BIOMIMETIC ARCHITECTURE AS A NEW APPROACH FOR ENERGY EFFICIENT BUILDINGS

By

MARIAN AZMY NESSIM

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
In
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Title of Thesis : **Biomimetic Architecture as a New Approach for Energy Efficient Buildings**

Keywords : **Climate change, Global Warming, Biomimcry, Smart Materials, Shape Memory Polymers**.

Summary :

This thesis took a new approach in handling the global warming problem by learning from nature or through studying biomimicry and trying to translate it to architectural elements. The researcher focused on the smart material because they sense and respond on their own to the environment. After reviewing different smart materials, the researcher worked with Shape memory Polymers that respond to temperature stimulus and through holding different experiments and running ANSYS simulation with different samples, the final SMP sample sheet was able to move and open allowing air flow rate that complied with Egyptian Ventilation Code.

TO MY FATHER’S SOUL

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NOMENCLATURE

TB : Thermo Bimetal

MEMS: Micro Electro-Mechanical System

SMP : Shape Memory Polymers

SMA : Shape Memory Alloys

SME : Shape Memory Effect

CTE : Coefficient of Thermal Expansion

HTMSMA: High Temperature Shape Memory Alloy

Tg : Glass transition is the reversible transition from a hard and relatively brittle state into a rubber-like state.

Tm : Melting temperature is the temperature at which a given material changes from a solid to a liquid, or melts.

Ttrans : Thermal transition temperature related to the switching phase.

Rr : Recovery rate

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ABSTRACT

The whole world is facing a real danger and an ongoing problem that has already started decades ago, but yet still increasing, this problem is the “Global warming” associated with the rise in Earth’s temperature which comes with a list of harmful consequences on our beautiful planet.

This Global warming is caused by the Greenhouse effect that traps the heat through a layer of gases, and one of the main resources of these gases especially the Carbon Dioxide is burning fossil fuel to generate electricity.

So beside those negative effects globally, we in Egypt already faced a huge problem with electricity that we were not ready for, a lot of remedies and actions were taken to solve this problem but still we need to adopt more sustainable solutions.

As an architect, among other architects we hold the responsibility of designing energy efficient buildings, and the best tutor to learn from how to design such buildings is our great mentor Nature, which led this research to study Biomimicry and try to translate it into architectural elements.

The researcher presented six different principles that Biomimetic Architecture is based on, of which Smart Materials were chosen to be the point of research that will enhance the efficiency of electric consumption in addition to design principles also inspired from Nature.

After introducing Biomimetic Architecture and learning from its principles, the researcher discussed different types of Smart Materials and chose most convenient material to work with and it was Shape Memory Polymers due to its numerous advantages.

Also the researcher reinforced the research with case studies of projects that could set examples to learn from and were similar to the end result and target desired to achieve.

The researcher used different samples of the chosen material to study through lab experiments and finally reached the sample that realized the target which was to become an actuator and respond to certain temperatures without the use of any mechanical or electrical means.

Simulation runs using ANSYS software were held on the result of these experiments to compare it to the standards of the Egyptian Natural Ventilation Code, and the outcome was very satisfying and promising and could contribute in saving in electrical consumption and therefore helps in relieving the problem of electricity we are facing in Egypt, not to mention that by decreasing the electrical consumption, the burning of fossil fuel will decline and this will have a positive impact globally.

CHAPTER 1

INTRODUCTION

Our beautiful planet with its amazing details created by GOD is facing today a real climate change caused by the human interference in its ecosystem which was never seemed possible to believe that humans were capable of changing the basic physical and chemical properties of this entire huge planet, huge chunks of glaciers are falling off and melting in the oceans as one of the symptom of the rising temperature of Earth.

In this section the researcher will try to introduce to the reader the definition of climate change, its causes and consequences because this is the base on which the whole thesis is built on, the researcher as an architect amongst other architects has a role in protecting this planet, and the target of this thesis is to reach a small detail that would add to architecture to help decreasing one of the causes of global warming, by decreasing electrical consumption.

1. Global Warming

1.1 What are Global Warming and Climate Change?

As we just pointed out, our planet is facing a real climate change and extreme weather conditions that we are not used to, this is due to Global warming. We can define Global warming and climate change as "an increase in average global temperatures". It has been proven that human activities and natural events are the main contributing factors to the increase in average global temperatures where the greenhouse gases, mainly Carbon Dioxide (CO_2), increases more and more leading to a warmer planet, this warming planet will result in further climate change which will affect the whole planet in different ways, as will be discussed below in details. [1]

Fig. 1 Shows melting of ice in arctic regions. (U.S. Department of Commerce/ National Oceanic and Atmospheric Administration, 2015, http://www.esrl.noaa.gov/gmd/aggi/)

1.2 What are the main indicators of Climate Change?

It is now clear that Global warming has consequences on the weather, those consequences are explained by the US agency, the "National Oceanic and Atmospheric Administration (NOAA)", as follows: there are seven indices that are predicted to rise in the near future due to the warming world and they are: "Sea surface temperature, ocean heat content, sea level, temperature over land, temperature over oceans, humidity and tropospheric temperature". On the contrary, there are three indices that are predicted to diminish in the near future due to the warming world and they are: "Sea ice, glaciers and snow cover". [1]

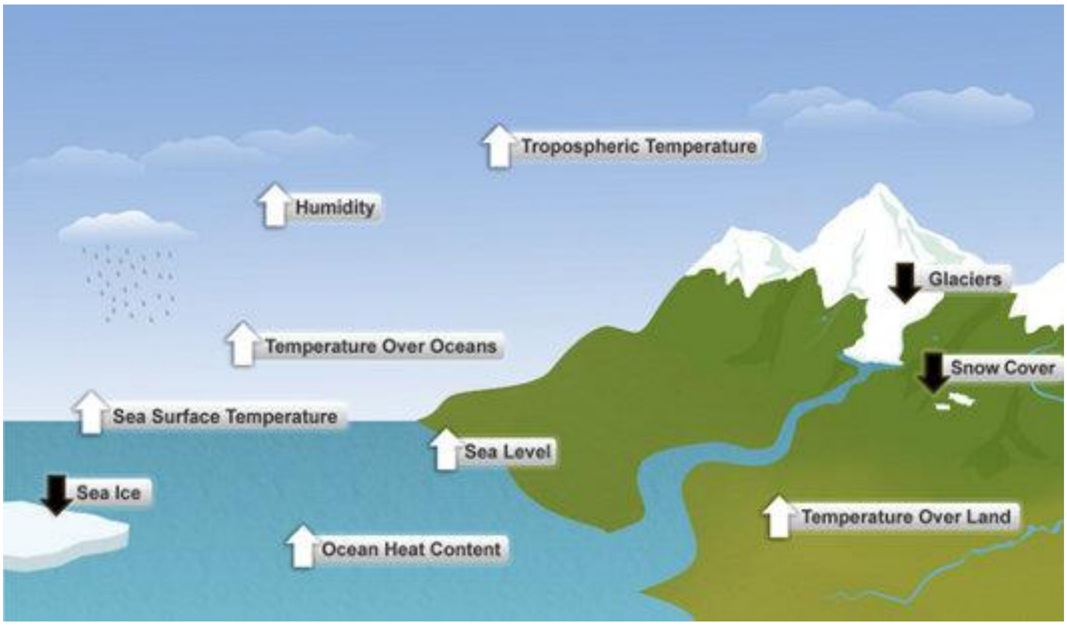


Fig. 2 Scientists in 48 Countries recorded ten indicators for a warming world as shown in the figure, and confirmed that the past decade was the warmest.
(U.S. Department of Commerce/ National Oceanic and Atmospheric Administration, 2010, http://www.noaanews.noaa.gov/stories2010/20100728_stateoftheclimate.html)

It is a growing crisis with economic, health and safety, food production, security, and other dimensions and we can now sense changes such as:

- Shifting weather patterns that threaten food production through increased unpredictability of precipitation.
- Ice-loss from glaciers and ice sheets.
- Rising sea levels which contaminate coastal freshwater reserves and increase the risk of catastrophic flooding.
- Ecosystems as diverse as the Amazon rainforest and the Arctic tundra, for example, may be approaching thresholds of dramatic change through warming and drying. [2]

1.3 What do we mean by the "Greenhouse Effect"?

Both terms "*greenhouse* and *greenhouse effect"* are used in conjunction together where we find the following occurs:

- The sun's energy heats the Earth's surface, this energy derived from the sun controls the weather and climate of the whole planet earth;
- After this energy hits the earth, it is radiated back to the outer space;
- Some of this radiated energy is trapped by a layer of atmospheric gases formed of water vapor, carbon dioxide and other gases, resulting in retaining heat in a way similar to the greenhouse glass panels;
- The layer of the atmospheric gases that trap the radiated energy is called "greenhouse gases".

So we can define the greenhouse effect as "the rise in temperature on Earth as certain gases in the atmosphere trap energy".

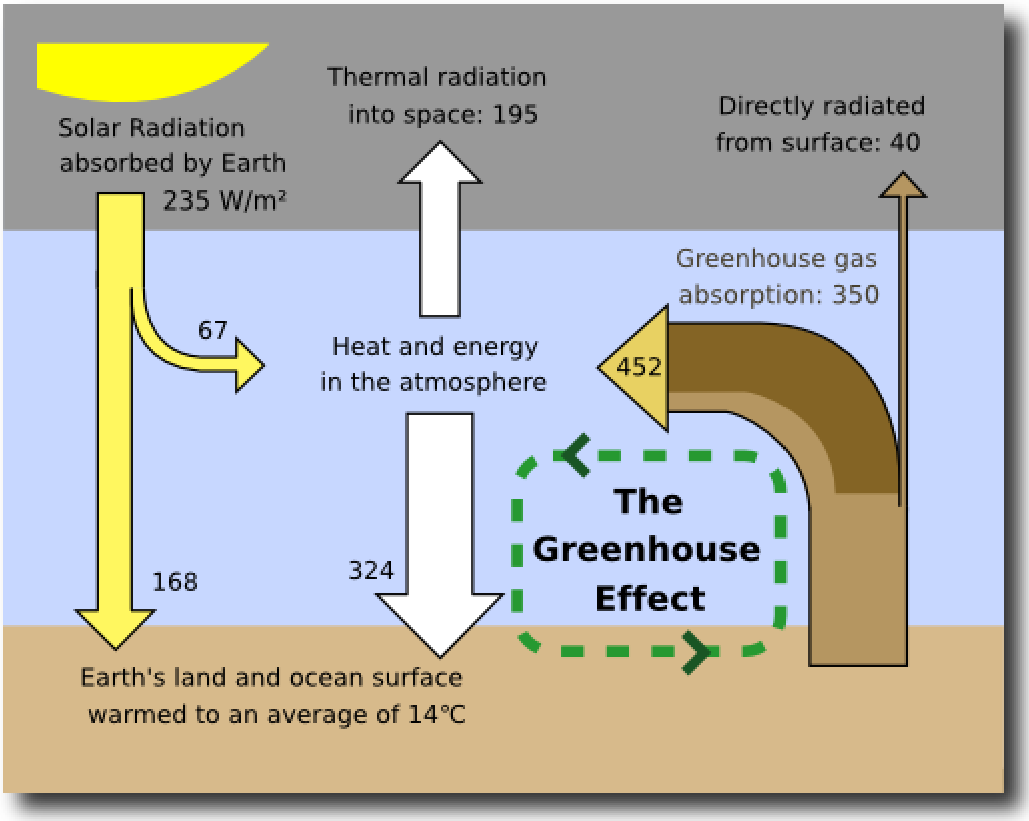


Fig. 3 Greenhouse effect in (W/m2).
(Wikipedia, 2016, https://en.wikipedia.org/wiki/Greenhouse_effect)

There are 6 main greenhouse gases and they are: carbon dioxide (CO_2), methane (CH_4) (which is 20 times as potent a greenhouse gas as carbon dioxide) and nitrous oxide (N_2O), plus three fluorinated industrial gases: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Water vapor is also considered a greenhouse gas.

