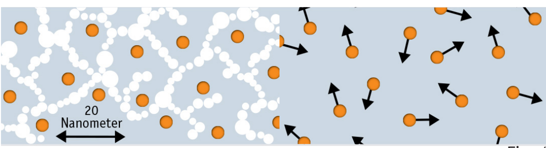


Fig 4

Fig 5

Fig 6

Fig 1. A resorcinol-formaldehyde polymer aerogel and an electrically-conductive carbon aerogel. [2]

Fig 2. The nano-sized cell structure of NASA's new polymer aerogel. The average cell size is about 10nm. [4]

Fig 3. A flexible, mechanically strong silica aerogel made from methyltrimethoxysilane. [2]

Fig 4. The restricted movement of the gas molecules in aerogels reduce heat conduction. [5]

Fig 5. Superinsulating properties of silica aerogel by insulating a delicate, moist flower from the raging heat of a Bunsen burner. [2]

Fig 6. A 2.5 kg brick is supported on top of a piece of aerogel weighing only 2 grams. [6]

Reference projects

Glazing systems incorporating aerogel insulation can offer architects and building owners **affordable and practical options** in a variety of fenestration systems, satisfying the relevant building codes and bringing diffuse light indoors.

The new Art Museum, known as the **Eli & Edythe Broad Art Museum**, at Michigan State University is a dramatic sculpture of angled stainless steel and glass. Designed by Zaha Hadid, special attention was paid for the three storey foyer with the big skylight as far as the diffuse light and the insulation concerned. The skylight is filled with silica aerogel having a **translucent effect**. The aerogel achieves a perfect combination of diffuse daylight inside the space with its very good energy performance.[7]

In order to understand even more the possibilities of aerogel, we indicate its application to an extreme environment such as Antarctica and the British **Research Station Halley VI**. The weather conditions in Antarctica include low temperatures, such as -58°C, and winds that can excess the 100mph (160km/h). In order to maximize the performance, without compromising insulation, the **Okagel glass cladding system** has been filled in with Lumira aerogel of 60mm. The Ug value of the 60mm aerogel is thus really low, 0.3 W/mK. The light transmission is 45% and the soundproofing effect is more than 52dB. [8]

Fig 7

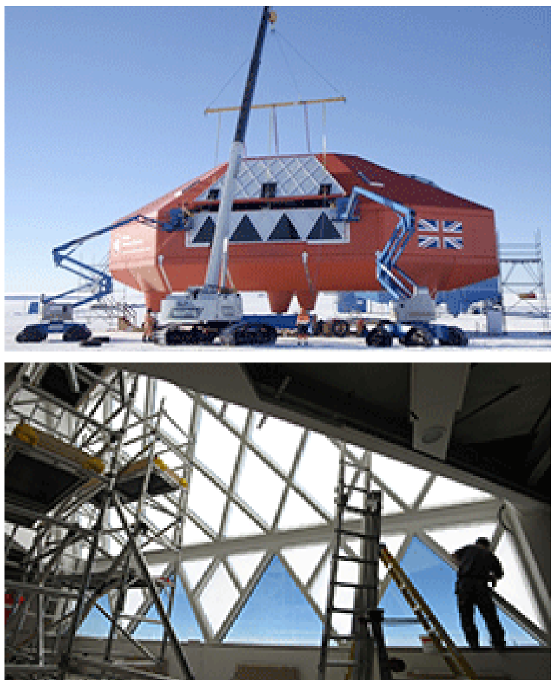


Fig 8

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Sivert Uvsløkk, Arild Gustavsen, 'Vacuum insulation panels for building applications: A review and beyond', Energy and Buildings, Elsevier, 2010

Fig 7. The skylight of Eli & Edythe Broad Art Museum. [7]
Fig 8. Halley VI aerogel window. [8]

2.DYE-SENSITIZED SOLAR CELL

Definition

Dye-sensitized solar cells (DSSC, DSC or DYSC) are **low-cost solar cells** belonging to the group of thin film solar cells. They use a photoelectrochemical system, which is based on a semiconductor formed between a photo-sensitized anode and an electrolyte. The modern version of a dye solar cell, also known as the Grätzel cell, was originally co-invented in 1988 by Brian O'Regan and Michael Grätzel. Michael Grätzel has been awarded the 2010 Millennium Technology Prize for this invention. [1]

DSCs **produce energy** through an artificial photosynthesis. The leaf structure is replaced by a porous titania nano/structure and the chlorophyll by a long/life dye. This makes a two/step process, unlike the one/step of the conventional PV. The layers they are engineered of are: a photosensitive layer made of ultrathin, nano-sized semiconductor crystals over a thin layer of titanium dioxide. When photons (from sunlight) hit the first layer, the freed electrons accumulate on the layer of titanium dioxide and create an electrical current. In the newest generation of DSC, a dye made of amorphous organic material is coating the titanium dioxide and carries the electrons from one layer to the other. The dye absorbs the light and attracts the electrons generating a charge. [2]

In contrast to the conventional systems, where both tasks of light absorption and charge carrier transport are carried through the semiconductor, in DSCs the **two functions are separated**. Light is absorbed by a sensitizer, which is attached to the surface of a semiconductor. Charge separation takes place at the interface via photo-induced electron injection from the dye of the solid. The use of sensitizers in combination with oxide films of nanocrystalline morphology permits harvesting a large fraction of sunlight. [3]

Special feature!

DSC remains efficient even when its orientation and its inclination angle is far from optimum. They can **work efficiently** under light levels around **30% - 50% of full sun**, which is a typical available light at a side of a building. That makes them really efficient for the use on a facade. [4]

Remarks

Generation of electric current with little light, can be used in low to medium temperatures (< –20°C to > +80°C), relatively long replacement life (approx. 500 to 5000 hours), but still such a lifespan is considered to be not that long.

A main disadvantage of dye solar cells can be the **low efficiency** as they are still **under research** for further investigation and development (< 5 % under standard testing conditions). Furthermore, they cannot be bent or curved or handled like conventional glazing, e.g. cut to shape. Also, no leakage is allowed between the edges of two glass substrates. Otherwise a long-term functionality is not guaranteed. [5]

Properties

Dye Solar Cells are made from **very thin layers** which are applied to a substrate (such as steel of glass). The three main layers of electrolyte, titania and ruthenium are encapsulated or sandwiched between glass. One of its key materials is the nano-structured titanium dioxide (TiO2), which offers **unique electric, mechanical and optical properties**.

Compared to conventional silicon based PV technology, DSC's technology has: [5]

• lower cost and embodied energy in manufacture due to its nanotechnology basis,
• produces electricity more stably in low light
• can be directly incorporated into buildings by replacing conventional glass panels rather than taking up roof or extra land area
• no need to use high-priced raw materials
• no toxic emissions during the production process.

DSC can be found in solid or liquid state. The different characteristics are indicated in the table 3.

Innovation

DSCs used to be fragile especially at the edges of the cells. A technology recently developed from the Fraunhofer Institute of Solar Energy Systems (Freiburg, Germany) ensures that the cells are now **stable for 10 or more years**. In that way, the cells are sealed by a glass solder to prevent leakage of liquid electrolyte while protecting sensitive internal components from premature degradation. [5]

Table 1-2. Collected energy during a clear sky (06/11/2011) and a cloudy day(21/10/2011) in UK.[6]

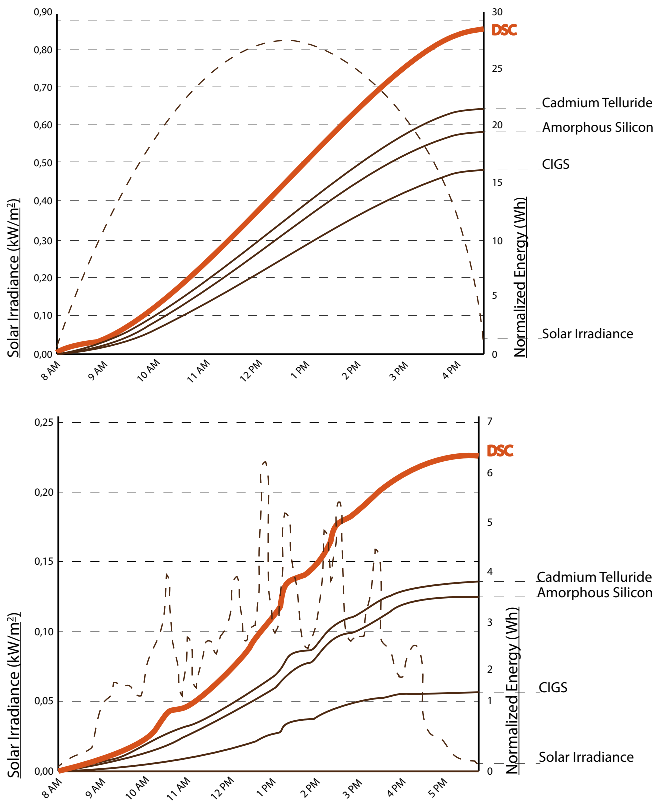


Table 1. 30-70% more enrgy collected by the DSC
Table 2. 65-300% more energy collected by the DSC

Table 1. Characteristics of solid and liquid DSC.[4]

CHARACTERISTICS	SOLID STATE DSC	LIQUID DSC
Expected efficiency by 2018 (based on active area)	18-20%	14-15%
Costs	Lower than Si PV likely lower than liquid DSC	Lower than Si PV likely higher than solid DSC
Complexity of manufacturing equipment	Much lower than Si PV likely lower than liquid DSC	Much lower than Si PV likely higher than solid DSC
Cell-to-cell sealing requirements	Low, electrical insulation mainly	Higher, assuring chemical compatibility between electrolyte and seal
Optional transparency	YES (grey:highest efficiency, coloration: no drastically affecting stability)	YES (red: highest efficiency, colors may have different stability charact.)

Applications

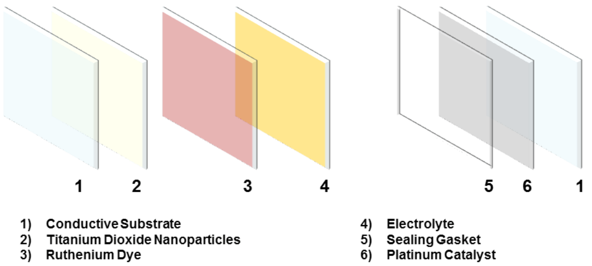
No other photovoltaic technology offers so much **flexibility** in terms of **transparency and coloration**. Its transparency makes it applicable for windows, doors, atriums and skylights, which in that way can produce energy. What is more the DSC moderate the sunlight and provide thermal and noise insulation. Building with different functions can choose to use different colours, according to the design and the needs. The panels can be easily optically integrated or create a design contrast. [6]

DSCs can be **grouped into modules**, with striped channels. They are available in individual housings or multi-housings or frames accommodating several modules (panels), which allow them to stand-alone or be attached mechanically or glued to flat surfaces, like walls and roofs. The maximum size so far is 30x30cm, voltage app 4.2V, current app 0.8A.

So far, the achieved efficiency is only 5% (in Japan an efficiency of 10.4% has been achieved for an 1 cm^2 surface) and thus it is still not available in widespread market, but international companies try to establish them in small numbers. [5]

Further readings

- http://www.solaronix.com/technology/dyesolarcells/



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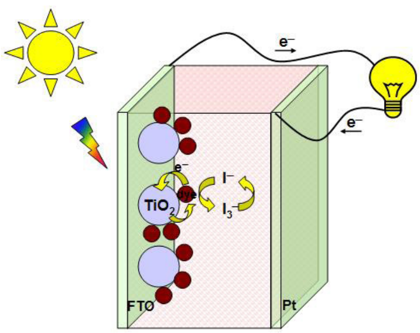

Fig 2

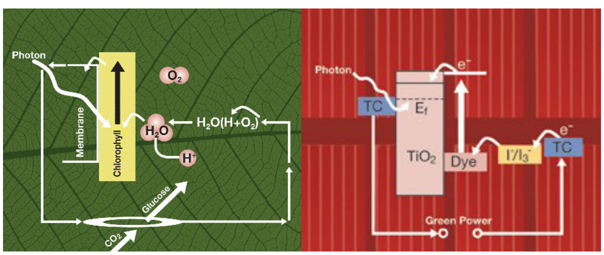

Fig 3

Fig 1. The different layers that make the DSC. [6]
Fig 2. Diagram of the way DSC works. [4]
Fig 3. Artificial photosynthesis by the DSC in comparison with the plants. [6]

Reference projects

Dye Solar Cells can be attached like conventional **silicon or thin film solar cells** on facades, roofs or integrated into them.
More specifically, the SwissTech Convention Center uses a multicolored Dye Solar Cell facade, which is designed by the architects at Richter Dahl Rocha and constructed by Solaronix.
The PV installation is located at the west facade and covers a total area of 300m². Around 355 panels were installed for 200m² of active PV area. Due to the inclination of the roof, the panels (1 - 2,5m) were grouped in two to five 50cm modules. The architectural design of the building is perfectly complemented by these 65 colored columns, fulfilling both the aesthetic ambition and the energy awareness of the designers. The transparency of red, green, and orange panels were tuned to meet the overall light transmission target of the architects.
The solar façade fulfills both functions:

- **passive prevention** of the incoming sunlight from overheating the majestic entrance hall
- **active producion** of renewable electricity from the sunlight.

Mixed and matched, the arrangement of colors ingeniously designed by artist Catherine Bolle gives a unique dynamic to the façade while providing a smooth color tone to the light transmitted into the hall. The annual production of the SwissTech Convention Center solar façade is estimated at 2,000 kWh, a respectable figure given the high transparency and orientation of the façade.


Fig 4


Fig 5

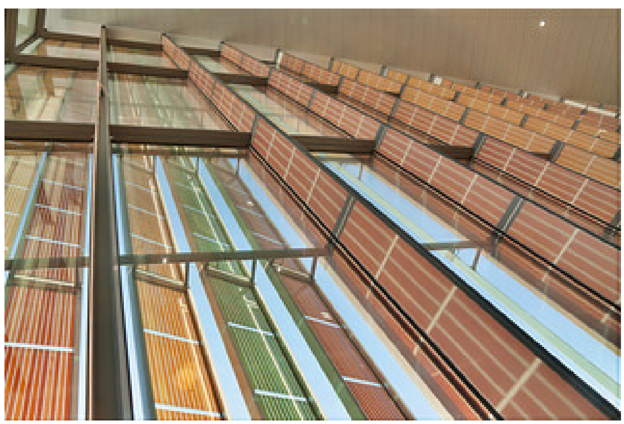
Fig 6

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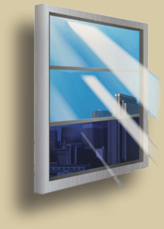
Fig 4. The west facade of SwissTech Convention Center. [8]
Fig 5. The dye/sensitized panels from the interior. [8]
Fig 6. Zoom in to the dye/sensitized panels from the interior of the building. [8]

3.ELECTROCHROMIC



Definition

Electrochromic materials are the smart materials that can **change color** when activated by an **electrical current**. Essentially, electricity starts off a chemical reaction which alters the way the material reflects and absorbs light. Their main function is to get darker when voltage (1-4V) is applied and more transparent when it is taken away. Maintaining a particular shade does not require constant voltage. In fact, according to Sage Electronics, you can run a house full of electrochromic windows for about the same amount of money that it takes to power a single 75-watt light bulb. [1]

Color-changing windows have been available for more than twenty years as NREL has been testing technologies and prototypes through an accelerating weather chamber since 1980.

Like other smart windows, EC windows are made by **sandwiching** the following materials: [2]

1. Glass or plastic panel
2. Conducting oxide
3. Electrochromic layer, such as tungsten oxide
4. Ion conductor/electrolyte
5. Ion storage
6. A second layer of conducting oxide
7. A second glass or plastic panel

The ions in the sandwiched electrochromic layer are what allow the change from opaque to transparent. The voltage drives the ions from the ion storage layer into the EC layer and the glass becomes opaque. Shutting off the voltage drives the ions out of the EC layers and into the ion storage layer. [2]

Special feature!

Electrochromic windows are not an all-or-nothing technology like liquid crystals. They can be adjusted to various levels of visibility (like suspended particle devices). [3]

Remarks

Smart windows have a huge **environmental benefit** as they are able to reflect almost all the amount of light (around 98%), keeping out the excess heat and reducing the required air-conditioning. When controlled by sensors, they can save up to 8% of the total energy consumption of a building, while they use only a small amount of electricity to switch from dark to light. [3]

Windows of such technology are more **expensive** to install and still they are not durable enough, with current windows degrading after only 10–20 years. What is more, the switching phase lasts a few minutes and not a few seconds as many might expect.
In the near future, though, we expect to apply such techniques as very thin coatings to existing windows, reducing the cost of the process. Their reliability and durability will also ensure a wide commercialisation.
EC windows might also be **combined with solar cells**. However, a window that doubles as a solar cell would be darker, even when clear, and less efficient than a conventional solar cell. [3]

Properties

The optical properties of the different EC materials differ substantially. Tungsten oxide is the most commonly used and absorbs light with a maximum of approximately 950nm. This gives to the material a deep blue color. Depending on the different applied voltage, a complete **set of tones** of the same color or switching between different colors is possible (graph 3)

As we can see also from the diagram 2, there are four initial functions for EC materials and devices: [5]

- display information through the electrochromic film, achieving excellent viewing properties with better contrast, particularly at off normal angels, than in the conventional liquid crystal based displays.
- creating a mirror with variable specular reflectance.
- creating variable transmittance, controlling the visible light and the solar energy introduced.
- creating a surface with variable emittance.