In 2013, the Annual Greenhouse Gas Index (AGGI) was 1.34, which means that the warming influence increased by 34% since 1990, not to mention that the AGGI went from 0 to 1in 240 years, in other terms it took 240 years to reach 100%, and 23 years for it to increase by another 34%. CO_2 is the largest amount of gas contributing to the AGGI either in terms of quantity and increase rate and so CO2 in addition to other gases of greenhouse gases is referred to as CO_2 equivalent. In 2013, the atmosphere contained 479 ppm of CO_2 equivalents of which 395 is CO_2 alone. [1]

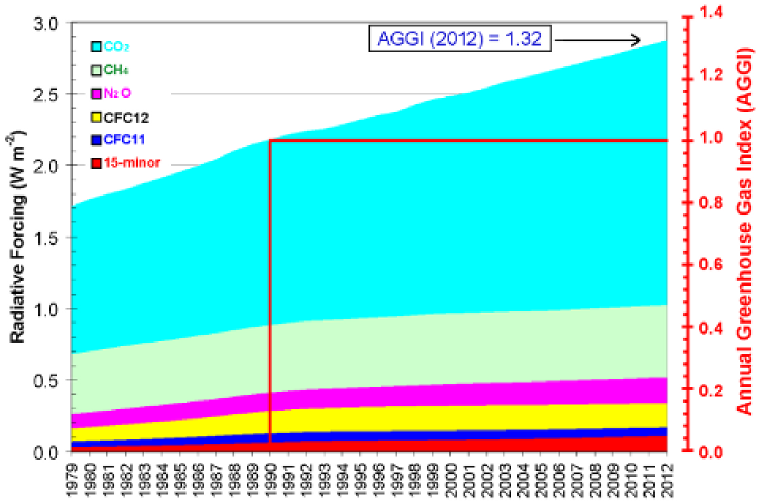


Fig. 4 Annual Greenhouse Gas Index
(U.S. Department of Commerce/ National Oceanic and Atmospheric Administration, 2015http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/)

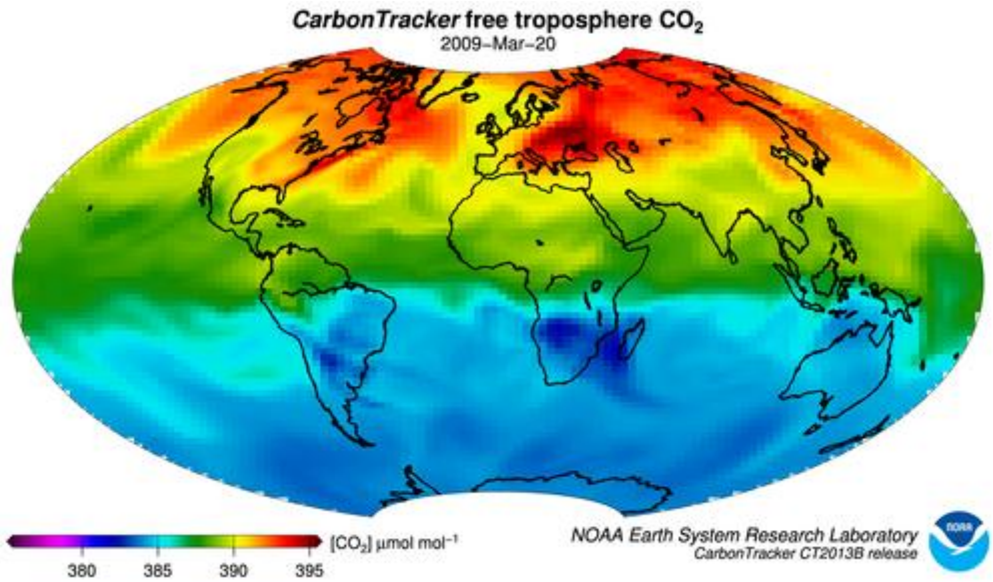


Fig. 5 Carbon dioxide weather shown is the daily average of the pressure-weighted mean mole fraction of carbon dioxide in the free troposphere as modeled by Carbon Tracker for March 20, 2009.
(U.S. Department of Commerce/ National Oceanic and Atmospheric Administration, 2015http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/)

1.4 Paris Conference for Climate Change - 2015

A lot of Climate Change Conferences were held over the years to analyze and discuss the causes and consequences of climate change and to take decisions and future actions that were to be imposed on government of countries mainly the developed ones.

Since 1995, the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC), have been meeting annually to promote the climate change agenda as well as seek long-term solutions to take us forward to a low-carbon and climate-resilient future.

Thousands of participants from government representatives to observer organizations take part in sessions. The COP 15 in Copenhagen in 2009 attracted over 24,000 delegates, including some 10,590 government officials, over 13,000 representatives of UN bodies and agencies, intergovernmental and non-governmental organizations, and 3,221 accredited media members. COP 16 / CMP 6 in Cancun last year had over 11,800 participants.

UNEP's work on climate change is shaped by the UNFCCC negotiations and aims at help countries strengthen their resilience to climate change by moving to low carbon societies, reducing emissions and improving the understanding of climate science to realize a Green Economy for the 21st century. [3]

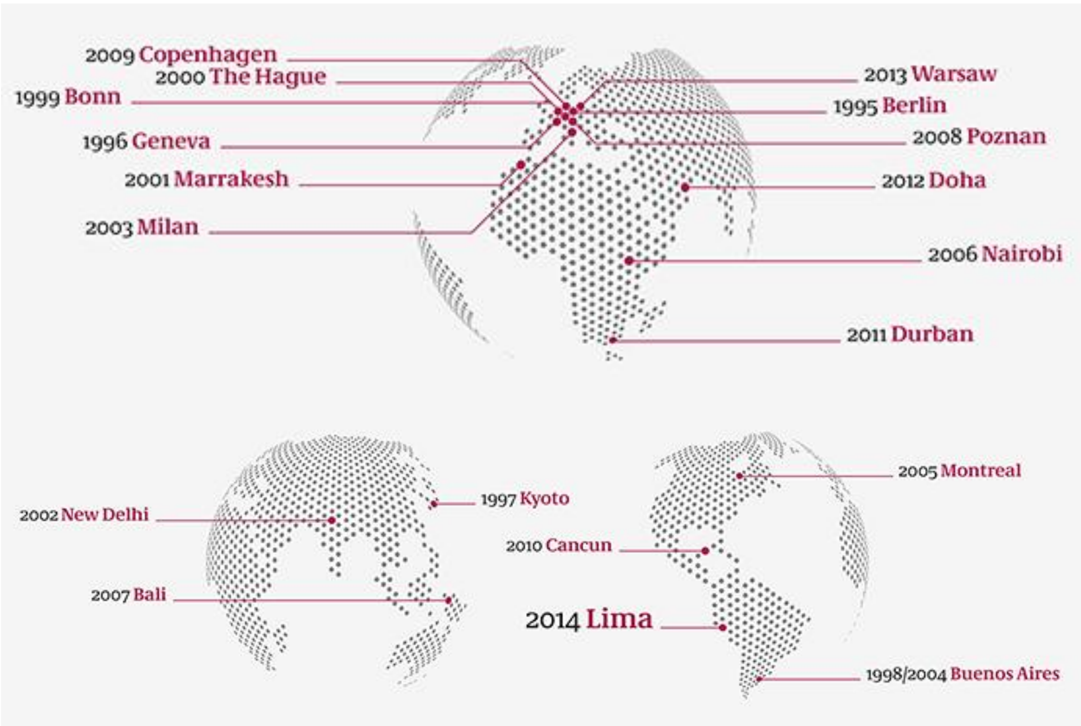


Fig. 6 United Nations climate change conferences
(United Nation Convention on Climate Change, 2016, http://unfccc.int/timeline/)

Last Climate Change Conference took place in Paris in 2015 and the main goal of the conference was to limit the rising temperature of the earth to 2 degree Celsius, and the following is a brief overview on the essential elements of Paris Climate Agreement:

The negotiating mandate for the Paris talks calls for a post-2020 climate agreement under the UNFCCC "with legal force" and "applicable to all Parties." In fulfilling this mandate, the Paris conference should produce a package: a core legal agreement and related instruments and decisions. Specific elements of the Paris package should include:

1. LONG-TERM DIRECTION

"Parties should reaffirm the goal set in Copenhagen and Cancún of limiting average warming below 2 degrees Celsius. The agreement should note the long-term transformation required to achieve this goal, as G7 leaders did earlier this year in calling for decarbonization of the global economy over the course of this century."

2. MITIGATION

"The agreement should establish binding commitments by all parties to:

• Submit and maintain nationally determined contributions (NDCs);
• Identify the measures by which they intend to achieve their contributions;
• Report regularly on their emissions and on their actions; and
• Update their contributions at common 5-year intervals. Countries' contributions should include an unconditional, quantifiable mitigation component, and may also include a conditional mitigation component that can be achieved with international assistance. Countries' initial NDCs should be submitted on their formal acceptance of the agreement, following domestic approval procedures. NDCs should be housed in an online registry. The agreement should set clear expectations that:
• All parties, through their self-differentiated contributions, are striving to put forward their best efforts;
• Subsequent contributions will represent a progression (e.g., in form, scope, or scale); and
• All parties will progress ultimately to absolute, economy-wide targets. The agreement should provide for common emissions accounting rules, including for land use-related emissions and withdrawals, and for international transfers of emission units. It also should establish a central project crediting mechanism, building on the Kyoto Protocol flexibility mechanisms, to accelerate links between carbon pricing systems. Supporting Mitigation and Adaptation in Developing Countries. A stronger support system should include:"

3. TRANSPARENCY AND ACCOUNTABILITY

"The agreement should provide for a transition from existing, bifurcated transparency procedures under the UNFCCC to a common transparency framework that:

• Requires all parties to report on their emissions; progress in implementing their NDCs; and support provided or received; and
• Subjects parties' reports to review by experts and by other parties.

This transparency framework should provide flexibility (e.g., in the timing or depth of review) to accommodate differences in capacity. The agreement should provide support to strengthen capacity in developing countries, with the clear expectation that all countries are working toward common standards. The agreement also should establish a facilitative implementation body comprised of experts and/or parties to consider questions of implementation raised by parties or arising from the review of a party's implementation, and to provide recommendations to strengthen implementation."

4. STOCKTAKING

"The agreement should establish a process to take stock of collective progress on mitigation, adaptation and finance every 5 years. The initial stock-take should take place no later than 2020."

5. UPDATING NATIONAL CONTRIBUTIONS

"Following these periodic stock-takes, all parties should be required to submit an updated NDC, with the expectation a Party's updated NDC will represent a progression beyond its earlier contribution. At the first updating, parties whose initial NDCs end in 2025 must submit new contributions through 2030; those whose initial NDCs end in 2030 must offer a new submission reaffirming or adjusting their contributions upward. After 2030, all contributions should follow a common 5-year timeframe. The updating process should include: the submission of new intended NDCs; an analysis of their aggregate effect on global emissions; in-session presentation and discussion of parties' intended NDCs; and submission of final NDCs."

6. ADAPTATION/LOSS AND DAMAGE

"To strengthen adaptation efforts, the agreement should:

• Set a collective aim of reducing the climate vulnerability and strengthening the climate resilience of ecosystems, economies and societies;
• Commit all parties to prepare, implement, and report on national adaptation efforts, with support provided to vulnerable countries with the least capacity to adapt; and
• Provide the opportunity, through regular stocktaking, to assess adaptation progress and priorities, and to exchange experiences and lessons learned. The agreement also should establish the Warsaw Inter- national Mechanism for Loss and Damage as a standing mechanism to develop approaches to address severe, irreversible climate impacts to particularly vulnerable developing countries."

7. FINANCE

"The agreement should set a collective aim of mobilizing finance and investment to support the transition to a low-carbon, climate-resilient economy. All countries should commit to invest their own resources in domestic climate efforts and to provide enabling environments for climate-friendly investment."

8. NON-STATE ACTORS

"The Paris outcome should recognize and encourage the contributions of non-state actors – including subnational governments, businesses, international institutions and civil society organizations – in support of countries' nationally determined contributions". [4]

After reviewing the climate change and the effort and conferences held to overcome this problem, we will shift to the electrical consumption here in Egypt according to the Ministry of Electricity and Energy.

The importance of analyzing the electrical consumption and energy resources is that nonrenewable energies derived from fossil fuel emits tons of CO_2 which is the main gas of greenhouse gases, hence contributing in raising the Earth temperature.

1.5 Energy Consumption

Description		2010/2011	2011/2012	Variance%
Peak load	**MW**	**23470**	**25705**	**9.5**
Total energy generated	GWh	146796	157406	7.2
Hydro	GWh	13046	12934	(0.9)
Thermal(1)	GWh	118500	129361	9.2
Renewable(2)	GWh	1704.4	2004	17.6
Energy Purchased from IPP's(3)	GWh	27.3	29	6.2
Private Sector (BOOTs)	GWh	13309	12855	(3.4)
Isolated Plants	GWh	209	223	6.7

Table1: Electricity Generated for 2011/2012
(Ministry of Electricity and Renewable Energy, 2015, http://www.moee.gov.eg/english_new/EEHC_Rep/REP-EN2013-2014.pdf)

(1) Includes commissioning tests
(2) Connected to National Grid (Wind & Solar energy)
(3) Power purchased from industrial plants self generation (IPPs) year 2011/2012 as follows: Petrochemicals (17.74 Gwh), Carbon Black (0.5 Gwh), Talkha Fertilizer (5.29 Gwh) and Ghazl El-Mahala (5.41 Gwh) Medelec (0.03 Gwh). [5]

Description		2012/2013	2013/2014	Variance%
Peak load	**MW**	**27000**	**26140**	**(3.2)**
Total energy generated	GWh	164628	168050	2.1
Hydro	GWh	13121	13352	1.8
Thermal(1)	GWh	135473	138795	2.5
New and Renewable Energy(2)	GWh	1497	1446	(3.4)
Energy Purchased from IPP's(3)	GWh	33	62	87.9
Power Generated from Private Sector (BOOTs)	GWh	14264	14154	(0.8)
Power Generated from Isolated Plants	GWh	240	241	0.4

Table 2: Electricity Generated for 2013/2014
(Ministry of Electricity and Renewable Energy, 2015, http://www.moee.gov.eg/english_new/EEHC_Rep/REP-EN2013-2014.pdf)

(1) Includes commissioning tests
(2) Connected to The National Unified Grid (Wind & Solar energy)
(3) Power purchased from industrial companies self-generation (IPPs) year 2013/2014 as follows: Petrochemicals (34 Gwh), Carbon Black (1 Gwh), Talkha Fertilizer and Ghazl El-Mahala (27 Gwh). [5]

From the above tables we conclude that the thermal source of energy is the greatest source, and so therefore we use the most source of energy that emits large quantities of CO_2. And Table 3 shows the quantity of energy consumed by different sectors.

Type of Usage	2009/2010	2010/2011	2011/2012	2012/2013	2013/2014
Industries	38916	40702	42098	39887	37320
Agriculture	4834	4927	5560	6230	6310
Utilities	5555	5759	6010	5904	5962
Public lighting	7050	6186	6537	6210	5692
Governmental Entities	5443	5977	6385	7664	8297
Residential	47431	51370	56664	59757	61962
Commerical & others	9674	10238	10715	14605	17392
Total	**118903**	**125159**	**133969**	**140257**	**142935**
Interconnection& BOOTs	1277	1775	1869	661	650
Grand Total	120180	126934	135838	140918	143585

Table 3: Energy Sold by Purpose (GWh)
(Ministry of Electricity and Renewable Energy, 2015, http://www.moee.gov.eg/english_new/EEHC_Rep/REP-EN2013-2014.pdf)

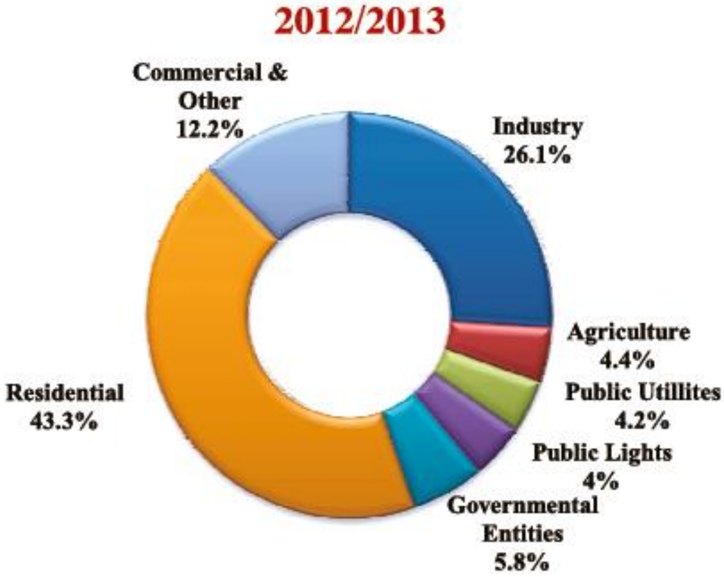


Chart 1: Electrical consumption in different sectors 2012/2013
(Ministry of Electricity and Renewable Energy, 2015,
http://www.moee.gov.eg/english_new/EEHC_Rep/REP-EN2013-2014.pdf)

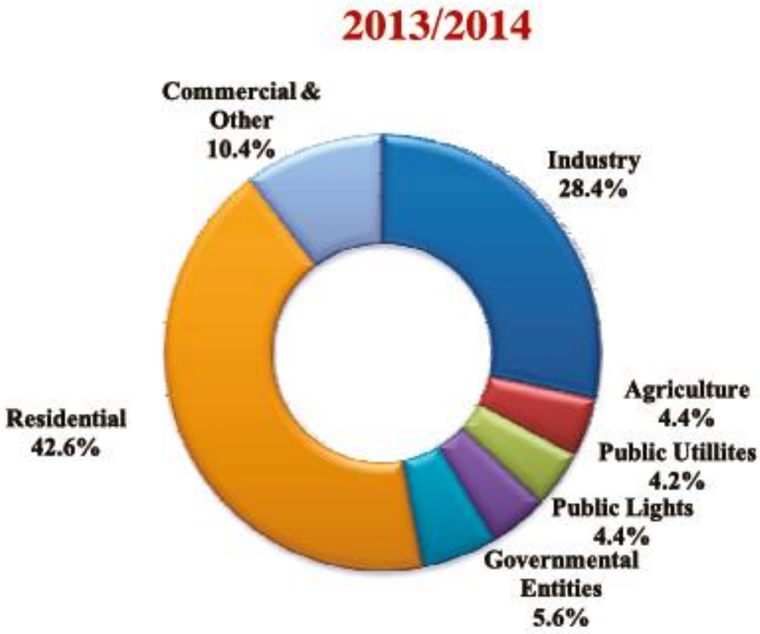


Chart 2: Electrical consumption in different sectors 2013/2014
(Ministry of Electricity and Renewable Energy, 2015,
http://www.moee.gov.eg/english_new/EEHC_Rep/REP-EN2013-2014.pdf)

From the above charts we conclude that the residential sector is the greatest sector in electrical consumption and this is the reason why architects should focus more on ways to reach thermal comfort while decreasing the usage of air-conditioning in residential buildings because the Air condition is a great consumer of energy and this could be achieved through a lot of means such as Passive designs in architecture, but through this thesis the researcher will introduce a new approach in order to reach thermal comfort, this new approach is “Biomimetic Architecture”.

2. Biomimicry

2.1 What do we mean by biomimicry?

The first time for the term “Biomimicry” to appear in scientific literature was in 1962, and it started to spread especially amongst materials scientists in the 1980s. The term “Biomimetics” or, less frequently used, “Bionics” was preferred by some Scientists. Not a lot of scientists wrote in this area but few from biological sciences writers such as: Janine Benyus, Professor of Biology Steven Vogel and Professor of Biomimetics Julian Vincent, have written extensively in this subject area. Julian Vincent defines it as “the abstraction of good design from nature” while for Janine Benyus it is “the conscious emulation of nature’s genius.”

There are two more terms related to the subject that are worth defining, first one is “Bio-utilisation” and second one is “Biophilia”. Bio-utilisation refers to “the direct use of nature for beneficial purposes, such as incorporating planting in and around buildings to produce evaporative cooling”. The biologist E.O Wilsob used to the term Biophilia to refer to a hypothesis where “there is an instinctive bond between human beings and other living organisms”.

Back to Biomimicry, there is an important difference that has to be highlighted between Biomimicry and Biomorphism from an architectural perspective. The Biomorphism approach is “using nature as a source for unconventional forms and for symbolic association”, and this was the modern architect’s frequent approach. This approach did create wonderful architectural pieces like the work of the famous architects Calatrava and Eero Saarine’s. Eero Saarine designed the TWA terminal based on the biomorphism approach (fig 7).

Fig. 7 TWA terminal (Pawlyn, M., 2011)

The reason why it is necessary to differentiate between Biomimicry and Biomorphism is because we as architects need a functional revolution rather than a symbolic revolution if we are targeting real transformations, and it is strongly believed that the Biomimicry approach will help us reach this target rather than Biomorphism approach. To date, biomimicry has only been applied in a limited extent to building design, where some frequent examples such as "termite mounds and spider webs" were the main source of inspiration. But in recent years, biomimicry has extended very rapidly and developed in other fields such as industrial design and medicine. [6]
So if we look closely at Living organisms we find out that they succeeded to endure changing climate by developing responsive mechanisms without either draining and consuming resources or disturbing ecosystems' equilibrium.

Definition of the term **Biomimicry** is derived from **"Bios"** meaning **life,** and **"mimesis"** meaning **to imitate** [7], and so it could be defined as follows**:**
"It is a new science that studies nature's best ideas and then imitates these design and processes to solve human problems." [6]
The main idea is that Nature which is imaginative by necessity, has already succeeded to solve many of the problems we are struggling with where we find that animals, plants, and microbes are the taking the role of skillful architects and engineers. They have figured out what works and what doesn't, what is appropriate and what isn't, and, most important, what continues and lasts on this planet Earth. Maximum economy, structural and behavioural adaptation, and functions integration are the strategies exploited by Nature in its evolution. The key word is Nature:

NATURE AS "MODEL"

"Biomimicry studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems".

NATURE AS "MEASURE"

"Biomimicry uses an ecological standard to judge the rightness of our innovations. After 3.8 billion years of evolution, Nature has learned: what works; what is appropriate; what lasts".

NATURE AS "MENTOR"

"Biomimicry introduces an era based not on what we can extract form the natural world, but on what we can learn from it". [8]

2.2 Origins of biomimicry

Historically, form has been the primary source of inspiration from nature, ranging from simple formal influences to the more symbolic translation into architectonic language. The Ancient Greeks fashioned the ornamentation of their columns and temples on local plant life to symbolize nature. Today designers are digitally developing an architectural vocabulary (most of which has yet to be constructed) which resembles forms found in nature. Can we find contemporary ways to "Touch This Earth Lightly" through biomimetic design and the analysis of an animal's physiological and behavioral adaptations to local environmental conditions?
Our knowledge of nature should be used more fundamentally as a resource for sustainable design and for the realization of more efficient buildings. [9]

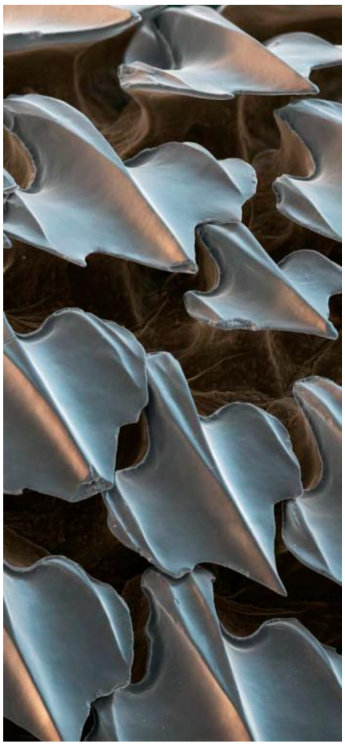
Around 1719, the French entomologist Réne-Antoine Réamur suggested that wasps' use of wood pulp demonstrated an alternative for paper production; this suggestion resulted in shifting the production of paper from using cotton and linen fibres. In 1809, Sir George Cayley, studied the streamlined form of dolphins and trout in order to reach lower coefficients of drag for ship hulls. [6]

Recently and especially in the last decade there has been a remarkable prosperous of biomimicry approach as we notice more and more designers comply with the demand for sustainable products. The following are some recent examples on adopting biomimicry in different fields of applications:

The Mercedes Company adopted biomimetic concept for its new car (fig. 9) which was inspired by the streamlined and roomy "boxfish" (fig. 8).

Fig. 8 The boxfish (Pawlyn, M., 2011)

Fig. 8 Although the "boxfish" is cubic in form, but it has a very low coefficient of drag. *(Ibid)*



Another great example on biomimicry is the Shark's skin. Sharks and other elasmobranchs have a very rough skin texture which creates a more streamlined surface.

Fig 10 shows scanning electron microscope image of spiny dogfish skin. *(Ibid)*

This characteristic was translated in the new biomimetic swimsuit as shown in fig. 10 and they proved to be so successful in allowing swimmers to make their way faster through the water which was the reason behind prohibiting it by "FINA", the governing body for world swimming. [6]

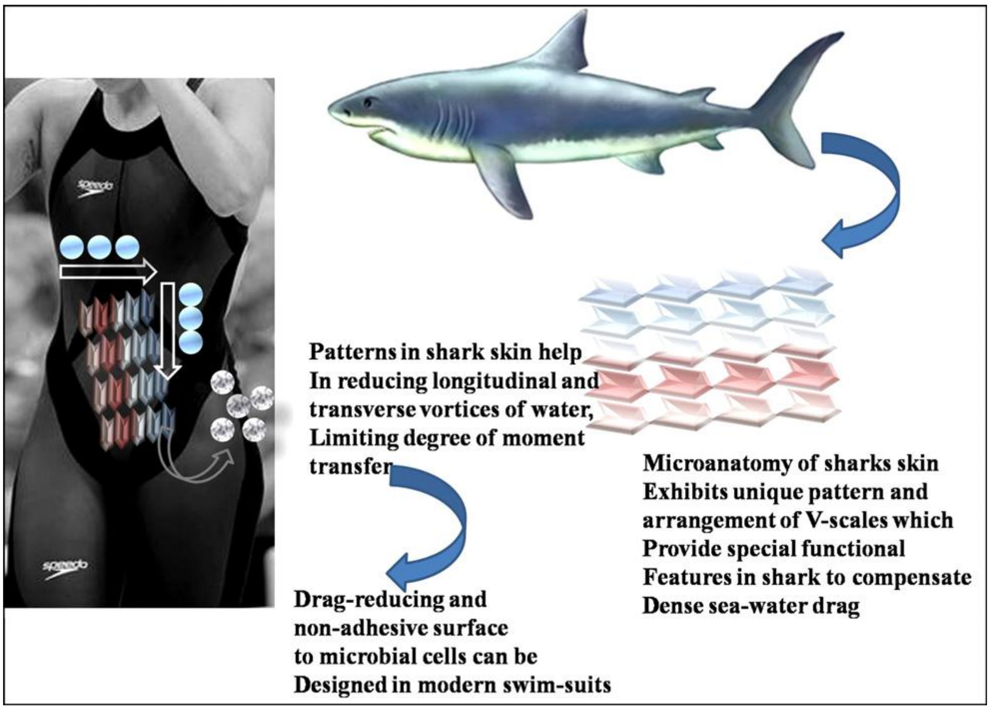


Fig 11 Low hydrodynamic surface drag was inspired by Shark skin and this was used in high efficiency swimsuits design with antibacterial effect. (Singh, A. et al., 2012) Surface drag of water close to the body which is called Riblet effect, is greatly reduced; this is due to Nature's unique design at microscale. Anti-microbial features mimicking shark skin micro-topography is shown in the figure by the arrows on the swim suit. [10]

Another example inspired by nature is Heliotropism which is a plants ability to follow the sun over time to increase solar exposure. The building shown in figure 12 used a heliotropic alghorithm to carve a void in the middle of a building in order to allow more sunlight in the internal space, consequently minimizing the use of artificial lighting and decreasing electric consumption.