Innovation

The newly developed **reflective hydrides** are similar to the EC materials but behave quite differently. Instead of absorbing light, they **reflect** it. Thin films made of nickel-magnesium alloy are able to switch back and forth from a transparent to a reflective state. The switch can be powered by low-voltage electricity (electrochromic technology) or by the injection of hydrogen and oxygen gases (gas-chromic technology). Furthermore, this material has the potential to be even more energy efficient than other EC materials. In short, EC technologies enable designers to use more glass while still meeting or exceeding building energy codes and standards and **improving occupant comfort**. [4]

Diagram 1. Change of transmissivity when different voltage applied. [6]

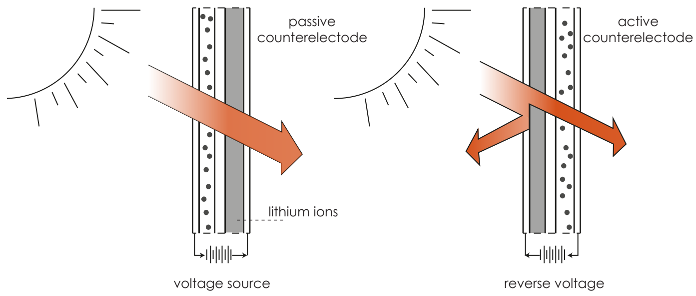


Diagram 2. Four main applications of EC devices. [5]

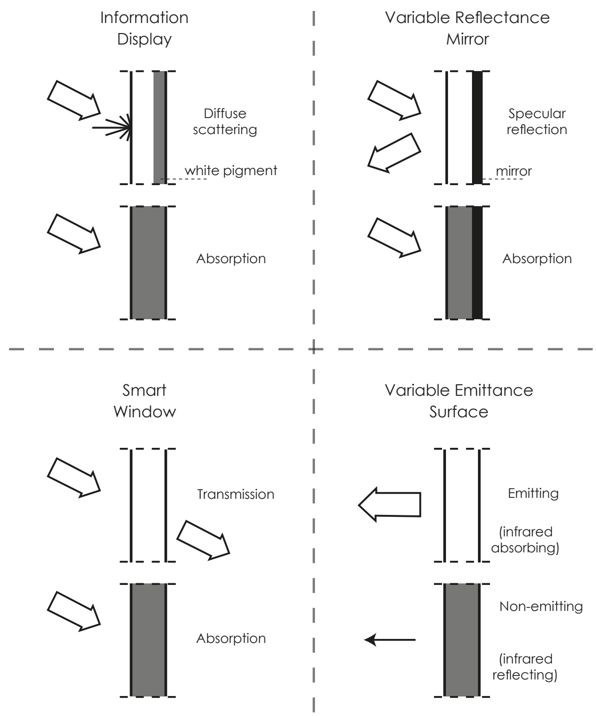
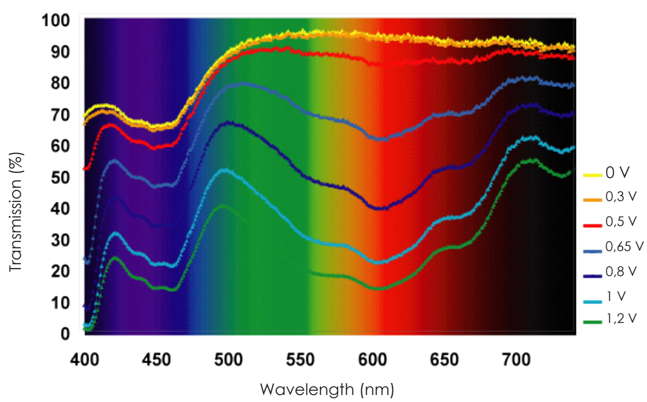


Diagram 3. Different tones achieved by different charge. [7]



Applications

Electrochromic materials are being applied widely in the automobile industry to automatically tint rear-view mirrors in various lighting conditions.
High speed trains use them as a division between the passenger compartment and the driver's cabin.
They have been also used in the Boeing 787 Dreamliner. Especially for airbuses, the technology has to be further developed in order to have the electrochromic windows widely applied as a 100% darkness is required from the passengers and the companies. Tests are being done and so far, even if **99% darkness** is offered, it is still not enough. [8]

With the proper sensors and control algorithms, an EC window system could automatically darken the windows when the sun is high and its rays are heating the interior, thus reducing the solar heat gain and the need for air conditioning. Respectively, when the sun sets or clouds cover the sky, the system would make the windows transparent again, maximizing the daylight and reducing the use of electric lighting. Such a dynamic control can save energy over both lighting and air conditioning.
Powering 2,000 square feet of the color-changing glass—the equivalent of more than 100 windows—would require **less power** than illuminating a 60-watt light bulb. [9]

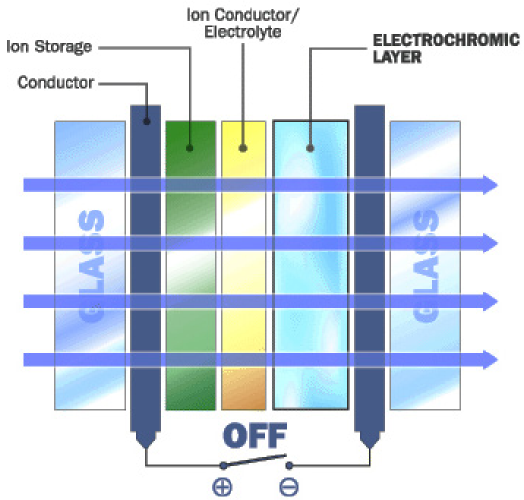


Fig 1

Further readings

- www.sageglass.com
- http://www.glass-apps.com/electrochromic-glass
- http://newscenter.lbl.gov/2007/01/22/a-dawning-day-for-energy-efficient-electrochromic-windows/


Fig 2

Fig 1. When switched off, an electrochromic window remains transparent. [1]
Fig 2. Application of EC windows in 787 Boeing. [12]

Reference projects

When EC windows were still in an early stage of technological development, Berceley Laboratory started an experimental project in 2003 to realize their potential to save energy. In the experiment two EC windows were compared with one low-emissive. As a result, the EC window saved more energy while providing more comfortable interior environment. [6]
Nowadays, EC windows are on the market with companies providing even exclusively EC windows. Saint Paul River Centre in Minnesota is just one example, where EC windows are applied to solve the **solar glare and the heat gains** problems without compromising the view to the park outside. The glazing is at the east facade and manages to reduce the carbon footprint by 80% and improve the energy efficiency by 20% in three years. [10]
Another example, that also earned the LEED gold status, is the Siemens Wind Turbine Facility in Kansas. Heat and glare control is provided in several spaces and private offices. In the cafeteria, all the facade is covered with EC glass panels. The system is **integrated** into the **building's automation system** so that sensors control the amount of light and heat that can enter the building. Thus, the facility saves energy from reduced artificial light and HVAC loads. [11]

Fig 3

Fig 4

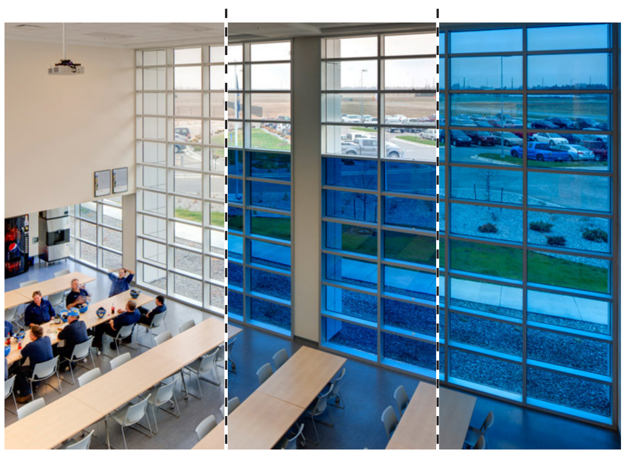


Fig 5

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10. http://sageglass.com/portfolio/saint-paul-rivercentre/
11. http://sageglass.com/portfolio/siemens/
12.http://bloga350.blogspot.gr/2013/04/airbus-considers-offering-dimmable.html

Fig 3. Exterior view of the experimental EC windows by Berkeley Lab. [9]
Fig 4. Interior view of the EC facade in Saint Paul River Centre during clear sky and in a cloudy day. [10]
Fig 5. Interior view of the EC facade in Siemens Facility with three different levels of sunlight. [11]

4.HYDROGEL

Definition

Smart hydrogels, or stimuli-responsive hydrogels, are three-dimensional networks composed of cross linked hydrophilic polymer chains that are able to dramatically change their volume and other properties in response to environmental stimuli such as temperature, pH and certain chemicals. Rapid and significant response to environmental stimuli and high elasticity are critical for the versatility of such smart hydrogels.

Hydrogels are in the group of **thermotropic** materials.

The homogeneity of thermotropic materials is related to temperature and they can be used for the light scattering. Thermotropic as solar control has the ability to provide diffuse daylight and it works based on a change in specularity.

As it is clear from the name, a hydrogel is a **water/polymer mixture**. This mixture can remain homogenous up to a certain temperature, in which the two components are bounded. The bonding is usually hydrogen bonding and can be broken when the temperature exceeds the switching temperature. Once the bonds break, the material is separated into distinct domains of different refractive index and turns to a cloudy white color. The switching temperature of hydrogels depends on the proportions of the components and it can be **from 5°C to 60°C**.

The inventor, Toyochi Tanaka, first observed this phenomenon in swollen clear polyacrylamide gels. Upon cooling, they clouded up and became opaque. Upon warming they regained their clarity. It was further found that some gel systems could expand hundreds times or collapse to expel up to 90% of its fluid content with a stimulus of only a 1°C change in temperature. Similar behavior was observed with a change of 0.1 pH unit. [1]

Special feature!

A change in specularity of hydrogels and all thermotropics gives the opportunity to have the diffuse daylight even during diminishing of the view, while two conditions of transparency or reflection (without diffuse daylight) can be achieved. 2

Remarks

The thermotropic behavior of hydrogel allows self-regulating control of the amount of light and heat transfer through the facade **without** applying **complicated installations** for active control. Hydrogel has the unique ability to change the conductivity of the glazing as well as its transmittance.

This effect is more pronounced when the hydrogel fills a cavity of double glazing, in comparision with the use of a polymer foil as a thermotropic. Despite the intensive research, hydrogel-based smart windows came out to market only **recently**. [2]

The main disadvantage of this technology is its inability to 'stop' or 'start' the transition. In many circumstances, the environmental response is not in sync with the interior need. So, all the parameters, including light, heat and view, must be in agreement as the optimization of only a single environmental factor cannot achieve the desired response.

Therefore, much more research has been allocated to the various electrically activated chromics, in all of which the user can control the conflicting behaviors. This control, however, cannot be incorporated directly into existing facade and window systems, as all the electrically activated technologies need a rather sophisticated infrastructure. Furthermore, to take full advantage of the potentials offered by the ability to turn the system on and off, there is usually an accompanying **sensor and logic control system**. For example, one popular scenario uses light sensors to optimize the balance between artificial lighting and transmitted daylight. [4]

Properties

Smart hydrogels are rapidly responsive, highly swellable and stretchable. The nano-structured smart hydrogels show very significant and rapid stimuli-responsive characteristics, as well as highly elastic properties to sustain high compressions, resist slicing and withstand high level of deformation, such as bending, twisting and extensive stretching. Because of the concurrent rapid and significant stimuli-response and high elasticity, these **nano-structured smart hydrogels** may expand the scope of hydrogel applications, and provide enhanced performance in their applications. [3]

The phase change of any thermotropic results in a noticeable reconfiguration in the structure of the material, such as changes in thermal conductivity. The main **problem** of hydrogels is **their water content** which requires a good sealing and accurate measuring when temperatures reach freezing points. Thus, some hydrogels can have two further transition states, turning opaque at low as well as high temperatures, making them beneficial for avoiding radiant loss from the inside during the winter. [2]

Fig 1

Applications

One of the applications of Hydrogel can be defined as a c**ooling system in the facade**. In this regard, one project designed based on the Hydrogel and called Hydro panel which will be explained in the reference project part. The panel is made by two surfaces containing hydrogel spheres in between. It works as a cooling facade system which absorbs water from the rain and keeps the facade cool for a longer time as the water evaporates slowly.

Hydrogels are also applied in biomedcine as drug delivery containers.

In building industry due to its properties Hydrogel is suited for solar control and is a good option for having smart and efficient window. [5]

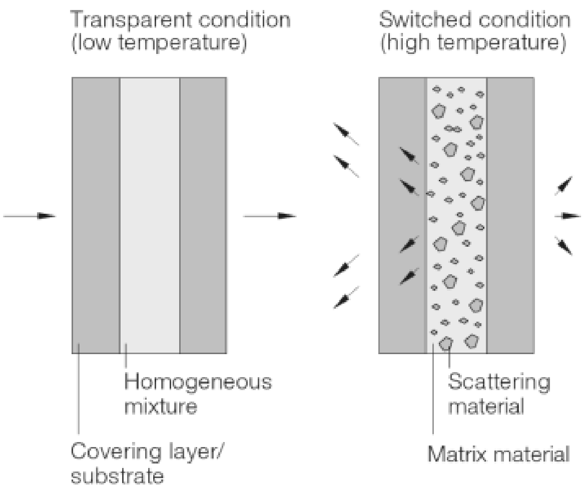

Fig 2

Further reading

- www.interpane.com

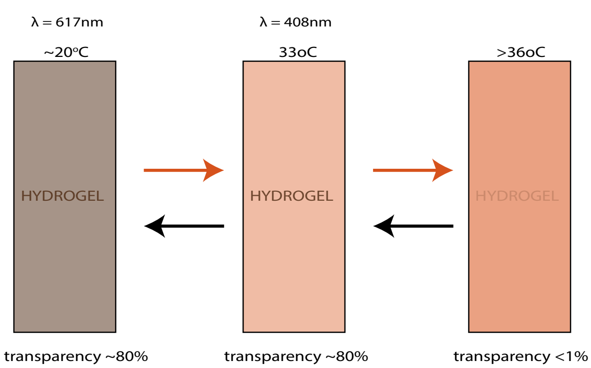

Fig 3

Fig 1. Invisible polymer hydrogel. [8]
Fig 2. Hydrogel in low temperature and high temperature. [5]
Fig 3. A sample of transparency of hydrogel in relation to temperature. [6]

Reference projects

Regardless of the fact that many intensive research has been done about the hydrogel, **hydrogel-based smart windows** came out to market only recently becuse of its uncertainty and problems that was mentioned before. As a consequence, only one conceptual project, which has not accomplished yet, described here.