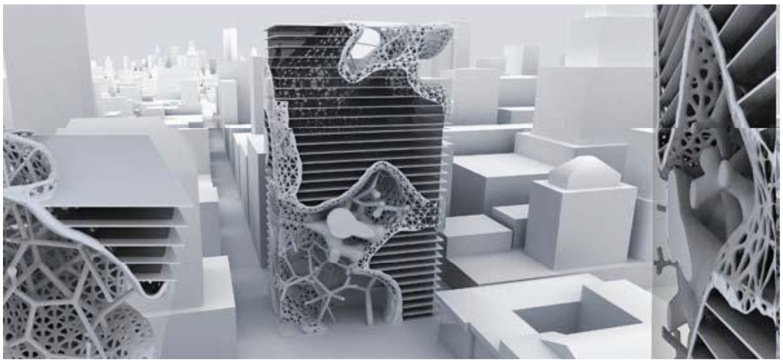


Fig. 12 Building inspired by heliotropism in plants
(Queen Wang, 2011,
http://queenawangatchelsea.blogspot.com.eg/2011_01_01_archive.html)

3. Thesis Structure

To translate biomimicry within architecture, architects must study well nature with its living organisms and means of living also materials that will provide us with properties that would fulfill the requirements for biomimetic architecture such as smart materials. There are lots of examples from nature that we as architects could learn from one of which is the human skin (Fig. 13).

Skin performs the following functions:

1. **Protection**: acts as an anatomical barrier from pathogens and damage between the internal and external environment in bodily defense; the adaptive immune system consists partly of Langerhans cells in the skin.
2. **Sensation**: contains a variety of nerve endings that react to heat and cold, touch, pressure, vibration, and tissue injury.
3. **Heat regulation**: the skin contains a blood supply far greater than its requirements which allows precise control of energy loss by radiation, convection and conduction. Dilated blood vessels increase perfusion and heat loss, while constricted vessels greatly reduce cutaneous blood flow and conserve heat.
4. **Control of evaporation**: the skin provides a relatively dry and semi-impermeable barrier to fluid loss. Loss of this function contributes to the massive fluid loss in burns.
5. **Aesthetics and communication**: others see our skin and can assess our mood, physical state and attractiveness.
6. **Storage and synthesis**: acts as a storage center for lipids and water, as well as a means of synthesis of vitamin D by action of UV on certain parts of the skin.
7. **Excretion**: sweat contains urea, however its concentration is 1/130th that of urine, hence excretion by sweating is at most a secondary function to temperature regulation.
8. **Absorption**: the cells comprising the outermost 0.25–0.40 mm of the skin are almost exclusively supplied by external oxygen, although the contribution to total respiration is negligible. In addition, medicine can be administered through the skin, by ointments or by means of adhesive patch, such as the nicotine patch or iontophoresis. The skin is an important site of transport in many other organisms.
9. **Water resistance**: essential nutrients aren't washed out of the body because the skin acts as a water resistant barrier.[11]

Thermoregulation in the skin takes place as follows:

1. Sweat is secreted by Eccrine sweat glands under the skin (a fluid containing mostly water with some dissolved ions) which travels up the sweat duct, through the sweat pore and onto the surface of the skin which causes heat loss via evaporative cooling; however, a lot of essential water is lost.
2. Tiny muscles under the surface of the skin called arrector pili muscles relax so that their attached hair follicles are not erect causing the hairs on the skin to lie flat and preventing heat from being trapped by the layer of still air between the hairs. These flat hairs increase the flow of air next to the skin increasing heat

loss by convection. Sweating is the only physiological way for humans to lose heat when environmental temperature is above core body temperature.

3. Arteriolar vasodilation occurs. The smooth muscle walls of the arterioles relax allowing increased blood flow through the artery. This redirects blood into the superficial capillaries in the skin increasing heat loss by convection and conduction.[12]

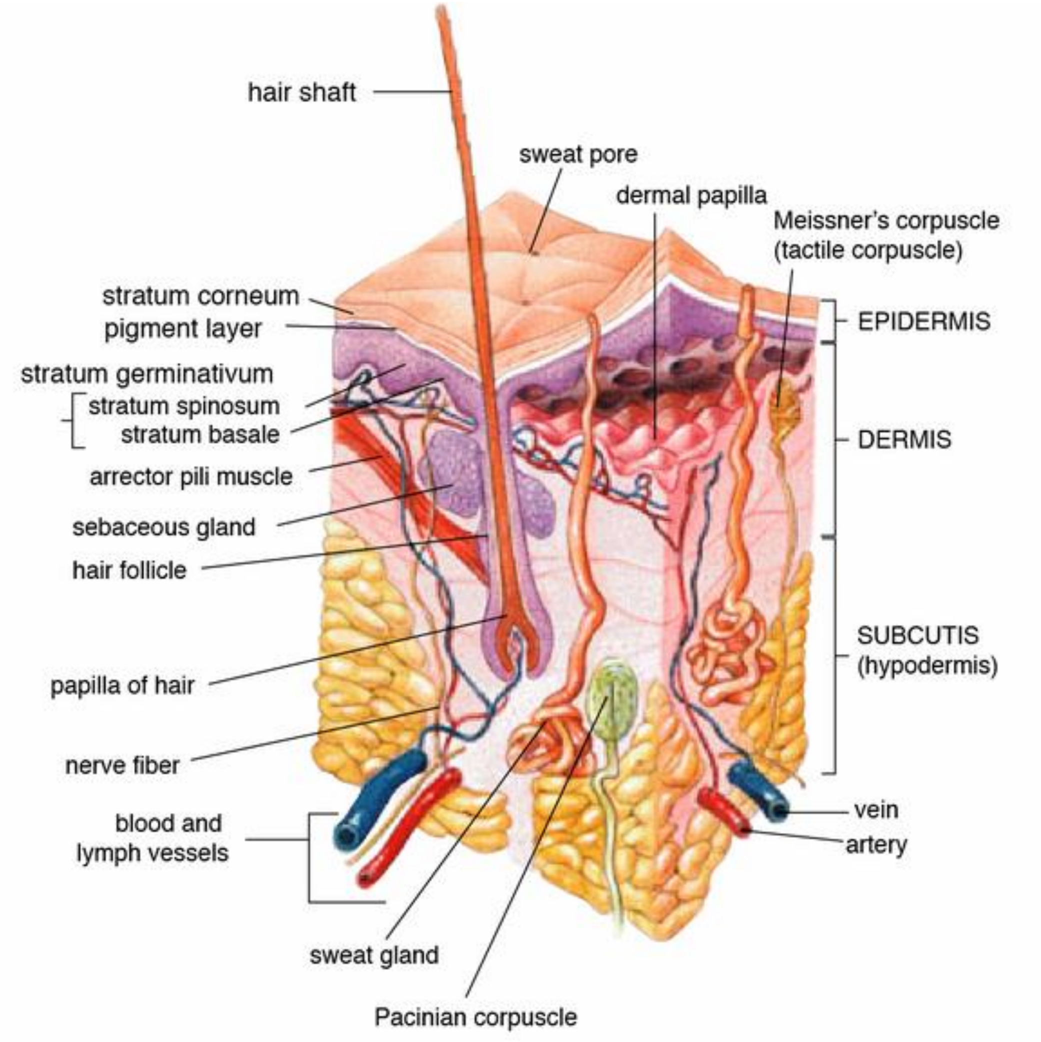


Fig. 13 Human skin
(Wikipedia, 2016, http://en.wikipedia.org/wiki/Human_skin#Functions)

Another example that we can be inspired by from nature is the Stomata Guard Cells: Guard cells are specialized cells located in the leaf epidermis of plants. Pairs of guard cells surround tiny stomatal airway pores (Fig. 14). These tiny pores in the leaf surface are necessary for gas exchange into and out of the plant; carbon dioxide (CO_2) enters the plant allowing the carbon fixation reactions of photosynthesis to occur. Oxygen (O_2) exits the plant as a byproduct of photosynthesis. The opening and closing of the stomatal gas exchange holes is regulated by swelling and shrinking of the two surrounding guard cells. [13]

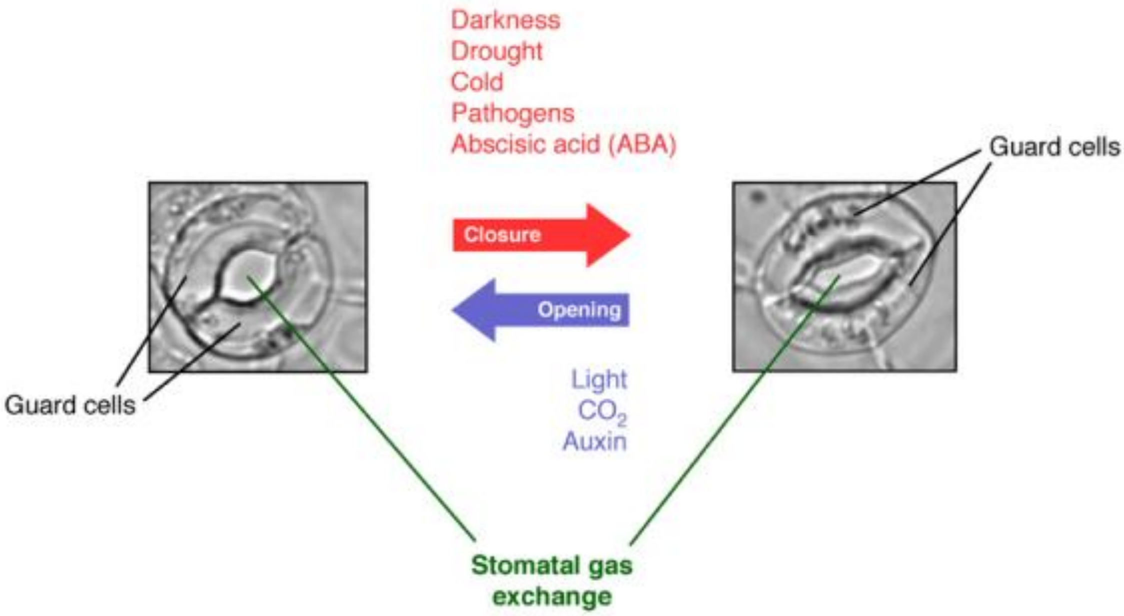


Fig. 14 Stomata Guard Cells
(Wikipedia, 2016, https://en.wikipedia.org/wiki/Guard_cell)

3.1 RESEARCH PROBLEM

Residential buildings account for 42.6% of total energy consumption in Egypt according to Ministry of Electricity and Renewable Energy's report for 2013/2014. Carbon Dioxide emission per capita reached 2.6 metric tons in Egypt in the year 2011 according to the World Bank and this is because our main source of energy is thermal which depends on burning fossil fuel releasing more Carbon dioxide into the atmosphere. As it was already discussed, greenhouse gases have a dramatic effect on the environment and the climate, and continuing to erect high maintenance and energy demanding buildings will not lead to a promising future. With this in mind, architects and builders should now seek solutions that would decrease those devastating effects on the environment through minimizing the energy consumption by trying to learn from the nature and mimic it as a successful model.

The Energy Code in Egypt has played a great role in regulating the architectural design and the usage of material in order to achieve energy savings, but still depended on conventional inert building materials and conventional ways of designs and didn't discuss any of the new technologies for construction or reviewed any of the recent smart buildings used which is why it still didn't reach what we as architects aspire. This is why we need to introduce a new approach through biomimetic designs using smart materials that mimic nature and integrate it with our local conventional building structures.

3.2 HYPOTHESIS

As the skin wraps our body, the building envelope wraps the building and so therefore it should act and perform the functions that the skin performs especially in thermoregulating the building which results in decreasing the energy consumed in buildings. And so if we mimic the human skin by using smart building material that acts on its own, we will achieve a building envelope that thermoregulate the building naturally without mechanical interference thus decreasing the energy consumed to reach thermal comfort.

3.3 OBJECTIVE

Reaching a building envelope that is a living and breathing building envelope, has the ability to respond to outer climate conditions and accordingly control the internal temperatures in buildings in a similar way to what nature does in our "human skin" or with the "stomata guard cells", without resorting to electrical or mechanical means to control the internal temperatures, hence decreasing the energy consumption and its devastating effect on the environment. This could be achieved through using suitable smart building material and integrating it within biomimetic architectural design.

3.4 METHODOLOGY

The methodology of this thesis adopted the following methods to reach its objective: Investigation – Invention – Analysis - Comparative Analysis- Lab Experiments-Simulation.

1. Reviewing the global warming problem, its consequences and the share of building sector in this problem.

2. Studying Biomimicry in architecture and its potential in decreasing the share of building sector in global warming.

3. Reviewing case studies and projects based on biomimetic architecture.

4. Focusing on building materials as an approach from biomimetic point of view and especially smart building materials.

5. Selecting a smart building material that would allow the building envelope to perform the same as the human skin and reviewing the reasons of selection.

6. Application of the selected building material in a case study and performing lab experiments and thermal analysis simulation to conclude the thermal comfort achieved.

CHAPTER 2

LITERATURE REVIEW

1. BIOMIMETIC ARCHITECTURE

In the following, the researcher will explore the potentials that biomimicry can offer to architecture, and illustrate how the biomimetic approach is implemented through six disciplines, after reviewing these six disciplines, the researcher will focus on a specific discipline which will be a step that would lead to the objective of the thesis.

1.1. Efficient Structures

"Materials are expensive and shape is cheap" a phrase said by Julian Vincent who observed that this is the opposite to technology. Nature makes extremely economical use of materials, and this is normally achieved through evolved ingenuity of form. Using folding, vaulting, ribs, inflation and other measures, natural organisms have created effective forms that demonstrate astonishing efficiency.

Why is nature this way? The pressures of survival in all its varied aspects- finding sustenance, thermoregulating, mating and avoiding predation, amongst many other factors – have, over aeons, ruthlessly refined the structures, and other adaptations that genetic mutation and recombination has created.

The process continues of course, but we can observe in nature today many of the best structures evolved throughout the history of life on earth. So, following the "less materials- more design" paradigm, we will explore an array of examples showing how a minimum of material can be used to maximum effect. [6]

1.1.1 Simple transformations of materials into structural elements

If one takes a square-section of solid material with a side dimension 24mm (fig 15), it will have the same bending resistance as a circular solid section of diameter 25 mm with only 81.7 % of the material.
Similarly, a hollow tube with only 20% of the material of the solid square can achieve the same stiffness. In engineering terms, material has been removed from areas close to the neutral axis and placed where it can deliver much greater resistance to bending-achieving the same result but with a fraction of the material.

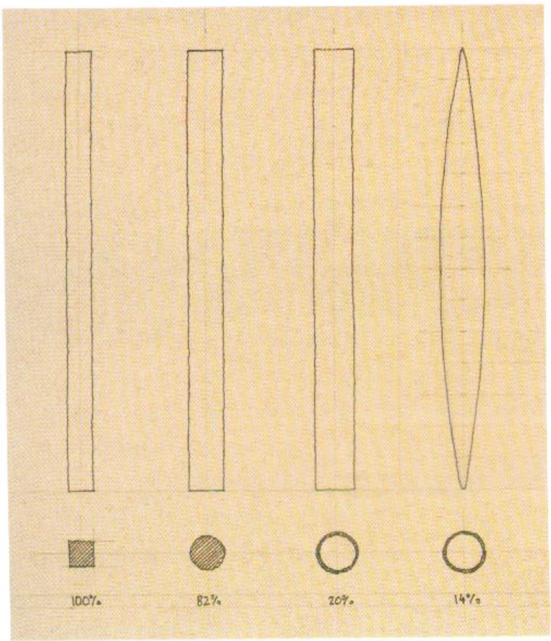


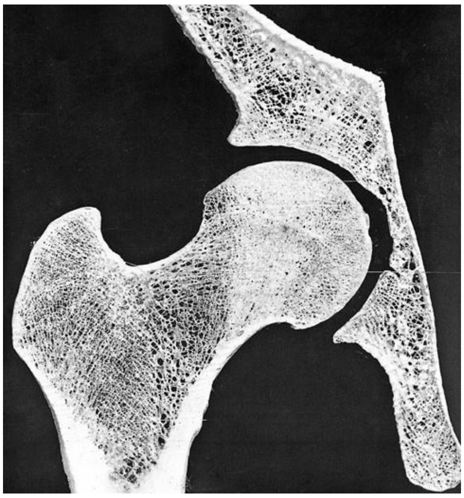
Fig. 15 Sketch showing how four equally stiff structural elements can be made with varying degrees of efficiency. By using shape and putting the material where it needs to be it is possible to use only 14% of the material of a solid square section. **(**Pawlyn, M., 2011)

The human bone is a great example that demonstrates this concept.[6]

Bone

And by bone I mean the human bone. Bone has some very distinctive characteristics responsible for fulfilling efficiently the task of the organism's primary construction where it represents a natural lightweight construction which acts as a role model for architecture. Bones work only in conjunction with muscles and tendons, forming the supporting system, also called the “musculoskeletal system”.

The constant stress distribution is valid for trees as for bones where there is no waste of material and there are no predetermined breaking points. The lightness of construction of the mammal skeleton has priority over its strength. [14]



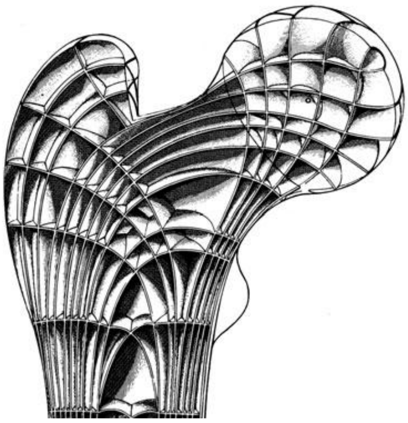


Fig. 16 direction of pure tension and pressure shown in the reconstruction model of the spatial trajectory surfaces. (Gruber, P., 2011)

Fig. 17 section through the head region of the thighbone the femur. ***(ibid)***

The end part of our long bones is formed by a so-called “spongiosa” or “cancellous bone”, which are minute beams out of fine bone lamella. They are oriented to follow pressure trajectories and tension where the average direction of the resulting force is aligned exactly with the orientation of the pressure trajectories, both being crossed at right angles by tension trajectories. In order to adapt the structure of spongiosa to the forces acting, processes of addition and removal of material are active continuously. The bones of vertebrates can disintegrate within their bodies in contrast to the adaptive growth of trees. The dynamic process of adaptation is disturbed with old age or certain illnesses, so that the bones become fragile and brittle. Nature abandons absolute strength, and accepts breakage when load exceeds a certain load limit for energy management reasons. The body creates an emergency splint out of fast growing connective tissue in case of breakage. The bone is rebuilt to its normal state as better as possible after the fracture is overgrown. [14]

1.1.2. Shells and domes

Nature is an accomplished maker of shells and domes. One such builder, whose specifications have been thoroughly scrutinised is the abalone (fig 18). It has evolved a shell which electron microscopy reveals to be made of polygons of aragonite, a form of calcium carbonate, bonded together with a flexible polymer mortar. The composite action of these two substances forms a material stronger than the toughest human made ceramics. [6]

Fig. 18 A scanning electron micrograph showing the series of calcium carbonate discs that form an Abalone shell.
(Pawlyn, M., 2011)

1.1.3. Skeletons

Intense selective pressure on reducing weight had a great impact on the evolution of birds. They are therefore a particularly good example of the "materials are expensive and shape is cheap". Bird skulls (fig 19) such as those of crows and magpies, are little short of engineering miracles. The effective thickness of the skull is increased while weight is decreased by creating multiple surfaces connected by a matrix of pillars and ties which form an outstanding combination of shell action with space frame technology, and all in a humble magpie. [6]

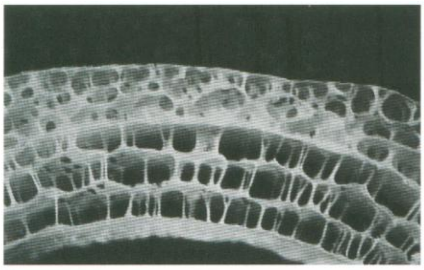


Fig 19 Bird skull. ***(ibid)***

In location of stress concentration, material is built up until there is enough to evenly distribute the forces; in unloaded areas there is no material. The result approaches perfect efficiency, in which there is no waste material and all the material that exists, is carrying its fair share of the load.

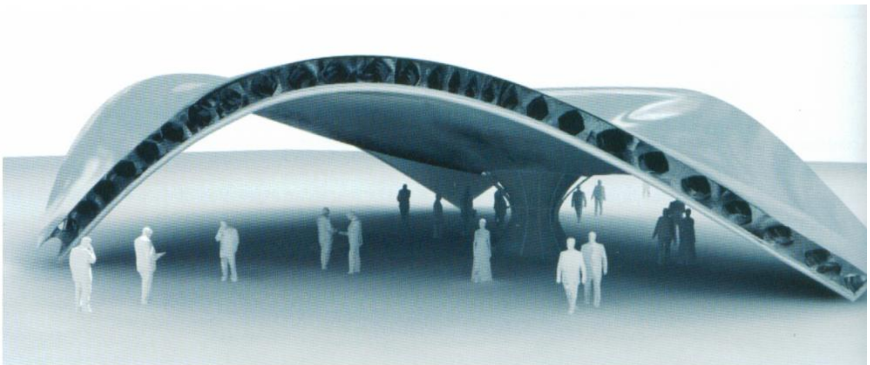


Fig 20 Canopy structure, designed by architect Andres Harris, using the same structural principles as bird skulls. ***(ibid)***

1.1.4. Webs / tension structures

Webs built by spiders have inspired a number of modern architects and engineers. Their forms range from the commonplace webs created by household spiders to the bizzare constructions of the female bauble spider (fig 21). The most common form of tension structure is a cable net, which generally involves a series of guyed masts from which the web is suspended. [6]

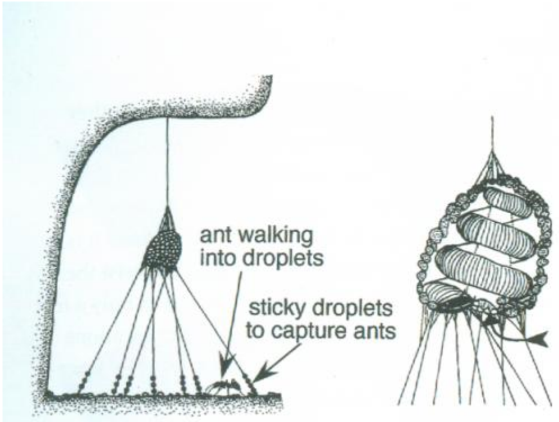


Fig 21 House of female bauble spider apparently under the influence of Bruce Goff. ***(ibid)***

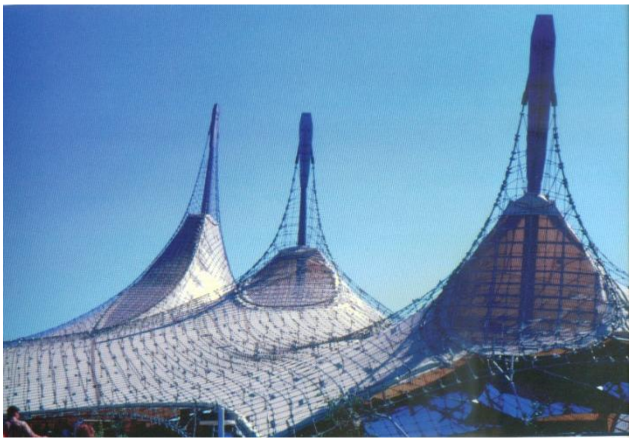


Fig 22 The West German Pavilion at Expo 1967, Montreal by Frei Otto – perhaps the closest we have come to the elegance of spider's web.***(ibid)***

1.1.5. Pneumatic structures

A leaf, generally speaking, has very little woody tissue in it and relies instead for its stiffness on pressurized cell membranes. Plants use energy to accumulate sugars in their cells, which promotes the in-flow of water and consequently internal pressure. The force of all the cells pressing against each other is what keeps the leaf rigid and explains why plants wilt when short of water. The effect is similar to a fully inflated lilo that is strong enough to stand upright or span as a cantilever. [6]

1.1.6. Deployable structures

Pneumatic technology represents one approach to creating deployable structures, in the way that its products can rapidly extended through inflation. Such structures have similarities with examples in nature, such as worms and anemones, although the means of extension varies: inflation in the case of pneumatics, the use of muscles in the worm and the pumping of seawater in the anemone.

Another approach to creating deployable structures utilizes mechanisms that simply unfold from a compact starting form to an enlarged final shape (fig 23 & 24). Biological examples of this method that have attracted the attention of biomimetic designers include the hornbeam leaf and the wings of various beetles. [6]

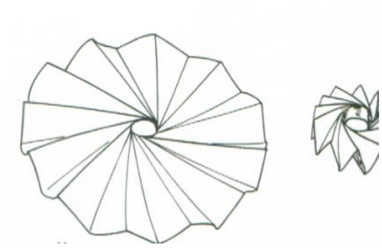


Fig 23 A deployable structure designed by Guest and Pellegrino with similarities to certain flowers. ***(ibid)***

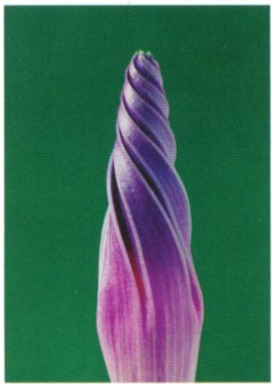


Fig 24 Convolvulus flower. ***(ibid)***

Some plants have evolved flower petals that can be rapidly deployed from a compact form to fully extended when the conditions are right. Deployables have been of great interest for military and aerospace applications because of the potential they offer for compact transportation and ease of transformation to their fully extended form.