The project is about making a **cooling prototype** for building skin. This cooling panel is made with spherical hydrogels which are sandwiched between two perforated sheets. The idea of evolutionary computation in this project is to try to optimize the best shape of the container for each hydrogel so that each one can hold enogh amount of rain water for a small hydrogel to grow.
Parameters: Front surface area should titled in a way that it faces the sun and have enough perforated area so that it allows the rain to pass and the sun to dry out the gel.
Back surface area should titled in relation to the front surfae in orther to let the wind pass into the building and it should have holes only above the water level so the water does not leak into the building.
The size of the the circle defines the surface left containing the hydrogel. [7]

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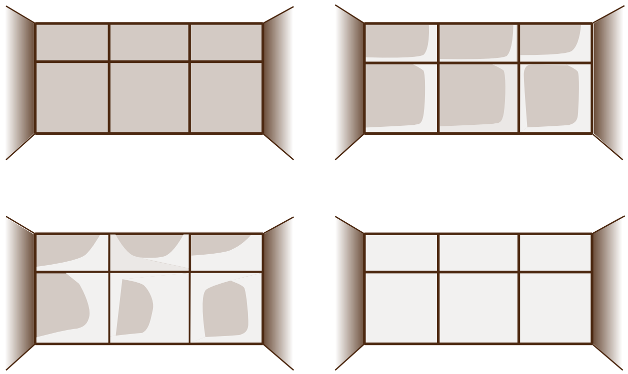


Fig 4

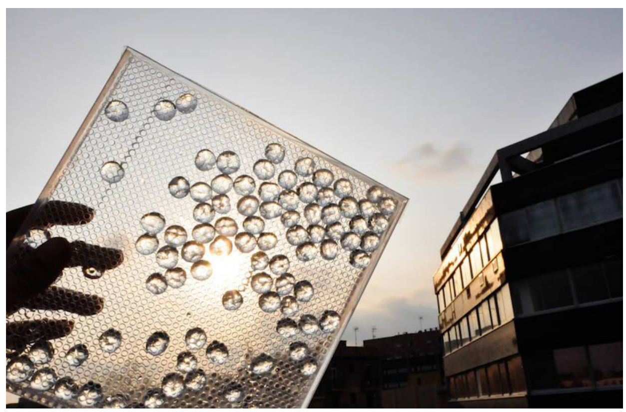


Fig 5

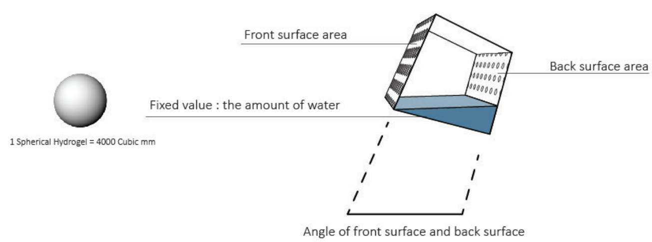
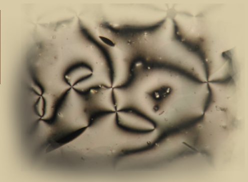


Fig 6

Fig 4. Switching process of a 1:2.5 scale model office facade equipped with thermotropic hydrogel windows. [2]
Fig 5. Hydro panel. [7]
Fig 6. Concept of Hydro panel as a cooling system. [7]

5.LIQUID CRYSTALS



Definition

Liquid crystals belong to an intermediate phase between crystalline solids and isotropic liquids. They are liquids, orientationally ordered, with anisotropic properties that are sensitive to electrical fields. As a result they can be applied to optical displays such as shading system. A liquid crystal panel is made out of a liquid crystal film between two sheets of polarizing material. Turning on or off an electric current through the liquid can create two situations of arranging the crystals; regularly or randomly.
When the electrical current is off, the crystals move randomly, in their natural state. So, the direct light is blocked. On the other hand, turning on the elecrical current aligns the particles rapidly and the light can go through, transforming the panel to transparent. This type of switchable glazing can **block up to about 90% of light.**
Liquid crystals have been processed into films in order that they can be used as electro-optic layers. Liquid crystal films (LC films) in principle compose of several functional layers: two PET substrate layers, which are coated on the inner sides with a transparent conductive oxide (TCO), e.g. indium tin oxide (ITO), to serve as electrodes, enclose a polymer matrix in which the liquid crystals are embedded. These liquid crystals are also known as polymerdispersed liquid crystals (PDLC). [1]

Special feature!

liquid crystals can be the best option when both **privacy** and the **maximum daylighting** are required.

Remarks

The use of liquid crystal is **rising** dramatically for discretionary projects, particularly high end residences and interior partitions where privacy and ample light are more important than energy.

For controling the **glare** issue, a decrease in the intensity of the visual transmission is of great importance. Whereas, if the need is to minimize heat exchange through the material, then a thermotropic is the best option. [2]

On the other hand liquid crystals: [2,4]

- require a permanently connected electrical field for the transparent state
- are not suitable for darkening rooms (light transmittance in the off state is approx. 76%)
- perform change in the light transmittance from specular to diffuse but not opaque.
- are **expensive** for replacement
- are relatively heavy
- are expensive for manufacturing and installing (currently approx. 1700-2000 euro/m^2, supplied and installed)
- are hardly satisfactory in the reduction of unwanted infrared radiation.
- have **limited view** from oblique angles due to the linear alignment of the crystals in the transparent state.

Properties

The main properties of liquid crystals are: [4]

- can be used in low to medium temperatures (-20OC to +60OC)
- switches instantly to transparent or private
- has very low electrical consumption: 24 VA/m2
- filters 99% of UV light
- has long replacement life (over **15 years** in use)
- relatively easy to use
- adequate fire resistance
- relatively high switching voltage required (100 V A C, Europe)

Innovation

Liquid crystal glazing takes tremendous privilege of the developments. According to the fact that liquid crystals are the primary chromatic technology, which has been used in large panel displays, they are largely promoted for the use in large scale on exterior surfaces. As such, unlike the development of electrochromics - which grew exclusively from the desire to use them on building facades - liquid crystal glazing came into the architectural market fully tested and refined. Issues regarding their durability, maintenance, sizing, mounting and packaging had been addressed and at least **partially resolved**. Consequently, architects only had to start employing them. [3]

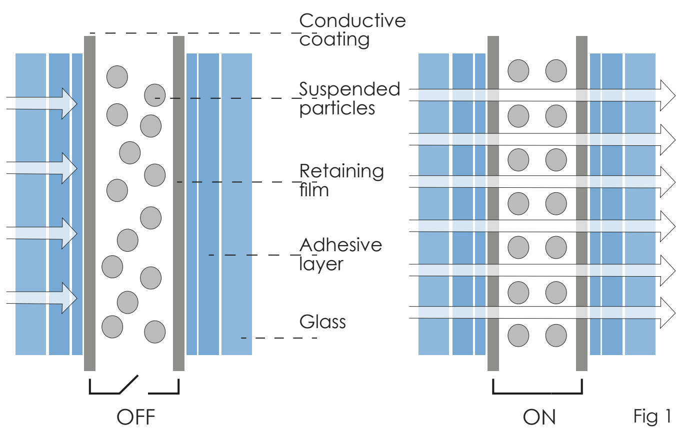


Fig 1. Function of LC windows [5] a) OFF b) ON

Applications

Generally, the liquid crystal panels are used for controlling the transmission of solar radiation in the building. In addition, they are also a good option in order to provide privacy via windows/walls. These switchable glasses are able to provide diffuse light even when they block it. The light scattering is controlled electrically in these smart glasses and the transition from transparent to translucent condition is so fast and with a flick of a switch.

Additionally, with applying the liquid crystal panels in the façade, better aesthetics can be achieved with the advantage of having a transparent facade. However, they are expensive to be used for the whole surface area of the façade. Therefore, their use is limited in the building envelope, interior division walls, etc.[5]

Further reading

- http://saint-gobain-glass.com

´SGG PRIVA-LITE´: light transmittance of 77% in transparent state and 76% in translucent state.
Available dimensions: 305 mm x 405 mm to 1000 mm x 3000 mm / thicknesses of 7 mm to 14 mm.

- http://www.polytronix.com

´Polytronix´: Polyvision Privacy Glass. thickness of 25mm.

- http://www.smartglassinternational.com/

SmartGlass: maximum size of 1450 mm x 3200 mm and minimum size of 200mm x 300mm.

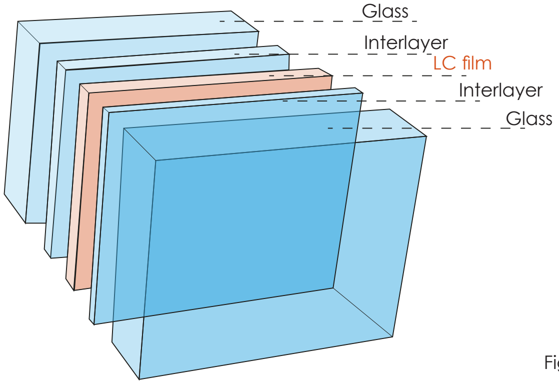


Fig 2

Fig 3

Fig 2. Layers of liquid crystal glazing. [5]
Fig 3. LC interior walls in Microsoft Portuguese Headquarters, Lisbon-Portugal. [7]

Reference projects

Canary Wharf, located at the West India Docks in the Borough of Tower Hamlets in East London, is home to the European headquarters of numerous major banks, professional services firms and media organizations. A shimmering sculpture of glass and steel, the elegant arch of the East Wintergarden provides a perfect counterpoint to the linear landscape of Canary Wharf.

LC SmartGlass was applied for this project to allow instant and precise privacy control when an event is taking place. A switchable glass product was the ideal solution to tie in with the minimalist design of the East Wintergarden and the theme of a "transparent venue".

LC SmartGlass panels were installed within the three revolving centre doors and double doors in either side of the venue entrance. All LC SmartGlass panels are manufactured using a lamination process which encapsulates a **PDLC film** between 2 or more glass sheets. Using a minute electrical current, users can immediately switch the LC SmartGlass from clear to private (opaque) and vice versa.

A total of 22 LC SmartGlass toughened panels make up the front entrance, 6 of which are curved panels that make up the three revolving doorways at the centre of the entrance. [6]

Fig 4

Fig 5

Fig 6

Fig 4. East Wintergarden. [6]
Fig 5. LC panels at the East Wintergarden on and off. [6]
Fig 6. LC panels at the East Wintergarden on and off. [6]

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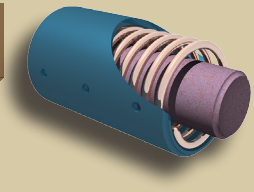
6.MAGNETOSTRICTIVES



Definition

"Phenomena of interaction between magnetic quantities and the stresses and mechanical deformation can be defined as magnetostriction".[10]

On the other hand, according to Buschow & de Boer (2004) magnetostriction is described as a change in material dimensions caused by a change in its magnetic state. So, by applying a force to the magnetostrictive materials, their **magnetic properties** can be changed, as well as their **dimensions** as a result of altering the magnetic field.[11]

Magnetostrictive materials act similar to piezoelectric and electrostrictive materials; however, shape changing in this group of material occures due to a **change in magnetic field** instead of an electrical field.

Iron, nickel and cobalt were the first three magnetostrictive materials studied by early researchers. However, because of the fact that their ratio of the saturation magnetostriction to their thermal coefficients of expansion is small, their applications are limited. The addition of other elements, such as terbium and dysprosium, can achieve giant magnetostriction (e.g. Terfenol-D) under relatively small fields.[12]

Applying an external magnetic field to a material contains **tiny magnets** causes the rotation of magnets which will be aligned with this field and as a result the shape change. Converesly the magnetic field can be changed as a result of relocation of tiny magnets by applying the external force on the material which causes streching or compressing of material.

Remarks

The main advantage of magnetostrictive materials over the conventional piezoelectric/magnetic materials is their very low hysteresis. This could be especially beneficial in dynamic application.

The main disadvantage, though, is their non-linearity. However, by applying a bias field, quasi-linear behavior around the bias operating point can be obtained. [2]

Terfenol-D material has the highest magnetostriction of any alloy (up to 0.002 m/m at saturation) and is composed by terbium, dysprosium and iron. Naval Ordnance Laboratory in USA invented in 1970 that the alloy with the that composition has a large magnetostriction as influence of a low magnetic field in room temperature. Thus, it has been used considerably in industry as giant magnetostrictive material (GMM).

However, it has some drawbacks, such as

- limited size,
- brittleness in tension and shear stresses,
- expensive and
- devolps eddy currents.

Properties

As Terfenol-D appears to have the highest magnetostriction, we present its properties:

- Density of 9.15-9.25 g/cm^3
- Tensile strength of 28 MPa
- Compressive strength of 700MPa
- Coefficient of thermal expansion: 12 ppm/°C
- Magnetostrictive energy density of 14-25 KJ/m^3

Table-1 demonstrates a comparison in magnetosriction for some feromagnetic materials. This phenomenon only happens at temperature below the curie temperature. The last three materials can generate very **high magnetostriction** based on high magnetic and anisotropy of rare earth materials like Terbium (Te) and Dysprosium (Dy). This useful property is retained up to very low temperature. [5]

Innovation

Due to the disadvantages that Terfenol-D appeared to have, Sandlund et al. in 1994 combined Terfenol-D particles with a passive polymer matrix to produce giant magnetostrictive polymer composite **(GMPC)** with the following benefits: [5]

- Eliminating eddy current
- Being relatively tough material which can tolerate better tensile and shear loadings.

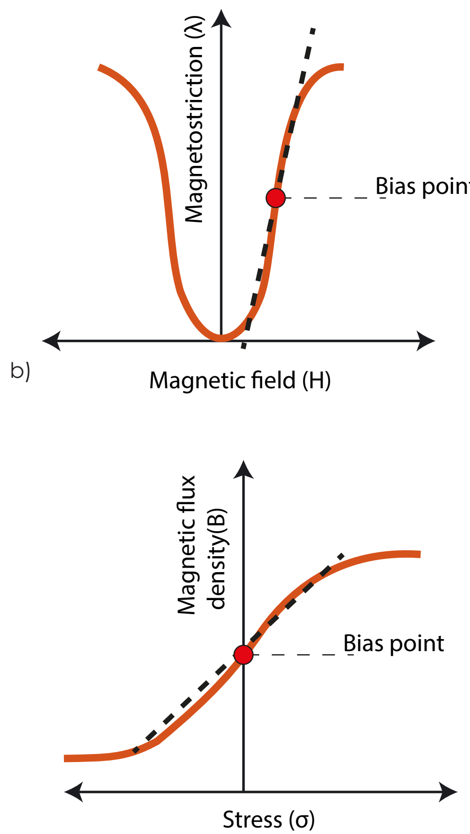
Finally, **Galfenol** (a composition of gallium and iron) was discovered in 1999 by the Ames Laboratory and the Naval Surface Warfare Center Carderock Division. It has similar properties to Terfenol-D with merits of:[1]

- Lower brittleness
- Having enough flexibility for producing in rolled sheet and in wire form
- Ability for machining with standard tools such as mills and lathes
- Possibility of welding to various materials

Table 1. Comparison of magnetostriction with some feromagnetic materials. [5]

Material	Magnetorestriction [ppm]	Cure temperature [°C]
Ni	33	770
Fe	14	360
Co	50	77
Permalloy	27	440
$DyFe_2$	650	362
$TbFe_2$	2630	430
$Tb_{.6Dy}.7Fe_{1.9}$	2400	380

Graph 1-2. Both the direct and inverse magnetostrictive effects are nonlinear. a) direct effect b) inverse effect. [6]



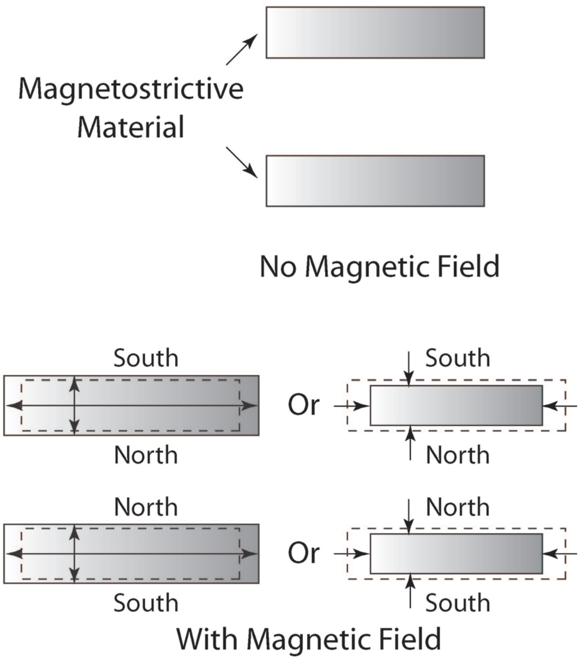


Fig 1

Applications

The primary applications of magnetostrictive materials included telephone receivers, hydrophones, oscillators and scanning sonar. The development of alloys with better properties led to the use of these materials in a **wide variety** of applications, such as surgical tools. Other applications include hearing aids, razor-blade sharpeners, linear motors, damping systems, positioning equipment, and sonar.

Magnetorestrictives are also used for following purposes:

- Mechanical **dampening** by two mechanisms:

1. When the structure deforms, it causes strain to an attached active material which transforms its vibration to a magnetic field. This magnetic field can be transformed to elecrical current for dissipation of energy. [2]
2. In comparison to conventional vibration damping, larger differential strain can be created by deforming the active material in opposite phase with respect to the base structure, producing residual strain. [2]

- Structural **health assessment**: Deffects of a structure can be measured by embedding tiny magnets in the base structure made from nonmagnetic composite material. The magnetic flux will be different in case of deffects such as cracks in material. [2]

Magnetorestrictives can be used to create **loud-speakers glass**. By attaching giant magnetostrictive material to the glass surface and feeding it with an audio input, the glass sheets will be vibrated and sound will be generated. In order to avoid the sound pollution, the street noise level should be measured to produce the sound approximately in the same level.[3]

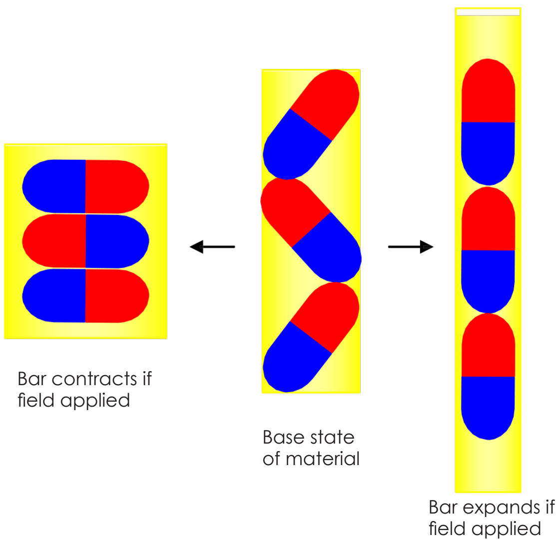


Fig 2

Further reading

- Manufacturer: Etrema is the world's leading supplier of TERFENOL-D materials.
http://www.etrema.com/

Fig 1. Applying magnetic field causes physical length change in the material. [9]
Fig 2. Magnetostrictive materials are made up from domains. If a magnetic field is applied the bar either decreases in length from its base state (centre to left) or increases in length (centre to right) depending on the polarisation of the applied field. [4]

Reference projects

There is no track record for using magnetostrictive materials in building facade, however it is applied in **suspended bridges** by cables such as the Millenium bridge in London and the Shandong Binzhou Yellow River Highway Bridge to mitigate the vibration caused by wind and rain.
Additionally, in a typical magnetostrictive actuator, a magnetostrictive material (central rod) is wrapped in a **metal coil**, which is housed in an outer casing. By passing a current through the coil, a magnetic field is formed within in, causing the rod to extend. Alternatively, the device may operate in reverse as a sensor, where external pressures change the length of the rod, which in turn generates a magnetic field that induces a measurable current in the coil. Such sensors are frequently employed for non-destructive testing applications, such as examination of suspender cables on bridges.[6]

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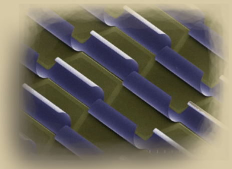
Fig 4

Fig 4. Centre span of the Millennium Bridge, London.[8]

7.MICRO-BLINDS



Definition

Invisible shading system for the windows can be constructed by depositing of thin metal blinds (micro-blinds) on glass. Micro-blinds can be adjusted based on the different requirements of the occupant, the solar radiation and the environmental conditions. Thus, the amount of passing light/solar radiation through the windows can be controlled, as well as the amount of gaining heat by the building due to solar radiation. This means that energy can be saved because of a major reduction in the required energy for heating/cooling of the building.[1]

Micro-blinds are **currently under development** at the National Research Council (Canada). The material is very small and thus **practically invisible** to the eye and consists of rolled thin metal blinds on glass. The metal layer is deposited by magnetron sputtering and patterned by laser or lithography process. The glass substrate includes a thin layer of a transparent conductive oxide (TCO) layer and a thin insulator between the rolled metal layer and the TCO for electrical disconnection.
When no voltage is applied, the micro-blinds are rolled, letting the light pass through. When electric field is applied, there is a potential difference between the rolled metal layer and the transparent conductive layer and the electrodes causes the rolled micro-blinds to stretch out and so block the light. [1]

Remarks

Smart windows, in which the light transmission through the window can be controlled, have been developed by using electrochromic layers, liquid crystals and suspended particles located between two glass panes or inside buildings.
The current technology for smart windows, though, is mainly based on the use of **electrochromic layers** and has different limitations such as lifetime, speed, maximum IR transmission and visual aspect. The discovery of Macro-blinds tries to address these problems. They have several merits such as switching speed, UV durability, customized appearance and transmission, and do not employ costly ITO, relative to the current smart windows technologies: electrochromic, suspended particles and liquid crystals.[2]

In general,

- micro-blinds can be made **invisible** to the eye, leaving the smart windows **colorless**.
- the dimensions and geometry of each micro-blind can be varried but typically is in the range of about 50 to 150 μm. However, in one smart window it is possible to have all the micro-blinds with the same dimensions or have different.
- a specific benefit of having micro-blinds with different dimensions is to overcome the possibility of a bad effect of diffraction of light through periodic structures.

By comparring micro-blind with other smart window materials, it can be said that microblinds have some advantages including switching speed, UV durability, customized appearance and transmission, and do not employ costly ITO(relative to the current smart windows technologies).

However, it has also drawbacks such as **cost**, reliability and visual appearance.

Special feature!

The micro-blinds are activated **extremely fast**, as they can change status from open to closed (and vice versa) in milliseconds.

Properties

By this technology, low emission coatings have been applied on windows for the purpose of limiting the transmission of IR (heat) through the windows. These **coatings** are very widespread regardless of the fact that they are characterized by fixed transmission characteristics. For having maximum energy efficiency, IR should be transmitted from the windows in the winter so it leads to heat the building. Whereas, It should block IR in the summer to help the building remain cool. The amount of visible light should optimize the comfort of ambient conditions of users and minimize the amount of general lighting needed. [2]

Generally it can be said that micro-bilnds are:
- Very thin
- Fast (milliseconds)
- Reflective (better solar range and energy)
- Neutral filter (no major tint)
- Inorganic (UV and temperature stable)

Innovation

Partial opening of the window pane, or grey levels, can be obtained by using different geometry-size of micro-blinds and having means of actuating them independently. The blinds can also be configured to provide grey level with additional refinement, and allow the window pane to be **used as a display**.[2]

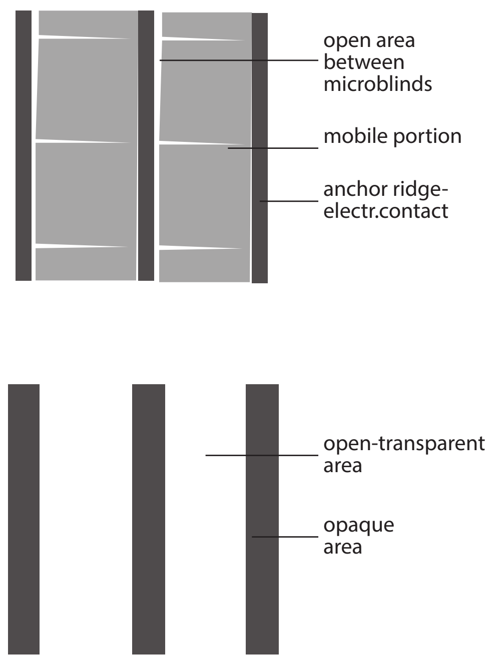


Fig 1. micro-blinds in a)closed and b)open state. [2]

Fig 4

Applications

The micro-blinds can be applied on the glass windows to reduce solar heat gain from the glazing and have the smart façade to maximize energy efficiency. The micro-blinds can be applied on a supporting layer on the window, or they could be applied to an illuminated panel, as can be found on a billboard. There is also the possibility to have it attached on an additional substrate and add it to an existing façade.[2]

Despite the benefits of microblinds for a smart facade, they are not available as a commercial product yet. However, the Na¬tional Research Council, Canada is developing this innovative technology for smart glass with possible applications in sectors such as building, aircraft, au¬tomotive and displays. [2]

Further reading

- Patent of microblinds:
http://www.google.co.jp/patents/US7684105

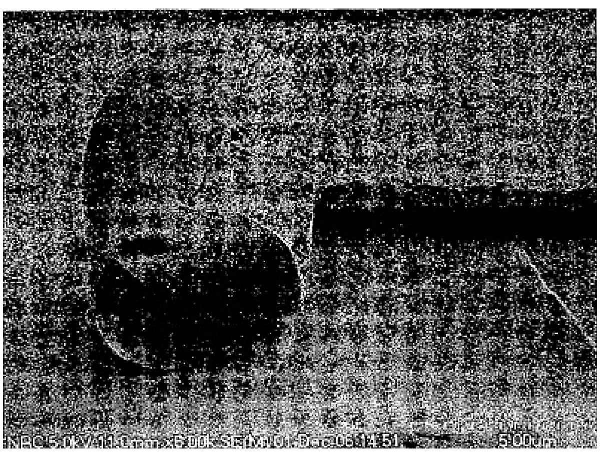


Fig 2

Fig 2. a micrograph image of curled micro-blinds on a 500 micron scale as developed by National Research Council of Canada scientists. [2]

How it works

Microblinds are still **under research** and there no projects as an example, but only the prototype for more experiments.

Figure 3 indicates the way micro-blinds work in the closed and open states. Once released, the mobile portions of the micro-blinds **curl by themselves** due to the inherent stress, which defines the open state. To close them, a voltage is applied between the transparent conducting layer and the stressed layer (or in the case of a TCO-coated substrate, the substrate and the stressed layer).

The applied v**oltage** must be **high** enough that the electrostatic attraction exerted becomes more than the inherent stress that induces the curling of stressed layer. The value of the actuation voltage is proportional to the stress and the thicknesses of the release layer and insulator. The voltage is applied by contacting the conductive and the stressed layers to outside electrical sources through contacts arranged on the edge of the frame, preferably **hidden** in the frame as a consequence becomes invisible to the viewer.

The dimensions of the micro-blinds don´t need to have a geometric progression: grey levels could be obtained with any distribution of dimensions, including having all blinds of the same size, as long as some of the blinds can be actuated independently from others. [2]

References

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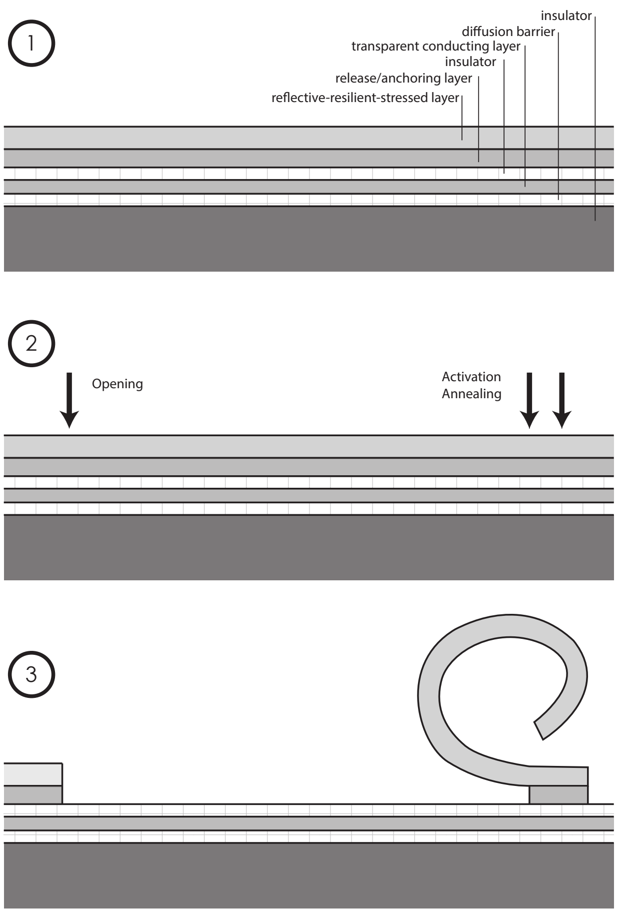

Fig 3

Fig 5. Cross-sectional views of the micro-blinds demonstrating the three major fabrication steps: [2]
1- deposition of the thin films with a controlled stress
2- patterning
3- and finally releasing of the stressed layers.

8.MINERAL AD/ABSORBENTS

Definition

Mineral Adsorbents (MAd) are the materials (or components) with a liquid or solid phase which can intake **gaseous** components from their inner surfaces and as a result some properties will be altered **reversibly** such as their volume, density, optical properties and energy state.

On the other hand, mineral absorbents (MAb) can take up **liquid** components on their inner surfaces and take them into their volume and reversibly change their viscosity where necessary. These liquid components even under pressure will not be released.

Some natural dry clays and synthetically produced silica gels can be accounted as MAds, even though they mostly consist of natural bentonites, which are often modified for diverse applications. Bentonites are clays and minerals containing smectite, usually montmorillonite, as well as other minerals such as mica and zeolites. In conjunction with their function as absorbents, some of these materials are more interesting because of their high swelling capacity.

By 1920s artificial MAds were already being produced. This was also around the time that silica gel was developed at the John Hopkins University in Baltimore, Maryland, USA.

In recent years, there has been an increase in the use of natural and synthetic zeolites, because of its promotion and improvement for new applications. Since 1987 bentonite in Germany has been in use in mats for sealing. [1]

Remarks

Bentonite has been the most usable mineral adsorbent (MAd) product in architecture to date.

Generally, it has been used in suspensions to seal layers of soil in earthworks. There are also systems of cardboard containers filled with bentonite powder or coarse granules on the market. They can also be used in the so-called “braune Wanne” or brown tank technique for sealing the basement of buildings through the external walls and the foundation area. In case water encounters (e.g. standing ground water or water from surface) the edge of the boards swells and fills any point of weakness, sealing the system against further entry of water.

Apart from calcium bentonites, stronger swelling **sodium bentonites** are also used. They can be categorised as mineral absorbents (MAb) as well. This material is very new on the market but it acts as multifunctional acoustic gypsum wallboards incorporating MAds, which, in addition to their inherent sound-absorbing and air moisture-buffering properties, can improve room air quality by binding and converting odors and pollutants. [1]

Generally the advantages and drawbacks can be summarised as follows:

Advantages:

- Market presence: can be manufactured in large quantities
- easy to apply and use
- relatively little or no dust released
- able to be incorporated into different constructions
- resistant against mechanical load
- insensitive to mechanical vibrations
- durable for a large temperature range (-18°C to +80°C)
- relatively inexpensive
- maintenance free

Drawbacks:

- not available universally
- suitable only under certain conditions for processing
- volume changes may be undesirable for specific applications
- no adequate fire resistance
- not stable enough for some applications
- relatively low absorption speed
- poor air circulation

Properties

• Texture and color: distinguishing adsorbent clay from ceramic color has little importance but may be very beneficial in tracing continuities. **Adsorbent clays** can be from coal black to pure white but the gray, green-gray and deep red are very common among them. Whereas, a fresh adsorbent clay from the ground usually has a greasy, soapy texture and can be cut with a knife, easily like a cake.

• Density: adsorbent clay is lighter than sedimentary clay with the same size and moisture content. The lightest one has denity of around 1.06 g/cm^3 (this is nearly light enough to float on water). However, after processing and heating up to 160°C and removing all non-structural water the density becomes about 2.50 g/cm^3.

• Refractive indices: there is a close relation between **water content and refractive indices** in this group of material, e.g. by heating Kaolinite up to 600°C the refractive drops from 1.57 to 1.53. [2]

Innovation

Mineral absorbents (MAb) can be used for different purposes regardless of the fact that they are widely used to waterproof the buildings. Bentonite in particular is one of these materials in which both the take-up and take-in mechanisms can occur.These smart materials are classed as inorganic ad/absorbents (IAd, IAb). Nowadays, various types of these material exist, such as:

• inorganic compounds (e.g. silica gels, dry clays)v
• mixture incorporating inorganic compounds (calcium bentonite)
• etc.

Table 1. The comparision of moisture adsorption capacity in different adsorbents material. [3]

Material	Moisture adsorption capacity	Heat of adsorption
Molecular sieve	excellent	excellent
Silica gel	good	good
Monmorillonite clay	fair	good
Calcium oxide (CaO)	good	fair
Calcium sulfate (Caso4)	fair	fair
Polyacrlate super absorbents	excellent	excellent
Natural and proteinacous fibers/ particles	fair	fair
Hydrogels	excellent	good
Carbon, activated/modified carbon	excellent	good

Table 2. Properties of adsorbents. [3]

Property	Molecular sieve	Silica gel	Monmorillonite clay	CaO	CaSO4
Adsorptive capacity at low H20 concentrations	excellent	poor	fair	excellent	good
Rate of adsorption	excellent	good	good	poor	good
Capacity for water at 77°F, 40%RH	high	high	medium	high	low
Separation by molecular sizes	yes	no	no	no	no
Adsorptive capacity at elevated temp.	excellent	poor	poor	good	good

Applications

Mineral adsorbents (MAd) have applications in **both** dehydrated and non-dehydrated condition. In dehydrated state, (such as silica gels and activated alumina) they can be used as desiccants, e.g. for the separation of gases and stored parts of water vapor. In addition, in the non-dehydrated state, they can be used as water vapor-sensitive moisture buffers in a number of fields, e.g. for constant air moisture content in rooms.

MAds can also be a good choice in **museums**, for example in glass display cabinets containing moisture-sensitive articles such as pictures or metal artifacts. MAds are often packed in water vapor-permeable bags for improving handling and for dust protection. What is more, in a bag with at least one transparent or translucent side, it is used to make the contents visible (when color indicators are incorporated at least).

Furthermore, the growth of **molds** can be prevented, especially in timber structures which may have high amount of moisture, flexible tubes of foil. They are filled in with MAds and sold in strips of different lengths, either with different fillings or simply with silica gel. This can be done by installing several strips on the inner side of the cladding.

Especially, bentonites and natural sodium bentonites are used in suspensions for their supporting and sliding properties.

Finally, they can also be used in panels, where they are contained in **textiles or cardboard**.

Other areas are also benefitted from these materials, including hydraulic, highway, tunnel and landfill construction, etc. It should be mentioned that the sealing effect of these products mostly depends on their ability for absorbing relatively high volumes of aqueous components and expand forming sealing gels, which fill or close any cracks or other gaps. This swelling pressure also helps to have strong product by fixing them more firmly in place.