Fig 25 Al-Husayn mosque canopies designed by Bodo Rasch. ***(ibid)***

1.1.7. Woven, fastened and reciprocating structures

A reciprocating structure is one in which the overall span is longer than that of its individual members and each beam supports, and is supported by, the other beams in the structure. Many bird's nest provide examples of this approach, and it is generally employed when the gap to be spanned-say, between the branches of a tree- exceeds the length of most of the available twigs. Short lengths of stick can be used to successively bridge the distance between two adjacent members that are at an angle to each other, eventually spanning the desired areas as a base for the nest. While the nests of some birds are relatively crude accumulations of sticks that rely on gravity and friction to hold them together, other birds use a range of fixing technologies to bind elements together. [6]

The long-tailed tit (Aegithalos caudatus) uses a combination of spider silk egg cocoons and fine-leaved mosses as a natural form of Velcro to hold its nest of twigs together. There are numerous examples of adhesives made from bodily secretions, including salivary mucus used by the chimney swift (Chaetura pelagica) to make its nests, and the little spiderhunter (Arachnothera longirostra) use pop rivets made of silk to attach its nest to large leaves. The highly sophisticated structures built by the village weaver bird (fig 26) (Ploceus cucullatus) employ as many as six different knots. [6]

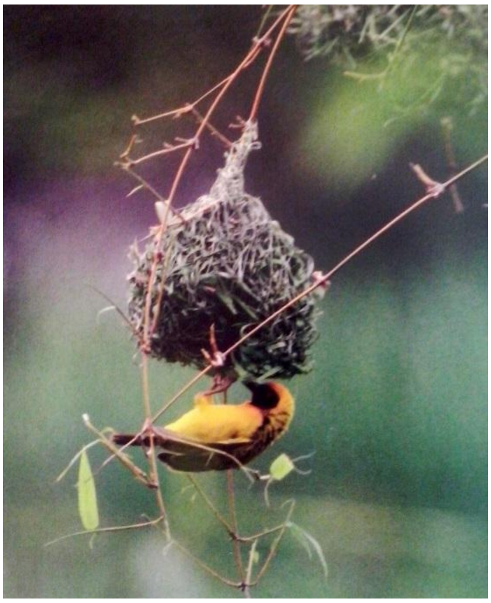


Fig. 26 Net structures built by the village weaver bird using as many as six different knots. *(ibid)*

1.2. Materials manufacture

Spider produces their silk with an array of "spinnerets" (fig 27) which are an aligned stream of polymers which are the spun into a thread with the spider's black legs. This silk, when dry, is stronger than "Kevlar" which is an aramid, or synthetic polyamide, fibre that we have succeeded to manufacture recently. But there is a huge contrast in manufacturing methods between the man made Kevlar and the silk manufactured by the spider. The manufacture process of the armid fibre requires boiling of petroleum in sulpheric acid at around 750 deg C. Then the mixture is subjected to high pressure to get the molecules into place. This process produces large quantities of toxic waste. And so, it requires very high temperature and pressure with harmful consumption of resources. On the contrary, spiders manage to do the same process at ambient temperature and pressure using raw materials of dead flies and water, no need for any of the above mentioned man made process which indicates that we seriously still have a lot to learn about manufacturing. [6]

Fig 27 Spinneret glands on the abdomen of a spider from which a fibre is spun tougher than any that humans have made to date. *(ibid)*

Our use of resources can be characterized as linear, wasteful and polluting, whereas in nature resources are maintained in closed-loop cycles. Our processes regularly produce toxic emissions, which can persist in the environment indefinitely; in few circumstances in which toxins are used in biology, they biodegrade soon after they have served their specific purposes.

Nature uses e very limited subset of the periodic table whereas we use virtually every element in existence, including some that really would be better left in the laboratory.

Materials that can sense and respond to changes in their environment are often referred to as “smart”. Clearly in architecture we create many systems that do this at the level of a building, and it is worth making a distinction here. In most instances of system engineering, there will be a sensor, processor and actuator; in a truly smart material, the sensor and actuator is the same thing and there is no processor. [6]

1.2.1 Pine Cone

One example studied by the center for biomimetics in Bath University is the pine cone, which stays firmly closed when it is on the tree. When the cone falls it starts to dry out and open up, eventually releasing the seeds inside (fig 28).The opening occurs because the scales of the pine cone have stems made from two materials that react differently to humidity: one of them shrinks more than the other, and the bending effect is similar to that of a bimetallic strip. This idea was developed into a multilayered textile with lots of small flaps that would open up when the wearer starts to sweat and close again when the skin beneath has cooled.

The concept came to fruition in the form of a tennis top worn by Anna Kournikova. A similar idea, also inspired by pine cones, was developed by Achim Menges at the Department for Form Generation and Materialisation at HfG Offenbach, using a composite of veneers (fig 29) that would either lie flat or roll up according to humidity levels. The potential for facades that can control the internal environment of a building without the need for additional mechanical control is extremely appealing.

Fig 28 Pine cones open because the stems of each scale are made from two materials which shrink at different rates when they dry out causing the stems to bend. ***(ibid)***

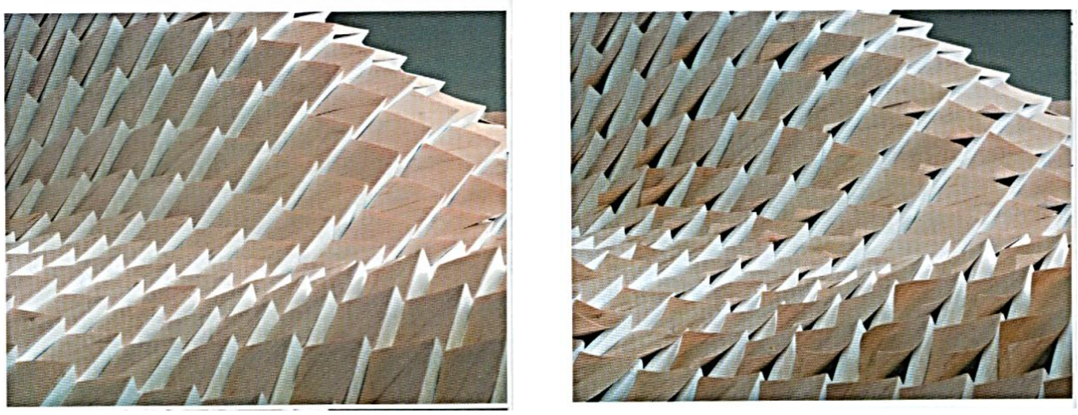


Fig 29 Steffen Reichert and Prof. Achim Menges explored a similar idea to the pine cone in developing a responsive surface made from two veneers. The result is a surface that opens and closes according to changes in humidity and without any sensing or actuation system. ***(ibid)***

1.2.2. Lotus effect

Nowadays the "Lotus effect" has gained its reputation as a term for “self-cleaning effects”. The same effect has appeared on surfaces other than plants such as insect bodies and wings and it will be discussed from different basis. [14]

1.2.2.1. Biological basics of the lotus effect.

Fine wax excretions, which make the surface hydrophobic, covers the surface of plants, especially the outer layer of the surfaces of plant leaves. One of the elements responsible for the weak adhesive forces of dirt particles, which can easily be removed with water, is this fine fractal structuring. This effect is particularly distinct in the leaves of the “lotus plant”. The botanists Wilhelm Barthlott and Christoph Neinhuis were able to prove that the connection between the structure of the surface, reduced adhesion of particles and hydrophobic character is the key to the self-cleaning mechanism of many biological surfaces. They standardised the pollution and the moistening factors for experimental testing of different plants. The advantages of particles removal on the plant are: better efficiency for photosynthesis and protection from infection which shows how important this process is to plants. [14]

Fig. 30 shows a lotus leaf with the red pigment being washed away completely. (Gruber, P., 2011)

1.2.2.2. Physical basics of the lotus effect

This phenomenon is based on the wetting of surfaces. The degree of surface tensions between water and air, water and solid surface, and solid surface and air, and the contact angle is explained by the “Young-equation”: “a contact angle of 0° indicates complete wetting, a contact angle of 180° complete non-wetting”.
Plant surfaces lie somewhere in between. The water takes the form of a sphere when it gains little energy out of adhesion which results in lowest total energy of the system this way. The surface tension of the liquid defines the contact angle of the droplet. [14]

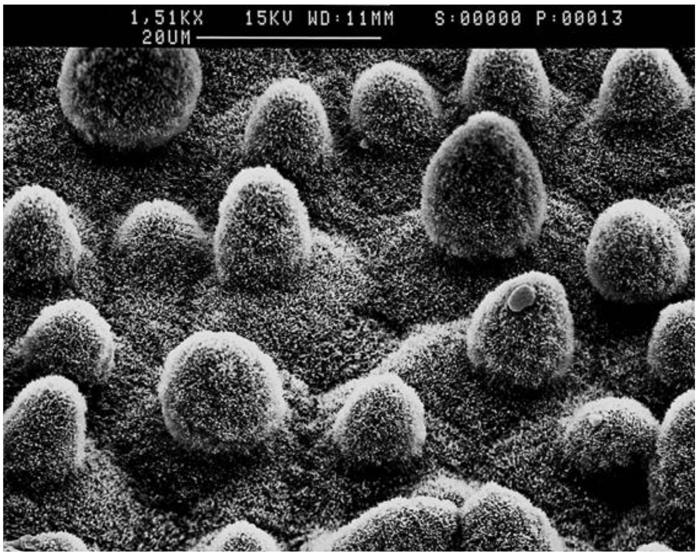


Fig. 31 REM photograph of the lotus leaf surface. *(Ibid)*

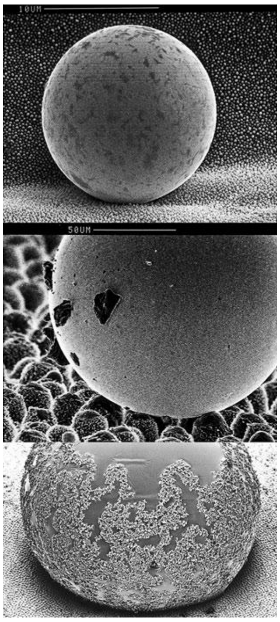


Fig. 32 Mercury droplets on leaf surface. *(Ibid)*

1.2.2.3. Transfer of the lotus effect

The Lotus effect has spread to products that imitate the effect in an artificial way. “Lotusan” is the name of paint that acquires self-cleaning characteristics. Lotusan combines the ameliorated hydrophobic characteristic of the ispo silicon colours with the microstructure taken from the Lotus leaf. The contact surface for dirt and water is extremely reduced. Together with the high hydrophobic characteristics a super hydrophobic surface is created. Water rolls off and takes the loose particles with it. The façade stays dry and beautiful. There are more products other than paint that have imitated the Lotus effect such as ceramic surfaces which can even repel honey, self-cleaning coatings and foils. But still the self-cleaning effect depends totally on wetting the surface to remove dirt. We can notice the difference in the degree of dirtiness when the object, like buildings facades, has unwetted parts. [14]

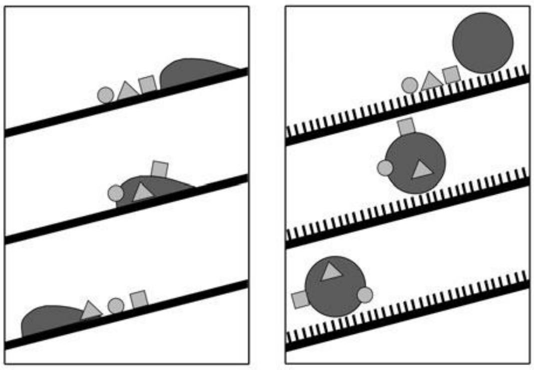
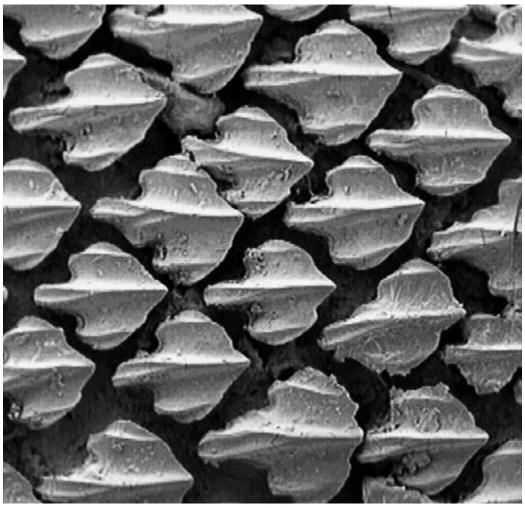


Fig. 33 Comparison between a smooth and hydrophilic surface in contrast to a structured and hydrophobic one. *(Ibid)*

1.2.3. Shark skin

Sharks, with their long evolution history, have adapted profoundly to their environment. In the 1980s Palaeontologist Ernst Reif discovered the structure responsible for the shark-effect. He found particularly structured scales, so-called “riblets”, cover the skin of sharks. Streamlines along the whole body of the shark is formed from grooves of scales that complement each other. Species that are faster in swimming and live in open sea have particularly fine grooves, that are distinctive on body parts and causes the water stream to disconnect from the body. Orientation, form and size of the scales and grooves are adapted to the specific positioning on the body and differ from species to species. This delicate structure has a positive effect on the detailed dynamics of the interface where the drag is reduced and according to experiments with grooved foil conducted by Dietrich W. Bechert, expert on fluid dynamics in the DLR, Deutsches Zentrum für Luft- und Raumfahrt, drag is reduced by up to 10%. Oil channels were used to carry out experiments with model scales because of similarities in fluid mechanics. [14]



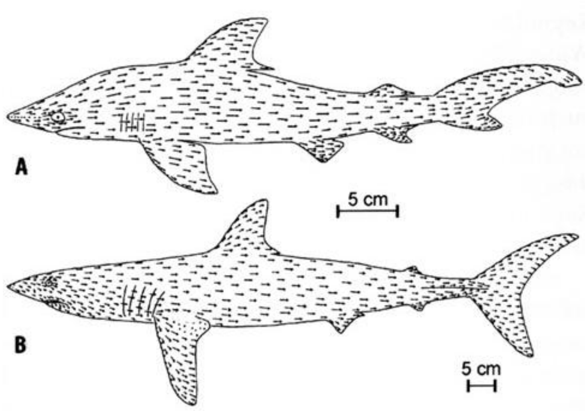


Fig. 34 Pattern and form of groove in different shark species. *(Ibid)*

Fig. 35 Shark skin structure. *(Ibid)*

More products were developed as applications to shark skin such as:

- Foils produced by “3M” to test on an “Airbus” for fuel reduction
- “Speedo” and “Strush” company produced textiles for swimsuits; where the surface consists of structure of tubes that makes heat exchangers, pumps and air conditioners more efficient.