In addition, incorporating MAds or MAbs are of great interest in architecture in the following products: [1]

- Bags with MAd filling
- Strips with MAd filling
- Gypsum wallboards incorporating MAd
- Bands (Strips) incorporating MAb

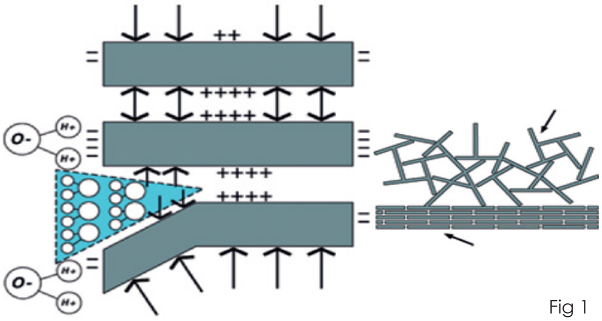

Fig 1

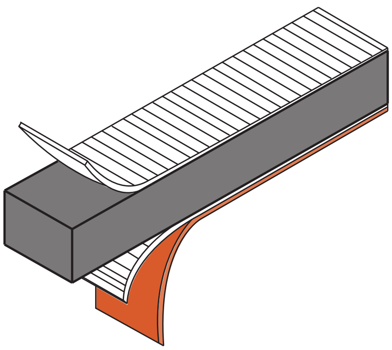

Fig 2

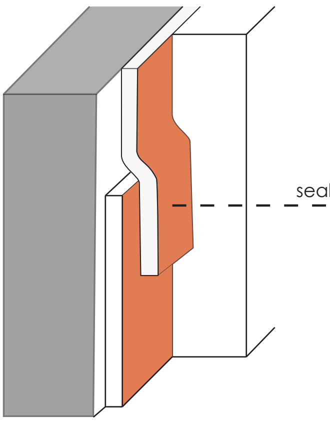

Fig 3

Further reading

- Axel Ritter, "Smart Materials: In Architecture - Interior Architecture and Design", Springer, Berlin, Germany, 2007

Fig 1. Bentonite swelling. [2]
Fig 2. Band (strip) with MAb (bentonite). [1]
Fig 3. Sealing effect ofmats with MAb (bentonite).[1]

Refernce projects

The **industrial monument** with the multifunctional catalytic gypsum wallboard ceiling (Cottbus, Germany, 2005) by **Marco Duchow and Alexander Duchow** is the first project using mineral absorbents for improving the indoor air quality. Its function as call centre, demands good interior acoustics of the column-free hall in the upper story of the industrial monument. Hamburg architects Marco and Alexander Duchow had been commissioned to give the historic room a modern character without losing the aesthetic of the old factory.

Following information from the major German manufacturer about the advantages of a new type of acoustic gypsum wallboard that promotes room air quality by its incorporated zeolite; they decided to use mineral absorbents for cladding the curved intrados of the roof construction.
With gypsum as the main constituent (90%), the boards have **moisture-regulating properties** and, because of the incorporated additional layers of catalytic zeolite powder (clinoptilolite <10%), it can also bind or convert various odours and pollutants. The actual physical and chemical processes involved are quite complicated but it should be mentioned that there is no possibility of pure ad/absorption processes without the boards becoming saturated over time.

After the acomplishment of the project, experiments demonstrated showing that the levels of cigarette smoke and the **pollutants** it contains (such as formaldehyde and acetaldehyde), odors from the carpet and mattress and the dodecene incorporated in the products, benzene from motor vehicle exhaust gases and paints, aromatic hydrocarbons in printed products and cleaning agents were significantly **low**, highlighting the acievement of mineral absorbents in this project. [1]

Fig 4

References

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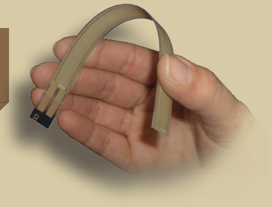
3. Hartmann M, and Eyal A,"Heat regulating article with moisture enhanced temperature control", U.S., 2010

Fig 5

Fig 4. View at night to the outside of the call centre. [1]
Fig 5. View into the call centre with air-cleaning ceiling formed with curved gypsum wallboard incorporating zeolite. [1]

9.PIEZOELECTRIC CERAMICS/POLYMERS



Definition

Piezoelectric ceramics (PEC) and piezoelectric polymers (PEP) are inorganic or organic materials. When these materials are located under a **mechanical load**, electric charges are produced on their surfaces as a result of deformation through changes of charge distribution. Thus, they **alter their shape** due to the **voltage applied**.
These phenomena can be defined as the piezoelectric and the inverse piezoelectric effect, respectively. The piezoelectric effect was invented by the Curie brothers in 1880 in natural Rochelle salt, tourmaline and quartz crystals. They found that electrostatic charges can be produced as a result of mechanical loading of the crystal surfaces. What is more, these charges portionally depend on the magnitude of the load.
Later, in 1950 a patent for a charge amplifier was granted to Walter P. Kistler, which helped ensure the considerable adoption of piezoelectric instrumentation technology. The first piezoelectric sensors were developed about ten years later. In 1969, the discovery of the first highly active piezoelectric polymer material occured. In the late 1990's a Finnish company developed a quasi-piezoelectric electret film, which is mainly used for sensors in different applications.
This kind of materials generate deformations under mechanical effects of electric charges reversely. While the piezoelectric effect is mostly used in **sensor technology**, the inverse piezoelectric effect is applied primarily for actuators. [1]

Remarks

Thermostrictive, piezoelectric, electroactive and chemostrictive smart materials are those that are currently of the **greatest interest** in the field of architecture, based on their availability, predicted long-term stability and other factors. However, in order to ensure the long-term functionality of these products, they must not be subjected to extreme mechanical or electrical loads. In addition reducing the size of cross section of the electrical connections causes damaging and breaking. Finally, direct contact with moist and/or corrosive media is detrimental and should be prevented. [1]
Other merits and demerits of these materials are: [1]

Advantages:
- market presence,
- different shapes and sizes (rolls/ cylindrical, spherical or curved shapes)
- use in low to medium temp. (< +250°C)
- very long lifespan (> 1000.000 cycles)
- largely insensitive to moisture with incorporation of ceramic insulation
- durable in compression
- possibile to cut and shape
- bending ability(depending on the electrodes used)
- fastened to smooth and flexible substrates (e.g. on or under floor coverings, on seating or beds, mechanically or by adhesive)
- use as energy-independent sensors (quasi-piezoelectric effect),
- lower overall mass when compared to traditional monolithic devices of the same volume
- reducing lateral vibration modes
- cross coupling and spurious activity by the damping effect of these materials

Drawbacks:
- only relatively low to medium voltages can be generated (< ±200 V/µm)
- Deformations must be within the permissible limits (i.e. max. 10 % in excess of the actuator's travel distance)
- relatively short travel distance achievable compared with multilayer linear actuators (< 200 µm, dependent upon dimensions and voltages among other parameters)

Properties

Piezoelectric film comes in a thin, lightweight form that can be glued to other surfaces. The film is relatively weak as an electromechanical transmitter compared to other piezo-forms. Large displacements or forces cannot really be generated. These films can be used, however, as sensors to detect **micro-deformations** of a surface. Besides, they can be used in anything from switches to music pickups. The same PVDF material also exhibits pyroelectric properties in which an electrical charge is produced in response to a temperature variation. Some properties of Piezoelectric materials are: [3]

- Density: 4100 kg/m^3
- Volume fraction: 45%
- Acoustic Impedance (Mrayl): 15
- q_m: 26
- high compressive strength

Innovation

There are several interesting new developments in the area of smart paint that utilize piezoelectric materials. These paints comprise tiny distributed piezoelectric particles throughout a polymeric matrix. A main purpose of applying this kind of paints is **damage detection and assessment**. [1]

Table 1. Properities of four different Piezo Composite Materials. [3]

Material type	Volume fraction (%)	$\varepsilon^t_{r\,33}$	tanδ	Acoustic impedance (Mrayl)	k_t	q_m	Density (kg/m^3)
pcm1-45	45	565	0,008	15	0,6	26	4100
pcm2-45	45	832	0,023	15	0,6	26	4000
pcm6-45	45	1880	0,022	13	0,66	25	4100
pcm6-15	15	620	0,023	5	0,72	13	1700

Table 2. Properities of different Piezo Ceramic Composites. [3]

Material	Navy type	$\varepsilon^t_{r\,33}$	d_{33}	k_{33}	Curie Temp (°C)	Density (kg/m^3)
PZT401	I	1400	315	0,67	330	7600
PZT5A1	II	1800	409	0,67	370	7650
PZT5H1	VI	3400	620	0,72	200	7350
PZT508-HD		3900	720	0,75	215	7900
PZT-5K2 HD		6200	870	0,75	160	8200
PZT-5K4 HD		7100	950	0,75	150	8200
PMN / PT	"Single Crystal"	4500-6000	1200-2000	0,88	125-140	

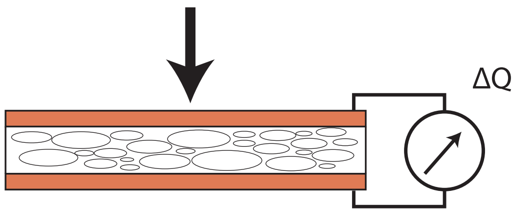


Fig 1

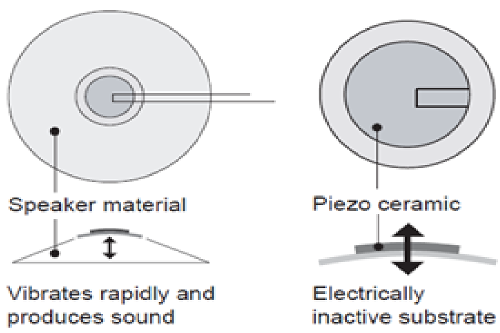


Fig 2

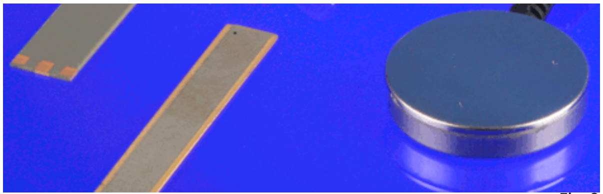


Fig 3

Applications

Piezoelectric materials have been used in skis to damp out undesirable vibrations. Here, the piezoelectric effect dampens vibrations by dissipating the electrical energy developed across a shunting. By using similar technologies in other situations in many products, vibratory movements can be selectively damped out.

Additionally, the most common type of sound sensor is based on the use of piezoelectric materials. A mechanical force produces a measurable electrical current. Respectively, acoustical sound waves produce a force in a piezoelectric material in a microphone, and as a result detectable current is produced.On the other hand, it can be used for sound absorption. The primary method is by friction, which basically decrease the elastic energy of the sound but energy-exchanging materials allow for more controllable and efficient exchange of elastic energy to another form.

Moreover, some materials of this category can produce energy as 'generators', directly producing useful energy. The energy can be in many forms: generated electricity (PV and thermo-PV), heat pump or engine (thermoelectric) as well as elastic energy (piezoelectric). The counterpoint to the energy-producing and absorbing materials is materials that focus on the form of the input energy instead of output energy. In other words, the purpose of energy-absorbing materials is to dissipate the input energy. Vibrations can be dissipated by the conversion to electricity (piezoelectric) or dampened by absorption produced by a material property change (magneto rheological, electro rheological, shape memory alloy).

Coatings based on these technologies are being explored in connection with 'structural health' monitoring. Deformations in the base material cause expansions or contractions in the piezoelectric particles in the coating that in turn generate detectable electrical signals. Piezoelectric devices can also be used in vibration monitoring. They have a particularly wide dynamic range and can be used for measurements over a wide frequency range. The measurement of vibratory phenomena leads to assessing the structural health of large structures. [1]

Further reading

- Manufacturers:
Morgan Advanced Materials
www.morganelectroceramics.com

Fig 1. schematic representation of the construction and functioning of an electret polymer film sensor. [1]
Fig 2. A common small piezoelectric speaker. It is based on the actuation capabilities of piezoelectric materials
Fig 3. Piezoelectric products. [3]

Refernce projects

Incorporating piezoelectric materials for active **sound reduction** and for **vibration absorption** in building components is as an important aspect. There are applications exploiting the piezoelectric efects as well as the inverse piezoelectric effects.

For example, **Aviva MUNICH building** in Munich's commercial district has remote-controlled, battery less, piezo radio switches for operating the Venetian blinds and lighting in the office rooms. A radio technology allows wiring and flushes mounted boxes to be dispensed. Thus, the arrangement of the interior walls is more flexible and walls can be moved relatively inexpensively.

The use of electret polymer film sensors has much more possibilities. One of the uses for these extremely pressure-sensitive and very thin sensors is for under floor coverings. In Finland in 2005, during an exoeriment, the floors of two detainment cells in a small police station were fitted with these devices. The sensors were placed between the concrete floor surface and the linoleum floor covering. If the police station is unmanned and prisoners escape from the cells, the system alerts a neighboring station over a digital mobile phone network. In Japan the Kaimin System was used to develop the "intelligent rooms". The system used polymer film sensors as sleep sensors in bed heads.

In Germany in 1995, a **weight-controlled** pavilion with optically changing envelope was constructed. It is a reactive structure to internal live load changes (with expansions and deformations) which can carry foot traffic. The building include seven modules of elliptical cross sections. Each module has two adjacent inner rings and one outside ring, which are attached to one another at the sides at the vertices of the ellipse. The external skin is formed of electro-optical glass elements. These elements are attached in rows to the outer ring and fastened on a crown of flexible supporting hairs with round cross sections and equipped with piezoelectric bender actuators. This ensures that the glass elements and the support hairs are not damaged on the relatively tightly curved surfaces. Voltages are generated depending on the vibrations caused by wind or people, which make the electro-optical layers change more or less dynamically from transparent to opaque. Therefore, the activities taking place can be distinguished not only from the deformations but also from the glass elements of the external skin. [1]

Fig 4

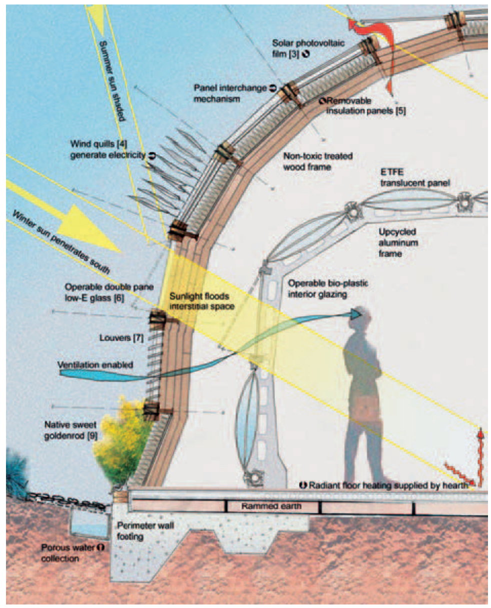


Fig 5

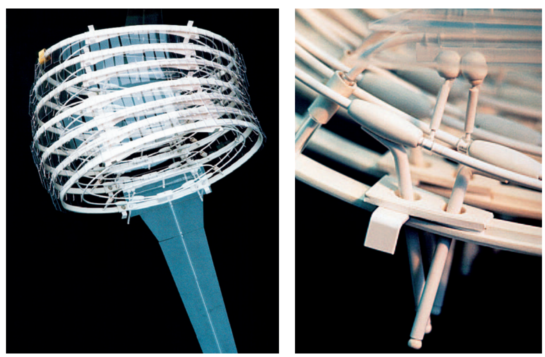


Fig 6

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3. www.morganelectroceramics.com

Fig 4,5. Building with solar cells (south side) and wind quills (north side) connected to piezoelectric cells. [2]
Fig 6. Demonstration model with supporting hairs equipped with piezoelectric bender actuators and individually attached electro optic/-chromic glass elements. [1]

10.PHASE CHANGE MATERIALS

Definition

Phase-change materials (PCM's) are the materials capable to **store or release energy** while changing their phase state between liquid, solid or gaseous.
Many materials exist in different physical states: **liquid, solid, gaseous**. Depending on environmental changes, those materials can change between these phases, absorbing, storing or releasing large amounts of energy in the form of latent heat. Therefore, phase change materials (PCM) are extremely interesting in terms of improvement of thermal comfort within a building and reducing energy consumption for heating or cooling demands.[1]

The phase change materials were first developed for use in aerospace industry. In 1960's NASA performed some experiments for application of PCM's for space flights and in 1990's German Aerospace Centre developed latent heat storage.[2]

PCM can be divided in several groups according to their phase change states, which are: solid-solid, solid-liquid, and liquid-gas. The change of the state of PCM's is usually caused by **increase or decrease in temperature**. Most suitable PCM for thermal energy storage are solid-liquid phase state PCM, because liquid-gas PCM are not practical due to large volume or large pressure required when in gas state and the transition of solid-solid phase state PCM is very slow.

Solid-liquid state phase PCM can be organic, inorganic and eutectics. Organic PCMs are paraffin and non-paraffin. Inorganic PCMs are salt hydrates and metals. Eutectics is a mixture of a minimum-melting composition of two or more organic or inorganic PCMs [3]

Remarks

The main **drawback** of using PCM's in building technology is a leakage problem, because PCM's need to withstand high number of phase change cycles and little change in volume. Best way to achieve this is encapsulation of PCM's. Such a technique allows to eliminate leakage problem and prevent incompatibility with structural materials.

One of the main characteristics to be considered while choosing proper PCM is **melting point** of PCM. PCMs suitable for application in building industry function with relatively low melting temperatures. "A phase change point outside the practical operational temperature range of the storage may make the wall completely useless as the temperature of the PCM may never reach the melting point."[4] The recommended melting temperature of PCMs for thermal energy storage in building for cooling or heating purposes falls in the range of 20-32 °C.[4]

Innovation

The fact that **microencapsulation** is the most effective way of using PCM's influenced the numerous researches on the best shell for this purpose. Because PCM's undergo many phase change cycles, shell has to be chemically and physically stable . Lately innovations include shells made out of polystyrene. [1]

Properties

Properties of PCM's may vary according to the type of the phase change material. Different PCM's might be useful for different applications. To select the proper PCM it is important to consider different aspects that influence the performance of PCM, and that are highly important for building industry. These characteristics include thermodynamic, kinetic, chemical and economic properties.[5]

- **Thermodynamic properties**: melting temperature and desired operating temperature range, high latent heat of fusion per unit volume, high specific heat, high density and high thermal conductivity, small volume changes on phase transformation and small vapor pressure at operating temperatures, congruent melting.
- **Kinetic properties**: high nucleation rate to avoid super cooling of the liquid phase, high rate of crystal growth to meet demand of heat recovery from storage system.
- **Chemical properties**: chemical stability, complete reversible freeze/melt cycle, no degradation after large number of phase change cycles, no corrosiveness, non-toxicity, non-flammability and non-explosiveness.
- **Economic properties**: low cost, large scale available.

Table 1. Comparison of energy stored and released during a 24 h period.[6]

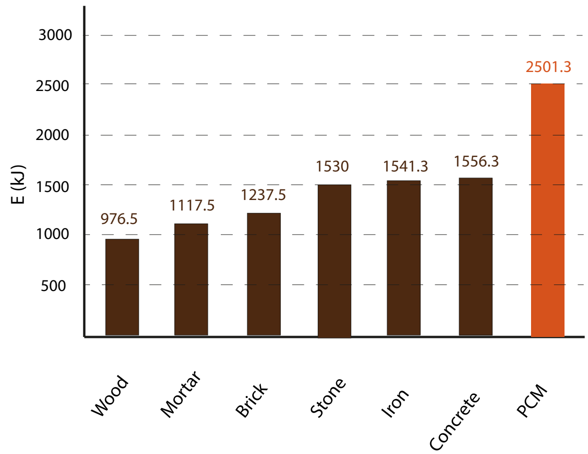


Table 2. Change in temperature required to store 5000 kJ.[6]

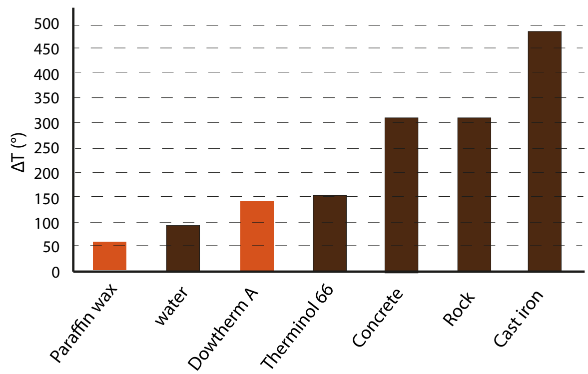
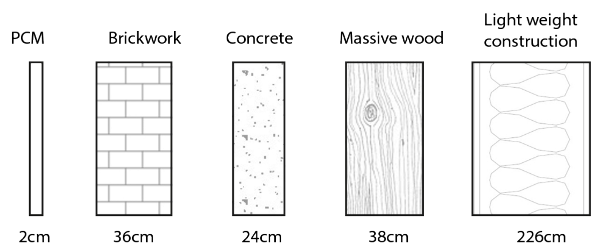


Table 3. Comparison of thickness required to store 5700 kJ over 10 K.[6]



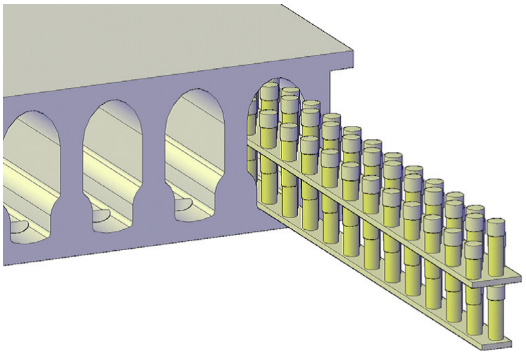


Fig 2

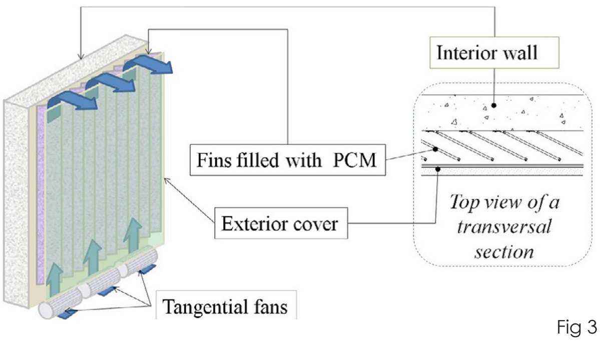


Fig 3

Fig 4

Applications

Phase change materials are widely used in **different industries** such as automotive, electronics, building, transportation, etc. Main purpose for PCM application is stabilization of temperatures and latent heat storage.

Companies such as BMW use PCM for latent heat battery to store extra heat when motor runs at operating temperature.

In transportation PCM's are used for temperature sensitive food transportation, where they substitute Diesel as a source of energy. They are charged while cheap power is available and release energy when cheap power is not available.

PCM's are widely used in electronic devices to prevent overheating and increase their performance. Due to overheating the lifetime, reliability and performance of electronic devices can be reduced significantly. PCM's are used to minimize peak heating loads.

The possibilities of PCMs application for building industry is very wide. It ranges from incorporation of PCM's in different building construction like roof or wall, construction materials and different building components like shading, glazing, etc.

PCM's are used to improve existing building storage mass, decrease cooling loads or increase thermal storage performance of a lightweight facade by incorporating PCM's in hollow core slab of roof or wall or using PCM's based systems like gypsum plasterboards. PCM's are also applied in active cooling systems to increase their performance.

Further readings

- http://www.glassx.ch/
- Axel Ritter, "Smart materials in Architecture, Interior Architecture and Design", Birkhäuser, 2007, Berlin
- Simone Raoux, Matthias Wuttig, "Phase Change Materials: Science and Applications (Google eBoek)

Fig 2. Integration of PCM in hollow core slab. [7]
Fig 3. Ventilated DSF in combination with PCM. [7]
Fig 4. Electronic Cooling. Neatly Packed PCM Profiles in BTS Telecom Shelter. [8]

Reference projects

Glassx is a company with base in Switzerland providing façade products with unique optical and thermal characteristics.

One of their products is **GLASSX®crystal G** - all-in-one façade element for homes and office buildings in light construction. It consists of a PCM core layer complemented by insulation glazing and integrated shading. GLASSX®crystal is framed and mounted just like a standard insulated glass unit. It can be streched from floor-to-ceiling, perform as parapet or skylight.

GLASSX®crystal is translucent, which allows daylight inside the building, it has good insulation and is able to store energy absorbing internal and external heat loads. This product with incorporated PCM's behaves like **glass** in terms of transparency, but thermally it acts like a **solid wall**. GLASSX®crystal is mainly used in several residential buildings and proved itself as reliable technique.

In the building built in 2005 by architect Dietrich Schwarz located in Domat-Ems, Switzerland,1500ft of GLASSX®crystal are used.

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7. Ruiz-Pardo A., Álvarez S. ,Cabeza L. F., Castell A. , Tenorio J.A.; ,Building integration of PCM for natural cooling of buildings'; in: Applied Energy 109 (2013) 514–522, p. 518

8. http://www.teappcm.com/

Fig 5

Fig 6

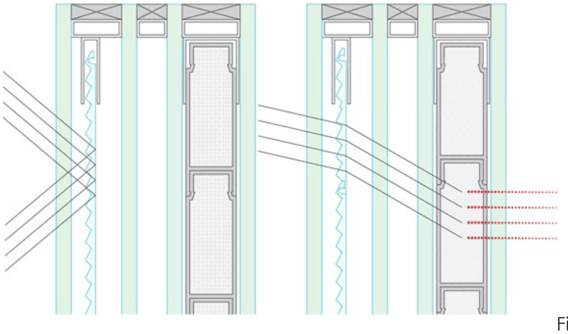


Fig 7

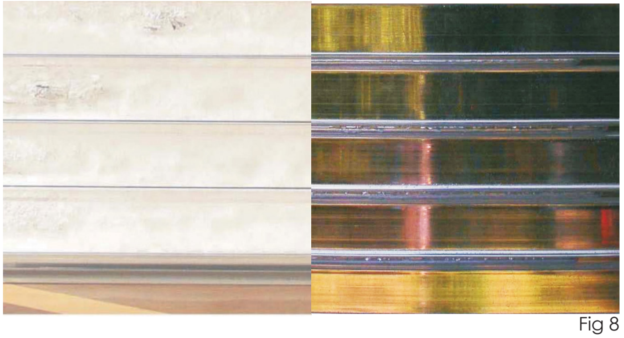
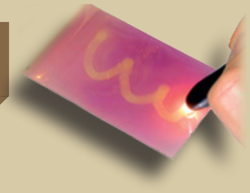


Fig 8

Fig 5. Front facade of Retirement residence, Domat-Ems, Switzerland, 2005 - Architect: Dietrich Schwarz.
Fig 6. Retirement residence, Domat-Ems, Switzerland, 2005 - Architect: Dietrich Schwarz.
Fig 7. Workin g princile of GLASSX®crystal.
Fig 8. Liquid and crystal state of PCM's incorporated in GLASSX®crystal.

11.PHOTOCHROMIC



Definition

Photochromic materials is a type of the **environmentally activated** chromic materials. [1] This is properties changing type of smart material - photochromic materials change their colour or transparency reversibly in respond to light intensity. [2]

Photochromic effect was first discovered by Markwald in 1899 and was called phototropy effect and considered to be only physical phenomenon. The term photochromism was first used by Hirshberg in 1950. [3]

Photochromic materials have two forms that have different absorption ratio. Depending on the colour of each form of the photochromic materials, the photochromic process in them can be positive or negative. The most common is positive photochromism, when the first form is colourless or slightly yellow and the second form is coloured. Negative photochromism refers to the case, when first form is coloured and the second is colourless.

When exposed to light with the particular wavelength molecular structure of photochromic material changes and starts to reflect light with different wavelengths, usually in the visible spectrum. When the light source is removed molecular structure turns to its original state.

Special feature!

Some photochromic materials like spiropyranes can also have **thermochromic** properties (see thermochromic material).

Remarks

Photochromic coating is expensive and therefore not cost-efficient. It is sensitive to heat, therefore function can't be controlled by users. Although small units have been produced in volume as a consumer product, cost-effective, large, durable glazing for windows are not yet commercially available because of its inadequate long-term behaviour, sensitivity to heat and relatively high manufacturing costs. The increasing usage of pure photochromic materials in the future is unlikely becuase of the limited application.

Innovation

Photochromic materials where of a high interest for architects because of ability to change colour and were seen only as aesthetic application for building design, however modern researches involve more technical aspects and possibilities of application of photochromic materials, such as indicators of changes of surface temperatures, energy state or time.

In order to improve photochromic application for building and automotive industry **hybrid photochromic/ electrochromic systems** are being developed.[3]

Professor Daniel Ruiz-Molina from Nanostructured Functional Materials Group, and Dr Jordi Hernando from the UAB's Department of Organic Chemistry tried to encapsulate photochromic material in the stable polymeric capsules with **oil core**. As a result efficiency of photochromic material increased. New product is able to change colour 10 times faster, has longer lifespan, lower fabrication costs and improved integration process.

Properties

Photochromic materials usually are produced using both organic and inorganic compounds. For architecture use most common photochromic materials can be divided in **four groups** according to the compounds used: spiropyranes, naphthophyrane, bacteriorhoodopsin and silver bromide. Depending on the compound, the properties of photochromic material might vary (Table 1-2).

General properties:[3]

- Temperature range between -20 °C and +250°C
- Large spectrum of colour range
- Absorption spectrum from 350nm to 780nm
- Availabile as suspension or powder

Table 2. Comparison of smart windows. [4]

System type	Spectral response	Interior visual result	Interior thermal result	Input energy
photochromic	specular to specular transmission at high UV levels	reduced intensity, but still transparent	reduced transmitted radiation	UV radiation
thermochromic	specular to specular transmission at high IR levels	reduced intensity, but still transparent	reduced transmitted radiation	heat (high surf. temp.)
thermotropic	specular to diffuse transmission at high and low temp.	reduced intensity - diffuse visibility	reduced transmitted radiation, emitted radiation and conductivity	heat (high and/or low surf. temp.)
electrochromic	specular to specular transmission towards short wavelength region (blue)	reduced intensity	proportional reduction in transmitted radiation	voltage or current pulse
liquid crystals	specular to diffuse transmission	min reduction in intensity - diffuse visibility	min impact on transmitted radiation	voltage

Table 1. Properties of different photochromic materials. [3]

	Spiropyranes, Spirodihydroindolizines	Naphthopyranes, Spirooxazines, Diarylethenes	Bacteriorho-dopsin (Br)	Silver bromide (AgBr)
	Organic	Organic	Organic	Inorganic
Application temp. range	40°C to +150°C	-40°C to +250°C	-20°C to +80°C (suspension) or +120°C (powder)	-20°C to +250°C
Absorption spectrum 1st form	350nm to 450 nm	380nm to 780 nm	570nm	
Absorption spectrum 2nd form	500 nm to 100nm	380 nm to 295nm	410nm	only variations of grey colour
Toxicity	Non toxic		Non toxic	Toxic

Applications

Probably everyone dealt with photochromic materials while wearing colour changing sunglasses. Reversible photochromics are also found in applications such as toys, cosmetics, clothing and industrial applications.
However the application of photochromic materials is not only limited to this. Photochromic materials are being used in supramolecular chemistry as molecular switches.
Another application of photochromic materials is 3d data storage. First researches on that topic were made in early 1960s and since then this echnology developed itself in a ready to use products like CDs, DVDs, etc.

Further reading

• Axel Ritter, "Smart materials in Architecture, Interior Architecture and Design", Birkhäuser, 2007, Berlin

Fig1

Fig2

Fig 1. Colour changing sunglasses[5]
Fig 2. 3d data storage examples[6]

Reference projects

Photochromic materials are less reliable than thermochromic or electrochromic materials. The application of potochromic materials in architecture is very limited.

"**The passive shading system from the future**" is a concept project from Institute of advanced architecture of Catalonia, that has not been constructed and is unlikely that it ever will. The main concept is to create passive shading system to provide coverage wherever its needed and let the sun in where it is desired by the passive control of the outside temperature.

Photochromic **paint** is incorporated into a transparent stretchable material to design "skin" elements attached on a frame with a flexinol strings. Because photochromic material elements are supposed to get darker when exposed to sunlight.

These shading elements are mounted on supporting structure which is fixed to secondary supporting structure and all this is mounted on the building.

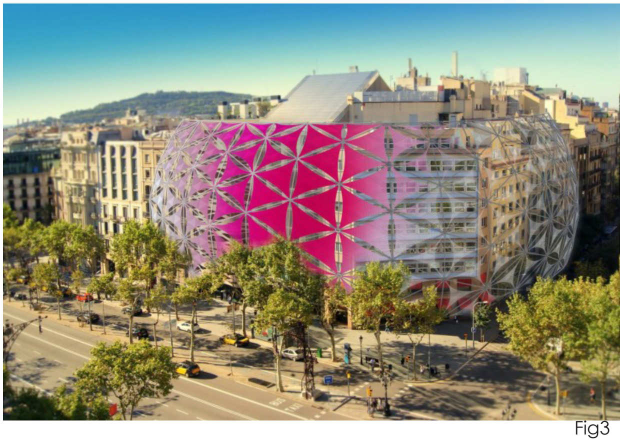


Fig3

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9http://www.iaacblog.com/maa2013-2014-designing-associativity/files/2014/03/r10-730x315.jpg

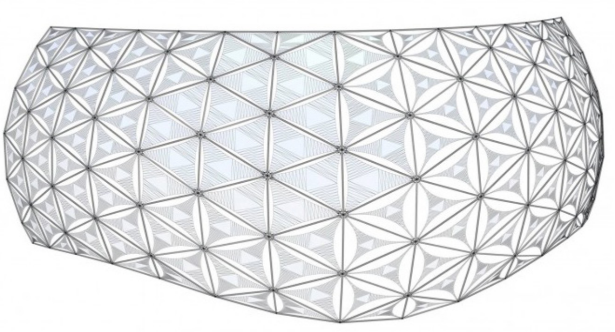

Fig4

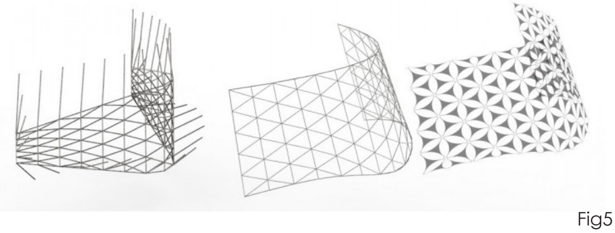

Fig5

Fig4. "The passive shading system from the future" proposal rendering[7]
Fig 5.: "The passive shading system from the future" 3d model[8]
Fig 6.: "The passive shading system from the future" assembly sequence[9]

12.SHAPE MEMORY ALLOYS

Definition

Shape memory alloys are innovative materials that have the ability to **return to a predetermined shape if heated**.
Shape memory alloys consist of two metallic compounds. Shape memory effect relies on a repeatable and fully reversible phase change transformation between two crystal structures. The crystal structure of shape memory alloys is a strong, hard austenitic net-like structure if it is above critical temperature, however it becomes soft, easily deformable martensitic crystal lattice below this temperature.[1] (Fig1)

There are t**wo different shape memory effects**: one-way shape memory effect and two-way shape memory effect.
One-way memory effect occurs when shape memory alloy is deformed in its cold state and can keep deformation until it is heated above critical temperature. After being heated, the material returns to its initial state and keeps it after cooling until it is deformed again.
Two-way memory effect occurs when material remembers two different shapes. This can be done after some "training" is applied. After the training, the material can remember low temperature deformation in the high temperature phase.[2] (Fig.2)

First researches regarding shape memory alloys were done in 1930's when A. Olander discovered pseudo-elastic behaviour of the AU-Cd alloy. After this shape memory effect was deeply studied by many scientist all over the world. [3]

Remarks

Shape memory alloys are very popular among architects because of variety of possibilities for design appllications. There is no reliable technique of using shape memory alloys developed yet. High costs of the material and its processing make its application difficult and less attractive. Thus most of the designs exist **only on paper** and it is unlikely that they will be implemented into reality in nearest future.