The research’s aim was to improve the design of the traditional swim suit and to reduce its drag in the water. The structure of the "fast skin" suit imitates the surface of shark skin and enables the swimmer to glide faster through the water by reducing friction through the v-shaped grooves. This design is implemented using a super elastic material that compresses the muscles and enhances the fit of the gear, which leads to more efficient swimsuits. The cut of the suit was adapted by means of a body scanner to the muscle groups and swimming movements. The seams, too, are elastic and work like tendons together with the elasticity of the fabric and create a tension within the suit, which enables full freedom of movement. [14]

1.3. Waste management systems

Plants through photosynthesis turn atmospheric carbon dioxide into sugars and, with the addition of other elements taken up through their roots, are able to grow and form the basis of most food webs. Nitrogen is fixed into the soils and by particular plants that have evolved a symbiotic relationship with bacteria called Rhizobium. When plants die, drop leaves or are digested and excreted by animals and microorganisms, the carbon, nitrogen and other elements are returned to the soil. Water, the universal solvent for nearly all biological reactions, is also cycled through ecosystems and ultimately evaporated into the air to be returned as rainfall. It would be worth summarizing some of the differences between biological systems and the kind of human systems that the current paradigm creates. [6]

BIOLOGICAL SYSTEMS	HUMAN-MADE SYSTEMS
Complex	Simple
Closed-loop flows of resources	Linear flows of resources
Densely interconnected and symbiotic	Disconnected and monofunctional
Adapted to constant change	Resistant to change
Zero waste	Wasteful
No long-term toxins used	Long-term toxins frequently used
Distributed and diverse	Often centralized and monocultural
Run on current solar income	Fossil-fuel dependent
Optimised as a whole system	Engineered to maximize one goal
Regenerative	Extractive
Use local resources	Use global resources

Table 4: Comparison between biological systems and human kind systems.

Another characteristic of biological organisms is that they use what is abundant. Nature is a great opportunist, and if at any point there is an unexploited resource in an ecosystem then an organism will arrive to occupy that niche or, in the longer term, evolve to take advantage of the opportunity presented.
There are interesting parallels here with architects that work with found materials or resources that exist on a site. The architects and students at the Rural Studio in Hale County, Alabama, have created some exceptional buildings using waste resources with great ingenuity. Carpet tiles, vehicles-license plates (fig. 36), truck wind screens and a whole range of other locally available resources have been transformed into architecture for poor communities in Alabama.
Biological organisms rarely bring building materials over long distances to the site; instead they bring evolved ingenuity to the site and create structures with what exists there.[6]

Fig. 36 During the course of evolution organisms have evolved to make use of what is abundant and we could gain a lot from developing our ingenuity with under-utilised resources in an equivalent way. The architects at Rural studio have designed some of the best examples of this approach sometimes using vehicle windshields, carpet tiles or, in this case license plates as shingles. (Pawlyn, M., 2011)

1.4. Water management

All creatures adapted to living in arid conditions have some means of reducing water loss. This often involves using non- living matter to create shade, trapping a layer of air next to the organism's surface to reduce the evaporative gradient or a combination of the two. Some birds that live in deserts have black plumage, which might seem like a bizarre strategy but the feathers are simply protein structures (made from non-living keratin), which, through their opacity, prevent most of the sun's heat reaching the bird's skin and consequently reduce water loss. Numerous species of cacti are covered in fine, white filaments, which not only reflect the sun but also help to trap humid air next to the living tissue so that the exchange of gases necessary for photosynthesis can continue while water loss is minimized. The umbrella thorn tree (Acacia totilis) retains large amount of dead branches, which appear to serve no function other than provide shade for the living tissue and for the soil beneath so that evaporation is reduced. [6]

1.4.1. Water storage

Some habitats are characterized by intermittent rainfall, with, in extreme cases, the whole year's meagre precipitation falling in a few hours. This goes a long way towards explaining why cacti often have ribbed stems like concertinas (fig 37). These structures can absorb large quantities of water very quickly without any significant new growth-simply by expansion. Other plants have adapted to intermittency by storing their water below ground in large, swollen roots. What does this suggest for architecture? Water storage in buildings is almost without exception in the form of rigid tanks, often built underground with considerable cost and embodied carbon. There could be potential for expandable storage vessels made from lightweight membranes to be incorporated into walls or landscape features. This would allow buildings to harvest a far larger proportion of the rain that falls during the infrequent rainstorms that characterise some arid climates. Such a strategy could make sense for remote sites that would otherwise require expensive infrastructure to connect to mains water. The chances of flash flooding caused by roof-rainwater discharge would also be reduced.[6]

Fig. 37 The ribbed forms of cacti allow them to quickly expand to absorb water when there is rainfall. *(Ibid)*

1.4.2. Water harvesting

There is no better example of what biomimicry can offer than the Namibian fog-basking beetle (fig 38). This creature has managed a way to harvest its own fresh water in a desert. This way could be summarized as follows: it climbs, at night, to the top of a sand dune and, because of its matt black color; it radiates heat to the night sky and become slightly cooler than its surroundings. Droplets of water form on the beetle's back when the moist breeze blows in off the sea. It tips its shell up allowing the water to run down to its mouth just before sunrise, it gets a good drink then leaves and hides for the rest of the day. If we look deeper at the beetle we'll find that it has a series of hydrophilic bumps on its shell and encloses between them a waxy hydrophobic finish. As a result to this, the droplets formed on the bumps stay in tight spherical form, which makes them much more mobile than they would be if it was just a thin film of water spreading over the whole shell of the beetle. So, although it is a small amount of moisture hung up in the air, the creature was still able to harvest it effectively. It's an outstanding adaptation to a resource-constrained environment, which is very relevant to the kind of challenges we already face here in our country with its limited water resources. [6]

Fig. 38 The Namibian fog- basking beetle – a biomimicry hero *(Ibid)*

1.5. Thermal environment control

HOMOEOSTASIS, the tendency for living organisms to maintain steady conditions, is one of the features that most closely link the buildings we create with biology.

Maintaining an appropriate body temperature is critical for all aspects of biochemical and physiological function, and animals expend a great deal of energy controlling their body temperature.

There are two main strategies by which animals regulate their body temperatures. Ectotherms, which include invertebrates, fish, and reptiles, obtain most of their body heat directly from the environment, and their metabolic rates fluctuate with ambient temperature. Endotherms, such as mammals and birds, produce their own heat through metabolic processes and are able to maintain constant body temperatures. Almost all heat produced is ultimately lost, making endothermy an energetically expensive process. Consequently, endotherms need to eat high-energy foods or feed very often.

An animal's size, or more specifically, the ratio of its surface area to volume, is very important when considering heat gain and loss. As geometrically similar shapes get bigger, their surface area relative to their volume decreases. Because the surface is where heat is gained and lost to the environment, larger animals are therefore better at retaining body heat. This body mass to surface area relationship is why bigger animals tend to occur in cold environments and smaller animals tend to occur in hot environments. When large animals occur in hot environments, they tend to have less fur to facilitate heat loss. In addition to varying body size, evolution has acted to change the surface area of animals through creating longer and bigger extremities in hot environments and decreasing extremity length in cold environments. In hot climates longer extremities, such as longer limbs and big ears, allow more heat to be lost to the air, and shorter extremities can help prevent heat loss, thus conserving heat. [9]

1.5.1. Keeping warm

The two main sources of heat for organisms are both based on solar energy: firstly direct solar gain and secondly indirect, through metabolizing food. The continual generation of heat from metabolism results in many biological solutions for keeping warm being based on reducing heat loss and, for land mammals in temperate regions there are two main physiological ways in which this is achieved: a subcutaneous layer of insulating fat and a dense layer of fur. Those like the polar bear and the reindeer that live in colder regions have further adaptations, such as hollow hair fibres for added insulation (fig 39). [6]

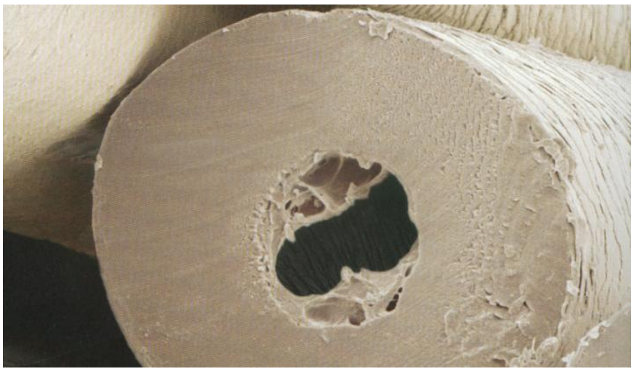


Fig. 39 Hollow hair fibres in polar bears – an adaptation that enhances insulative performance. *(Ibid)*

Reindeer fur includes a very dense under-layer of fur that traps air against the skin to reduce convection loss, while longer, guard hairs minimize chill by repelling water. There are also some examples of insulation found in the plant kingdom, such as the groundsel trees that grow on the slopes of Mount Kenya. They accumulate a thick layer of dead leaves from previous years that provide insulation to the trunk and prevent water within vascular tissues from freezing. Penguins have evolved plumage (fig 40) that allows them respond to two very different conditions. While swimming, the bird's feathers are held flat against the body for optimum streamlining; on land, the penguin lifts its feathers so that the mass of downy filaments at the base of each forms millions of pockets of trapped air for effective insulation. [6]

Fig.40 Penguins can lift their feathers so that the mass of downy filaments at the base of the shafts create millions of pockets of static air which provide very effective insulation. *(Ibid)*

1.5.2. Keeping cool

Many organisms that live in hot regions go to great lengths to avoid picking up heat. Some of them avoid radiative gain by staying out of the sun altogether or skipping across the sand rapidly to minimize absorbing heat through conduction. Elephants employ radiation, convection and evaporation when they use their huge ears to lose heat (fig. 41). The ears are permeated by blood capillaries, and elephants enhance heat loss by spraying their ears with water and flapping them. [6]

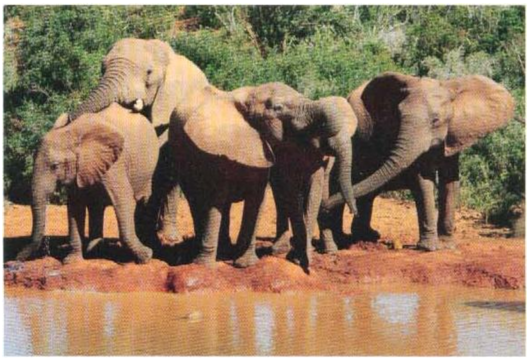


Fig. 41 Elephants use their richly vascular ears to shed heat sometimes spraying them with water from their trunk to enhance evaporative cooling. *(Ibid)*

Lizards are ectotherms, meaning they use their environment to regulate their body temperature. Temperature regulation in lizards is achieved through a combination of their skin characteristics and their behavior. The common side-blotched lizard has a skin coloration pattern that is dark in color on the back to allow the absorption of sunlight and light in color on the abdomen to reflect heat from the ground. Lizards obtain or dissipate heat from the environment through their behaviors. A lizard will adjust its body position to be perpendicular to the sunlight to absorb heat or parallel to the sunlight while curling up its toes to avoid heat gain by minimizing the area of the body touching the ground. They spend the hottest hours of the day in the shade to prevent overheating. [9]

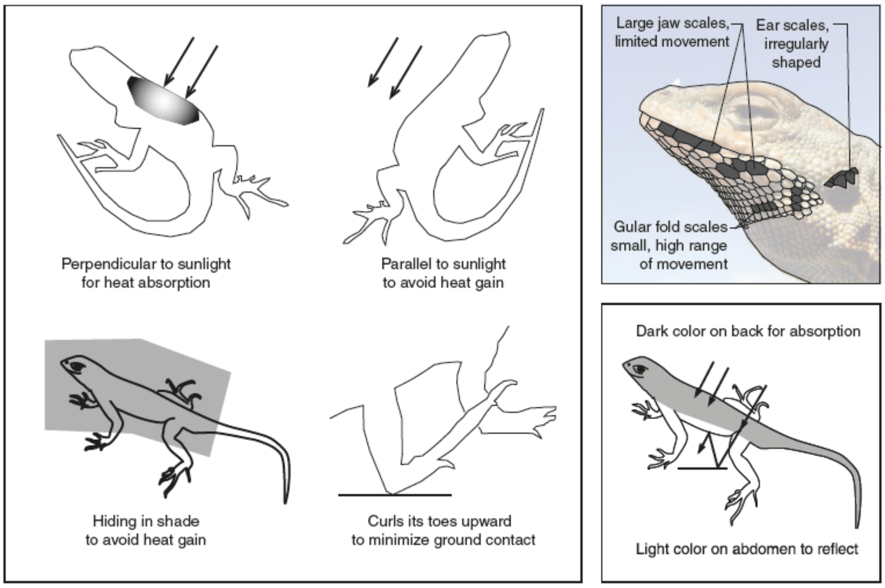


Fig. 42 The side-blotched lizard has many behaviors that help its ability to thermoregulate in the desert climate: standing perpendicular to the sun to absorb heat, standing parallel to the sun to avoid its rays, curling its toes upwards to minimize contact with the hot floor, and moving to shade when it is too hot. (Mazzoleni,I., 2013)

Another example for heat protection in hot climate zones like desert and savannah is the termites' buildings. They succeeded to adapt to hot climate by creating their main living space underground, into kilometre long subterranean pathway systems. Food locations are connected to the building above ground (which can be many metres high) through channels. The construction and form of termite mounds differs from one specie to another, but all are characterized with a sophisticated climatisation system. The above ground mound consists of a material which is porous yet very hard, in addition to a system of channels responsible for the ventilation in the mound. Mushroom shaped nest below the mound is cooled by sucking cool air upwards from subterranean channels. The reservoir of cool air is regenerated during the night due to reversing the air stream.