Innovation

One type of shape memory alloys that is called ferromagnetic shape-memory alloy is able to change shape when magnetic field is applied. [2]

Properties

Shape memory alloys can be manufactured in **any shape** and size.
Yield strength is lower comparing to steel, but some SMA have yield strength higher than plastic or aluminum.
Nickel_Titanium and Copper-Zinc-Aluminum alloys are most suitable for architectural application3.

Nickel_Titanium properties:
• available in large amount
• long practical lifespan
• strong shape memory effect
• better tensile strength compared to other SMA
• better elongation compared to other SMA
• ower costs compared to other SMA

Copper-Zinc-Aluminum properties:
• Easier production compared to nickel-titanium alloys
• Weak shape memory effect
• Worse tensile strength compared to nickel-titanium alloys
• Worse elongation compared to nickel-titanium alloys.

Table 1. Transformation temperature range of different alloys. [4]

Alloy	Composition	Transformation temperature range ^0C
Ag-Cd	44/49 % Cd	-190 to -50
Au-Cd	46.5/50 % Cd	30 to 100
Cu-Al-Ni	14/14.5 % Al	-140 to 100
	3/4.5 %Ni	
Cu-Sn	15% Sn	-120 to 30
Cu-Zn	38.5/41.5 % Zn	-180 to -10
Cu-Zn-X	A few % of X	-180 to 200
In-Ti	18/23 % Ti	60 to 100
Ni-Al	36/38 % Al	-180 to 100
Ni-Ti	49/51 % Ni	-50 to 110
Fe-Pt	25% Pt	Approx. -130
Mn-Cu	5/35 % Cu	-250 to 180
Fe-Mn-Si	32% Mn, 6% Si	-200 to 150

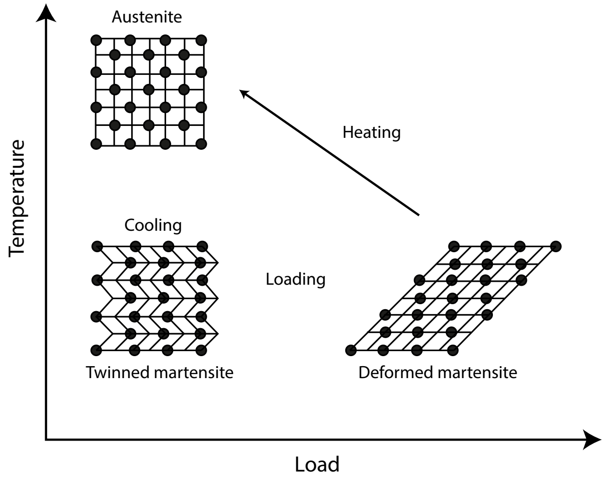

Fig.1

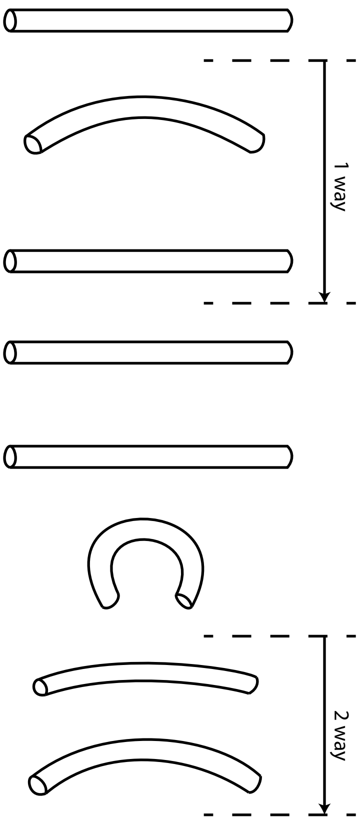

Fig.2

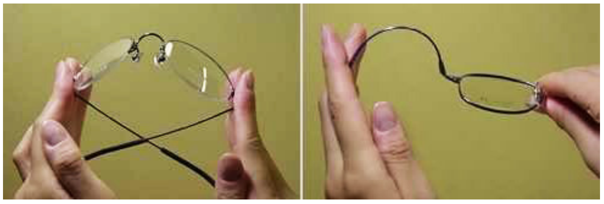
Fig.3

Applications

SMA can be applied in many different ways for different purposes. SMA applications include frames for eye-glasses, medical equipment, mobile phones antennas, etc.

SMA are widely used for **robots**. Hands, arms and legs made out of SMA are able to produce smooth movements like those of the human. Moreover, SMA are compact and strong and are able to control movement of an artificial joint by applying electric current with different time and size characteristics.

Nokia proposed new technology for mobile phone **utilization** using SMA. This technology would realease mobile phone parts after applying high heat, without any direct human assitance.

Shape memory alloys are also very common in medcine as diferent kinds of dental implants.

Further reading

- http://www.orangevoid.com/
- Shape Memory Alloys: Modeling and Engineering Applications (Google eBoek)

Fig 1. Austente and martensite phases.[5]
Fig 2. One-way and two-way shape memory effects.[6]
Fig 3. Glasses frame made out of SMA[7]

Reference projects

PixelSkin02 is a robotic prototype of interactive facade skin. ixel skin is a modular product made of robotic pixel-tiles as its generic unit. This surface concept uses the Shape Memory Alloy (SMA) to actuated triangular panels.

"Each tile consist of 4 such triangular panels with integrated SMA wire. Surface embedded micro-controller controls the opening of each pixel-tile by adjusting power-supply 20 times per second. Depending on the supplied opening-coefficient, each set of four panels **acts as a pixel** (255 states between fully open and fully closed). Technique called multiplexing allows to individually control the opening of each pixeltile." (Orangevoid)8.

PixelSkin02 was only tested on small prototype and it wasn't yet applied on real building.

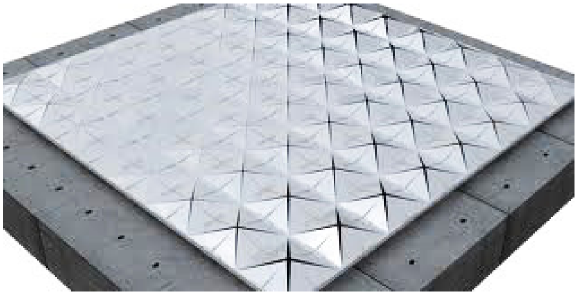

Fig4

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Fig4. PixelSkin02 tile mock up[9]
Fig 5.: PixelSkin02 facade proposal[10]

Fig.5

13.SUSPENDED PARTICLE DEVICES

Definition

Suspended particle device is a system where very thin organic liquid based suspension layer of fine polyiodides or parapathite particles (1 μm long) is used. This layer is placed between two glasses or plastic pieces. SPD activates applying **voltage**. When no voltage is applied, particles are randomly organized and block the light. Application of electric field forces **particles to orient** similarly and light can pass through.[1]

Such a behaviour of particles allows to control the amount of light and heat that enter the building. The amount of light and heat absorbed by SPD also depends on the **particle concentration**, type and colour. This makes SPD very attractive, because of easy and fast control that ca be manual or automatic, combined with modern technologies such as sensors, applications, etc. [2]

Special feature!

Unlike in products that use electrochromic technology, the response time of SPD technology does not depend on the size of surface of the product.[3]

Remarks

The size of SPD's is only limited by available coating web press machines used to produce SPD's.[3]
Common size of SPD's is limited to 120 cm width and 250cm height, but it is possible to extend width up to 200cm. [3]
Light absorbing particles used in SPD's block all areas of the visible spectrum except for dark blue. Therefore in switched off state SPD's products have dark blue to **blue colour**.
SPD film is flexible material that can be applied to curved surfaces. SPD's can be applied to indoor or outdoor conditions if certain protective measures are taken.

Despite of advantages of using SPD's it is essential to take into account that this technology **requires electricity**.

When using SPD technology it is important not to use direct current volatge, as this might lead to misfunction and SPD's will gradually darken. To avoid this alternating current voltage has to be used, because it prevents particals' tendency to migrate.[5]

Innovation

'Research Frontiers' patented technology that enables incorporation of SPD's on the existing windows.

Properties

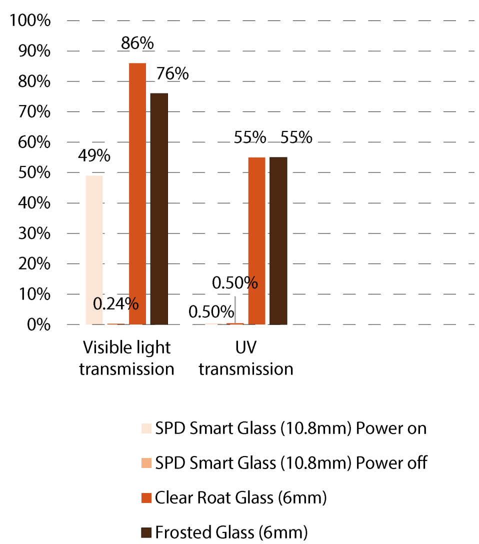
Visible light and UV transmission through SPD's depends on the layer thickness of SPD's film and the concentration of suspended particles, but the average visible light transmission is

- around 50% when SPD is switched on and
- 0.3% when it is switched off.
- UV transmission is around 0.5% for both states.
- Application temperature range: -40C to +120C. At temperatures below -40C, performance speed decreases.
- Power needed for SPD's is around 0.7W per m2.

Table 1. Visible and Solar transmission of dfferent smart windows. [4]

	Visible Transmission	Solar Transmission	Visible Reflectance	Solar Reflectance
Thermochromic				
Temperature of sample ⁰C				
20	0.73	0.44	0.13	0.21
30	0.60	0.37	0.20	0.24
40	0.27	0.18	0.52	0.37
50	0.21	0.13	0.59	0.41
Electrochromic				
Bleached	0.50	0.35	0.12	-
Coloured	0.15	0.09	0.09	-
SPD				
Clear (Switched on)	0.445	0.334	0.108	0.157
Tinted (Switched off)	0.004	0.11	0.07	0.11

Table 2. SPD smart glass transmission graph.[5]



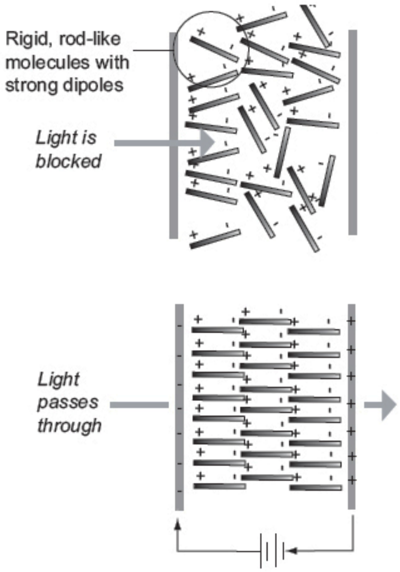


Fig3

Fig.2

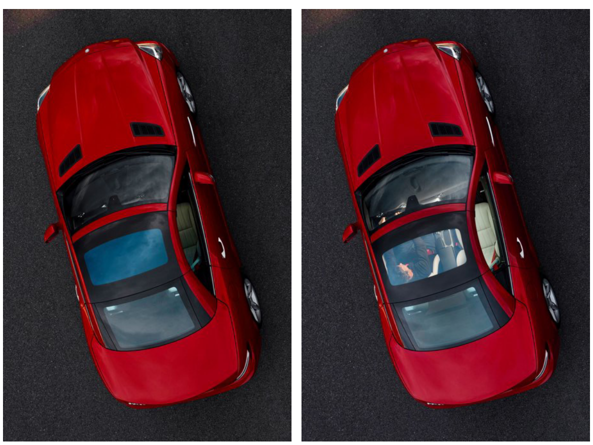


Fig.3

Applications

SPD technology is used mainly for **glazing** in different industries, such as aircraft, automotive architecture, marine industries.

Automotive and aircraft industries use SPD technology to protect interior from direct sunlight and reduce glare probability. SPD provide more light minimizing glare problems and increase comfort inside the vechicle.

For marine technology SPD's are useful to reduce **heat load** from skylights, portholes and partitions.

SPD technology is also very important for art industry, becuase of possibiiy to protect light-sensitive artifacts such as manuscripts, textiles and paintings.

Application of SPD's for architectural glazing is quite common and variety of different products is available on the market.

Further reading

- http://www.smartglass.com/

Fig 1. Working principle of SPD's. [1]
Fig 2.SPD's application to save sensitive art objects. [6]
Fig 3. Application of SPD's in automotive industry. [7]

Reference projects

The Globe of Science and Innovation is based in Cern in Switzerland. It's aim was to represent researches performed in **Cern**. The concept was to make building sustainable to represent new green technologies to the public. Theefore wooden structure of 27m height and 40meter wide was used.

At the top of the wooden structure is a skyight . The decision was to make it out of smart glass to control the amount of light in auditorium and avoid reflection from the big screen. As a result **SPD smart glass** of 50 m2 was placed on top of the dome.

Head of public outreach from The Globe of Science and Innovation, Bernard Pellequer states that SPD meets all practical requirements as long as it follows the concep of research and innovation approach of the building.

Fig4

Fig5

Retherences

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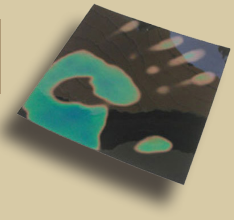
8. http://www.smartglassinternational.com/

Fig6

Fig 4. Skylight made of SPD smart glass, switched off. [8]
Fig 5. Skylight made of SPD smart glass, switched on. [8]
Fig 6. The Globe of Science and Innovation in Cern. [8]

14.THERMOCHROMIC



Definition

Thermochromic material is a material that is able to change **colour or transparency** as a reaction to **temperature changes**. This type of materials belong to a group of liquid crystals that undergo one more phase changing from crystal to liquid. This phase is called mesomorphs. In this stage thermochromic material maintains physical properties of crystals but can move like liquid.[1]
Changes in temperature affect molecular structure of the thermochromic material which results in difference between reflective properties of the material. As a consequence, original and newly obtained structure reflect different radiation in the visible range of electromagnetic spectrum and material's colour changes.[2]

The thermochromic effect was first noticed in 1909 by chemist Hans Meyer, but detailed explanation of it was given in late 1953 and 1963 by E. Harnik and G.M.J. Schmidt, and J.F.D. Mills and S.C. Nyburg. In 2003 microencapsulated thermochromic composites incorporated in different plastics were developed.[3]

There are two primary types of TC's, **liquid crystals** and **leuco dyes**. Liquid crystals type TC's can be made with response to accurate temperatures, but colour range of liquid crystals is very limited. On the other hand, leuco dyes have large spectrum of colors, but their response temperatures are more difficult to set with accuracy.[4]

Remarks

Thermochromic materials can be used for energy control in buildings to **prevent overheating**.
Fot this purpose, thermochromic materials with higher visible transmittance and transition temperature close to room temperature are used.

Thermochromic layers that adapt directly to changing sunlight intensity do not require any additional power supply. Windows with thermochromic layers do not require special installation, which makes this type of smart glazing cheap and attractive compared to electrochromic or other available technologies.

Despite all advantages, thermochromic windows are not very popular for building applications. This is because technology is not yet reliable for large areas and is not economically feasible.

Innovation

Incorporation of thermochromic material into plastic film of polyvinyl butyral (PVB) made it possible to easily apply thermochromic materials for glazing. Thermochromic PVB can be bought in rolls and processed with conventional fabrication equipment to gain adaptive glazing that meets designer's needs.[5]

Properties

For an effective performance of the thermochromic material the following characteristics are important:

- Transition temperature has to be between 20°C and 25°C, which is close to room temperature.
- Change in the optical properties should be as big as possible.
- Typical light transmission changes from 50% to 10% and back to 50%. Speed of the change depends on different physical factors, such as location, orientation of the window, time, season.
- Solar heat gain vary down to 0,13 if the full direct sunlight is present.
- Shading coefficient vary down to 0.15 if the full direct sunlight is present.

Table 1. Visibel and Solar transmission of dfferent smart windows. [6]

	Visible Transmission	Solar Transmission	Visible Reflectance	Solar Reflectance
Thermochromic				
Temperature of sample °C				
20	0.73	0.44	0.13	0.21
30	0.60	0.37	0.20	0.24
40	0.27	0.18	0.52	0.37
50	0.21	0.13	0.59	0.41
Electrochromic				
Bleached	0.50	0.35	0.12	-
Coloured	0.15	0.09	0.09	-
SPD				
Clear (Switched on)	0.445	0.334	0.108	0.157
Tinted (Switched off)	0.004	0.11	0.07	0.11

Table 2. Comparison of smart windows. [2]

System type	Spectral response	Interior visual result	Interior thermal result	Input energy
photochromic	specular to specular transmission at high UV levels	reduced intensity, but still transparent	reduced transmitted radiation	UV radiation
thermo-chromic	specular to specular transmission at high IR levels	reduced intensity, but still transparent	reduced transmitted radiation	heat (high surf. temp.)
thermo-tropic	specular to diffuse transmission at high and low temp.	reduced intensity - diffuse visibility	reduced transmitted radiation, emitted radiation and conductivity	heat (high and/or low surf. temp.)
electro-chromic	specular to specular transmission towards short wavelength region (blue)	reduced intensity	proportional reduction in transmitted radiation	voltage or current pulse
liquid crystals	specular to diffuse transmission	min reduction in intensity - diffuse visibility	min impact on transmitted radiation	voltage

Applications

Thermochromic materials are very attractive from aesthetical point of view. At the end of 20th century they were widely used in different daily use products like tooth brushes, mugs, rings, etc. The main purpose was nothing more than just **colour change** ability of thermochromics materials that was able to attract more customers.
First serious development of thermochromic based product was switching hydrogel enclosed between glasses. However, such a product was very costly and therefore didn't gain any popularity.
Nowadays, thermochromic materials are widely used in textile, furniture and decoration industries. Products such as papers, paints, different textiles incorporating TCs, thermochromic inks are available on a market.

The application of thermochromics also depends on the type of thermochromic material. Liquid crystals are difficult to work with and need high technology machines. Liquid crystals TC's are used in thermometers, stress testers, etc.
Leuco dye TC's are easier to work with, they are use dmainly for pakaching, advertising, textiles.

Further reading

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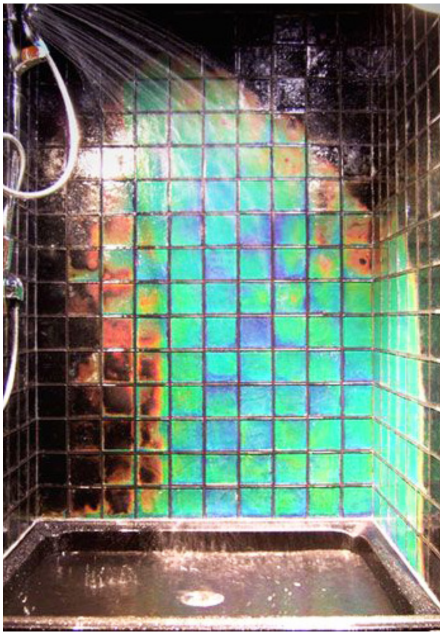

Fig.1

Fig.2

Fig.3

Fig1. Thermochromic tile for interior decoration of the bathroom. [7]
Fig.2. Mug design using thermochromic technology. [8]
Fig.3 Thermochromic wallpaper. [9]

Reference projects

PPG Industries and **Pleonit**, developed commercial window glass sytem that combines Sunlight Responsive Thermochromic interlayer (SRT) designed by Pleonit and SOLARBAN-low-emissivity glass designed by PGG. Product control solar heat gain and reduces energy costs.
Thermochromic film designed by Pleonit blocks both UV and IR transmition. The amount of visible light using this technology is only 45% to 90 % depending on sunlight intensity, however it is never 100% opaque. It darkens to a neutral grey when heat loads increase and returns to clear state as direct sunlight decrease.
Window wall (Fig. 4-5) is a mock up, constructed from 6mm AZURIA tinted glass, laminated to 5 mm clear glass with 1,5cm airspace filled with argon (90%) and air (10%) and 5mm layer of SOLARBAN® 60 low-e glass from PPG.

Fig.4

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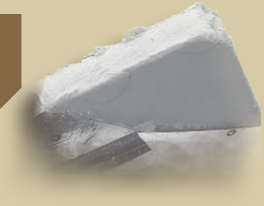
Fig.5

Fig4. Thermochromic wall mock up exposed to sunlight. [10]
Fig.5 Thermochromic wall mock up when direct sunlight is gone. [10]

15.VACUUM INSULATED PANEL



Definition

Vacuum Insulated Panel (VIP's) is **insulation** material that consists of two main parts of inner core material and barrier envelope (film). It provides better insulation than conventional insulation materials.

The common core materials are fumed silica, PUR foam and fiberglass. Entrance of water vapour and other gases into core material can significantly cause reduction in the thermal resistance of VIP. This can be avoided by the barrier (envelop) of VIP which protects the core material against water vapour and gases. The **fumed silica** is the best core material due to its low heat conductivity and higher service lifetime. However, it is one of the most expensive materials. The other core materials (PUR foam and fiberglass) are cheaper but they provide higher heat conductivity and lower service lifetime. To prevent the thermal resistance reduction of VIP during its lifetime, some chemicals such as getters and desiccants can be added in the core material to absorb gases and water vapour. This is not required for silica core material, but it is required for others.[1]

The VIP's envelop consists of multilayer polymer or several thin layers (100-200 nm thin) of the metal foil laminate. It should be mentioned that the vapour and gas transmission rate from metal foils is extremely low. However, the high thermal conductivity is the disadvantage of these metal films. So, it is common to combine the metal and plastic to produce metalized plastics and multilayer laminated foils.[1]

The following types of multilayer films are available in the market:

a) Metal foils; which consists of an outer polyethylene terephthalate (PET) layer, aluminum barrier layer and a PE inner layer

b) Metalized films consisting of up to three layers of aluminum-coated PET for the outer and barrier layers and a PE sealing layer

c) Polymer films based on nylon, polyester or polypropylene. However, the application of this type is limited because of higher gas and vapour permeability rate.

Remarks

The barrier envelop, that is needed to maintain the vacuum, forms a cold bridge at the panel corner because of extending from the warm side to the cold side of the panels.[2]

Three different kind of **thermal bridge** can be identified for the application of VIP in building; in this essay only three of them are explained with elaboration: Thermal bridge due to

1. VIP envelope
2. component edge constructions(spacers)
3. mounting system (load bearing structure such as window frame, post, etc.)

VIP's are **not as flexible** as conventional thermal insulation materials. They are difficult to cut because of vacuum layer, Therefore if non standard size panels are needed it is essential to order them separately, which results in high costs. Due to the price, VIP's application for residential buildings is not common, however if very low thermal conductivity or limited space constrains are required VIP's might be economicaly feasible solution.[3]

Innovation

The VIP is **damage sensitive** material and needs high level of attention during the construction process. To increase the durability of VIP, the vacuum insulated sandwiches (VIS) are used. This type of VIP is more robust and is covered by a stainless steel casing. VIS can perform as art of load-bearing system and even take loads.[4]

Properties

The thermal performance of the VIP depends on envelope thickness and its thermal conductivity, panel dimensions, core material thermal conductivity and seam dimensions.

The general properties of VIP are:

- Thermal conductivity of VIP is 4.10-3 W.m-1K-1
- High thermal resistance
- Environmentally and sustainable friendly
- Low effective weight
- Good acoustics insulator because for sound transfer medium is needed, which is absent in VIP.

Table 1. Thermal conductivity of aerogel and other conventional insulation materials.[5]

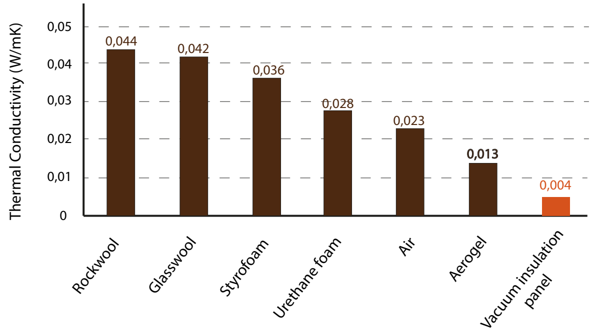


Table 2. Insulation thickness comparison between VIP and other insulation materials. [6]

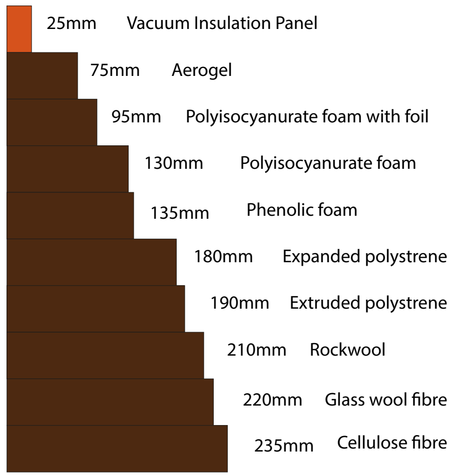


Table 3. Comparison of the mass density of VIP with other insulation material. [7]

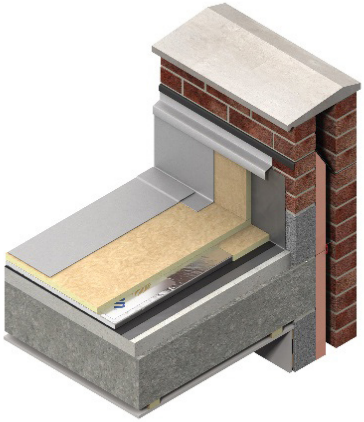


Fig 1

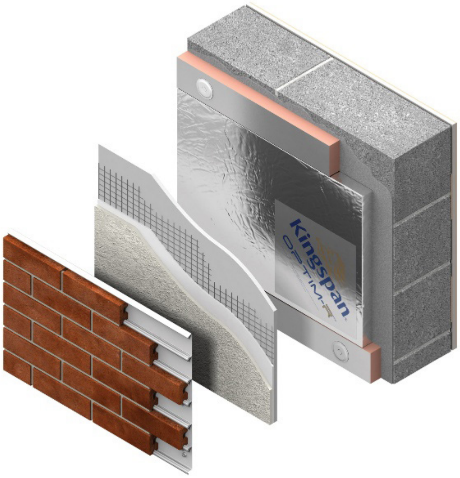


Fig 2

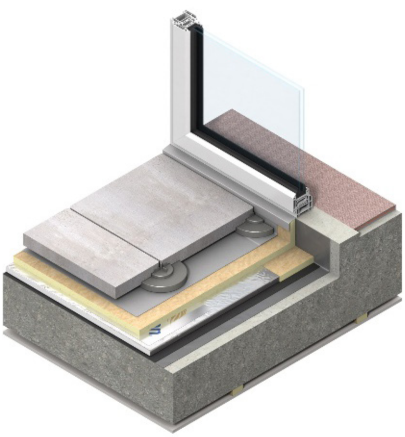


Fig 3

Applications

VIP's are mainly used in building industry. The fact that less thickness compared to traditional insulation is required to achieve same thermal insulation performance, makes this product very attractive for architects and engineers. Despite the fact that vacuum insulation panels are relatively innovative product, they are already introduced to the market in large-scale production.

Vacuum insulated panels application for buildings is very broad. It ranges from existing building insulation on the inside or outside to door or window frame insulations.

Because of its characteristics, VIP is very interesting for **renovation purposes**. It is possible to install VIP outside in order to save interior space. Vacuum insulated sandwiches are used in curtain walls, doors and window frames. VIP's are also used for roof, balcony, terraces, etc. Different building installations, such as pipe insulation, under insulation of floor heating also use VIP's.

Further reading

- http://www.va-q-tec.com/
- MartinTenpierik- Vacuum Insulation Panels Applied in Building Constructions-M.J. Tenpierik, Delft, 2009

Fig 1. VIPs used in flat roof constructions. [8]
Fig 2. VIPs used in external wall applications. [8]
Fig 3. VIPs used in balconies and terraces. [8]

Reference projects

In 2005 **Martin Pool Architects**' in Munich designed residential and office building that is an example of low energy building design. This was the first large scale building using VIP's technology.
Building is located in Munich in a well-known area where property price is relatively high and **space** is **limited**. This is six-storey high residential/office building with seven apartments and six office spaces. Total area is around 1350 m^2. It achieves heating requirement of just 22 kWh/m^2.
In order to achieve such a value, 25cm insulation would be needed which would take 125m^2 more space, which was equal to 10% of useable area.
In order to make it low energy design building and save space, **2cm thick VIP'**s and 8cm layer for cover and protection were used. The minimization of the stairs between interior and balcony were achieved because of application of VIP. In some areas VIP's were integrated in window façade systems.

Fig 4

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Fig 5

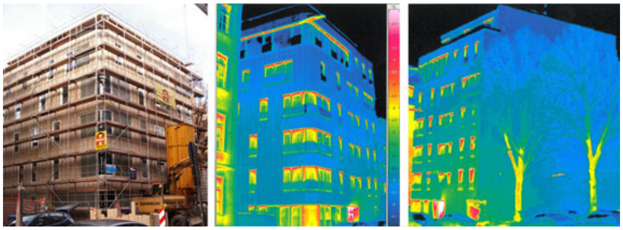

Fig 6

Fig 5.: The six-storey residential and office building in Munich-Lehel. [9]
Fig 6 Facade of resibential building in Munich-Lehel. [10]
Fig 7 Infra red pictuers, front and back side of building. [11]

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APPENDIX Complete table with all materials

Material	Advantages	Disadvantages
1-Aerogel	- Having lowest density in solid materials - Having lowest optical index of refraction - Having lowest thermal conductivity - Having lowest speed of sound through a material - Extremely durable	- extremely fragile and brittle
2-Dye-sensitized solar cell	"- Low cost - Producing electricity in low light - Retrofitting in existing building -No toxic emission during the production	-Cannot be bend or curved - Low efficiency - Limited lifespan"
3-Electrochromic	- Creating a surface with variable emittance - Controlling the visible light - Achieving excellent view with reasonable contrast	- Expensive - Undurable(degrading after only 10-20 years)
4-Hydrogel	- Self regulating control - Withstanding high level of deformation - The capability to avoid radiant loss from the inside during the winter - Providing diffuse light even during diminishing of the view - Changing the thermal conductivity in high temperature and improving the thermal insulation	- Inability to stop or start the transition from transparent to opaque - Requiring a good seal and special measure in the freezing temperatures
5-Liquid crystals	- Switching quickly to transparent or translucent - Providing diffuse light with maximum daylighting - Filtering 99% of UV light - Relatively easy to use - Adequate fire resistance	- Expensive for manufacturing and installing - Expensive for replacement - Relatively heavy - Having limited view from oblique angles - Hardly satisfaction
6-Magnetostrictives	- Using in dynamic applications - Having very low hysteresis - Using for damage detection and assessment	- Brittleness in tension and shear stresses - expensive - Disability for machining with standard tools such as mills - Non-flexible
7-Microblinds	- Lightweight - Very thin - Invisible shading system - Very quick activation	- Under development - Expensive - Not completely relaible
8-Mineral ad/absorbents	- Easy to apply and use - Releasing relatively low dust or not at all - Able to be incorporated into different construction - Resistant against mechanical load - Insensitive to mechanical vibrations - Durable for large temperature range - Maintenance free	- Not available universally - No adequate fire resistance - Volume changes may be undesirable for specific applications

Material	Advantages	Disadvantages
9-Piezoelectric Ceramics/ Polymers	- Market presence - Different shape and sizes - Very long life span - Durable in compression - Possibility to cut and shape - Bending ability - Using for damage detection and assessment	- They must not be subjected to extreme mechanical or electrical loads - Detrimental effect by having contact with moist and/or corrosive media
10-Phase Change material	- Capability of storing or releasing large amount of energy - Low cost - Availability in large scale - Non flammable - No degradation	- Leakage problem
11-Photochromic	- Large spectrum of colour range - Reducing the light transmission without missing transparency	- Relatively high manufacturing costs - Inability to be controlled by users - Are not commercially available
12- Shape memory alloys	- Returning to a predetermined shape if heated - Long practical lifespan -Manufacturing in any shape and size	- Expensive - No reliable technique for using them
13- Suspended particle devices	- Ability to be applied to curve surfaces because of its flexibility - Can be applied for indoor and outdoor conditions	- Requiring electricity
14- Thermochromic	- Doesn't require any additional power supply - doesn't required special installation - Relatively cheap - Ability to use with higher visible transmittance	- Is not reliable for large areas - Is not economically feasible
15- Vacuum insulated panel	- High thermal resistance - Very low thermal conductivity - Low effective weight - Good acoustic insulator	- Expensive - Subjected to thermal bridge - Non-flexible - Very sensitive to damage