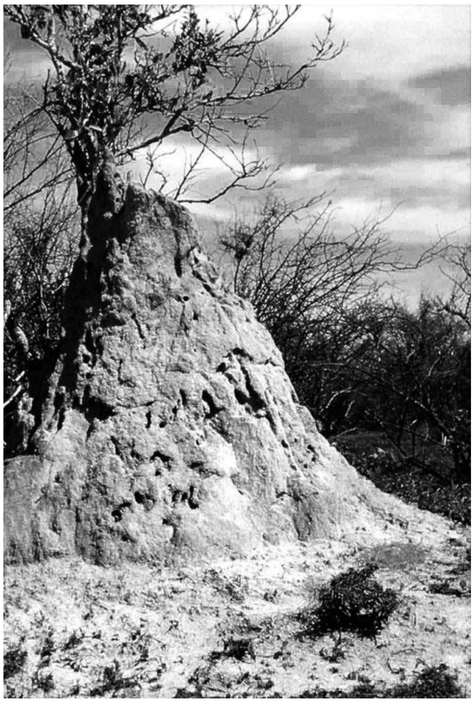


Fig. 43 Termite mound (Gruber, P., 2011)

There are particular systems that use deep channels that reach the ground water to gain additional cooling energy through evaporation. The orientation of "Compass termites" asymmetrical flat shaped mound is along the axis from east to west, in order to avoid the hot summer sun. All the above mentioned effort done with ventilation, material selection and orientation is for the mound to control temperature and humidity, to provide a stable and controlled environment for the termites and their offspring in the nest, and for some species also for their symbiotic fungi. The termite mounds resemble a real role model for an effective passive ventilation system that could be used in controlling the internal climate and so we find efforts made to translate this concept in architecture. This could be realized through the material that termites generate out of sand and their saliva which is porous but yet very hard; this material could be used in suitable climate zones for adobe buildings as an additive to clay, due to its prestructured nature. [14]

1.6. Energy Production

Biomimicry has been applied to the design of a number of renewable-energy technologies, and has delivered similar improvements to those we have for building technologies. For instance, a new form of wind-turbine blade, developed by a marine biologist with the engaging name of Dr Frank Fish, was inspired by the turbulences on the flippers of humpback whales (fig. 44 & 46).

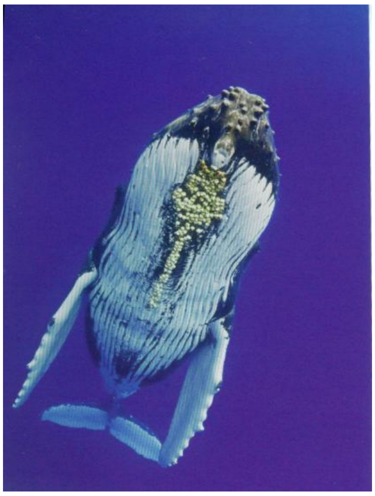
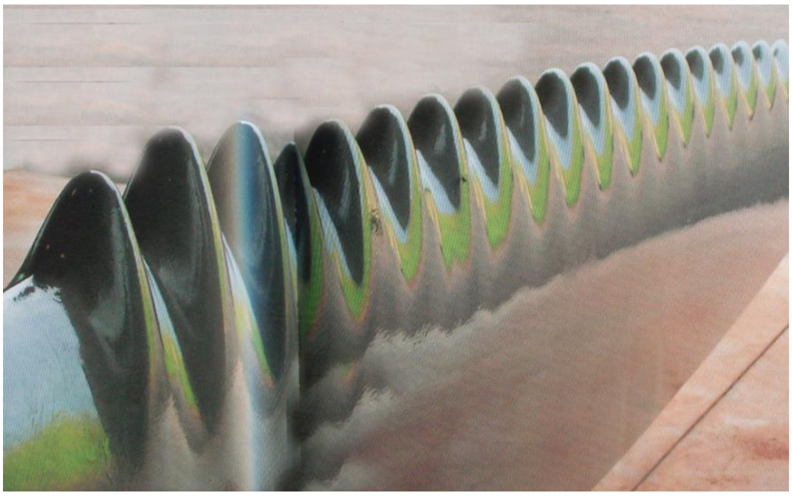


Fig. 44 Humpback whales have lumps (tubercles) on the front of their flippers which improve hydrodynamic performance at slow speeds. (Pawlyn, M., 2011)

These lumps on the front of the creatures' fins induce vortices which create more lift and allow whale to maintain maneuverability at low speeds. Dr Fish's new blade incorporates the same idea to produce a wind turbine that will maintain operation at low speeds. The reason this is of radical importance is that all wind turbines have a minimum speed of operation, below which they will stop turning only start again once the wind speed has picked up enough to overcome inertia.

Fig. 45 "Biowave" marine energy generators partly inspired by swaying motion of seaweed species in ocean waves. *(Ibid)*

Fig. 46 Wind turbine blades that mimic whale tubercles in order to maintain energy generation in lower speeds. *(Ibid)*



The developers Whalepower Limited claim that the blades can improve output by 20 % over a year and result in quieter operation (fig. 45). Further solutions from biomimicry could help address the opposite problem-excessive wind speed, during which wind turbines are generally taken out of operation with automatic braking systems to prevent damage. Many leaves, for instance, change orientation or roll up in high winds to minimize wind loading on the trunk of a tree. If wind- turbine blades were designed to flex, either laterally or longitudinally, under wind loading, then they would present less resistance to the wind. Clearly this means that a smaller proportion of the available energy would be captured in very strong winds, but the big advantage is that the turbine could remain operating in these conditions. [6]

From all above, the following could be concluded as an aide-memoire for architects applying biomimicry:

General:

- Collaborate and learn enough about other disciplines.
- Introduce biologists and ecologists in the design phase from its begining.

Substantial increases in resource efficiency

- Define functional challenges and see how can biology help deliver that function.
- Assign the material in its right place (use efficient structures)
- Design in a way that is adaptable to local conditions of the site and to the rapid changing conditions.
- Make full use of 'free' sources of energy such as the reliable wind direction, stability of the ground temperature and the cool deep seawater temperature.

Shifting from linear to closed-loop systems

- Change your perception to underutilised resources in order to realize it as an opportunity rather than a problem by adding elements to the system that helps transform waste into value.
- Try to reach synergy between technologies by assessing the inputs and outputs of each.
- Reconsider conventional approaches to resource ownership and explore the possibilties of leasing services instead of purchasing products.

Shifting from a fossil-fuel economy to a solar economy

- Focus on designs and ways that shift buildings from nett consumers of energy to nett producers.
- Integrate the systems within the building so that they become a part of the skin or structure of the building instead of being separate elements in order to increase the economics of solar energy.
- Utilising fossil fuels in production of high performance materials rather than burning it. [6]

Conclusion:

The research reviewed in the previous section the six principles of Biomimetic Architecture and discussed how nature succeeded in designing efficient structures with minimal use of materials and adopted various kinds of efficient forms, implemented different ways to control its thermal environment, harvested and stored water, produced no waste or toxics, used abundant and local materials,made use of clean and renewable energy resources and manufactured materials that responded to the surrounding environment and fullfilled its function.

We as architects need to learn from all those six principles as was mentioned before in the breif aide memoire because up till now we failed in accomplishing those principles in our buildings so we desperately need to learn carefully how nature succeded in doing it and start implementing them in our designs.

And so the resaercher focused on one principle of those six principles as an attempt to introduce it in the buildings, this principle is the second one which concerns "Material Manufacturing" and could be translated to "Smart Materials", materials that can sense and respond to changes in their environment. And so therefore the researcher will review different smart buidling materials that could be applied in architecture and will discuss its history, theory and applications in order to select the smart building material to be studied.

Architects need to combine designs dreived from "Biomimicry" with "Smart Materials" to reach a holistic building and help in reducing electrical consumption and more burning of fossil fuel.

2. SMART BUILDING MATERIALS

In this section the researcher will review different smart materials and its classifications and will discuss certain types starting with its history then going through its theory and applications until we reach the chosen material upon which Lab experiments will be conducted to be integrated within architecture design and construction.

2.1. Definition

There are several definitions for smart materials one of which is NASA's definition as: "materials that remember configurations and can conform to them when given a specific stimulus".
Another definition given by Encyclopedia of Chemical Technology is:
"Smart materials and structures are those objects that sense environmental events, process that sensory information, and then act on the environment".
So what is the difference between "Smart Materials" and "Conventional Materials"? What does 'smartness' require? Does it requires special materials and advanced technologies? The answer is No; there is nothing a smart material can do that a conventional system can't. For example a "photochromic" window that changes its transparency due to the amount of incident solar radiation, could be replaced by a conventional system consisting of a globe thermometer in a feedback control loop that sends signals to a motor which repositions louvers on the surface of the glazing through mechanical linkages, resulting in changing the net transparency.
Is this practical? Probably not, but still feasible and possible to achieve with commonly used conventional technology and materials. (Many buildings currently use such a system.) And so we can deduct that the most unique aspect in these materials and technologies is their behavior aspect. Smart materials and technologies whether a molecule, a material, a composite, an assembly, or a system, will exhibit the following characteristics:

- Immediacy : they respond in real-time.
- Transiency : they respond to more than one environmental state.
- Self-actuation : intelligence is internal to rather than external to the material.
- Selectivity : their response is discrete and predictable.
- Directness : the response is local to the activating event.

This last characteristic, directness, could be the characteristic that poses the greatest challenge to architects. Taking our building systems as an example, they are neither discrete nor direct, and if we take the HVAC system precisely we find that a simple act as changing the temperature in a room by a few degrees will set off an unnecessary flow of processes in the HVAC system, resulting in affecting the whole equipment operation throughout the building. If the concept of directness is to be applied to HVAC, it goes beyond making the equipment more streamlined and local and so we must ask fundamental questions about the prospected behavior of the system. The current efforts made are focusing on achieving high-performance buildings by improving the operation and control of these systems. But here we have to stop and ask why do we need these particular systems to begin with?
The majority of our building systems, whether HVAC, lighting, or structural, are often referred to as building services because they are designed to service the building.

But laboratories and industrial uses, though, buildings exist to serve their occupants. On the contrary to the buildings that heat and cool the entire volume, the human body requires management of its thermal environment and so we find the human eye perceives a tiny fraction of the light provided in a building while the lighting standards require constant light levels throughout the building. If we can introduce this concept to buildings and begin to think of these environments at the small scale – what the body needs – and not at the large scale – the building space – we can achieve a great reduction within energy and material investment of the large systems while not compromising with human comfort instead provide better conditions for the human occupants. [15]

2.2. Fundamental characteristics

We started by identifying the characteristics that recognized smart materials from other materials and by listing the five fundamental characteristics which differentiated smart material from the more traditional materials used in architecture and they were transiency, selectivity, immediacy, self-actuation and directness.
If we apply these characteristics to the organization of these materials then we can group them into:

1. Property change capability
2. Energy exchange capability
3. Discrete size/location
4. Reversibility

These features could either be used to optimize certain behaviors to maintain steady state conditions in the environment or to optimize a material property to better match temporal input conditions.
As we begin to investigate these distinguishing characteristics previously mentioned, we recall that energy fields are based on many types of energy: potential, electrical, thermal, mechanical, chemical, nuclear, kinetic, and they can all be exchanged or converted according to the First Law of Thermodynamics (the law of the conservation of energy).
The physical characteristics of smart materials are identified and controlled by these energy fields and the way this energy input to a material is converted. If this way affects the internal energy of the material either by changing the material's molecular structure or microstructure then the input results in a Property change of the material. But if this way alters the energy state of the material composition, but does not alter the material itself, then the input results in an Energy Exchange from one form to another. Hence the Property change type could be defined as: when the material absorbs an input energy it undergoes a change, whereas the Energy exchange type could be defined as: it is the state where the material stays the same but the energy undergoes a change. Not to mention that both mechanisms operate at the micro-scale, as none will affect anything larger than the molecule, and even, many of the energy exchanges take place at the atomic level. And so, we cannot 'see' this physical behavior at the scale at which it occurs. [15]

2.2.1. Property change

The Property changing class is the class of smart materials with the greatest number of potential applications to the architecture field. As defined before, these materials, in response to a change in the conditions of the material environment, undergo a change in a property or properties like chemical, thermal, mechanical, magnetic, optical or electrical properties. These environmental conditions could be ambient or could be produced as a result of a direct energy gain. This class Includes all color changing materials, such as thermochromics, electrochromics, photochromics, etc., in which the substantial surface or molecular spectral absorptivity of visible electromagnetic radiation is modified by means of a direct energy input to the material (current, voltage) or by an environmental change (incident solar radiation, surface temperature). [15]

2.2.2. Energy exchange

The following class of materials that is relied upon to have substantial infiltration into the field of architecture is the Energy Exchanging class. Also as defined before, these materials, which can also be called First Law materials, change an input energy into another form to produce output energy in compliance with the First Law of Thermodynamics. Even though we find that the efficiency of energy conversion for smart materials such as photovoltaics and thermoelectrics is considered much less than that of conventional technologies, but still the potential utility of the energy is much greater. For example, the direct relationship between input energy and output energy realizes many of the energy exchanging smart materials like piezoelectrics, pyroelectrics and photovoltaics, as excellent environmental sensors.
The output energy form can add direct actuation capabilities such as those currently demonstrated by electrostrictives, chemoluminescents and conducting polymers. [15]

2.2.3. Reversibility/directionality

Most of the materials in the above mentioned classes whether Property change class or Energy Exchange class exhibit the characteristic of either reversibility or bi-directionality. A lot of the electrical converting materials can reverse their input and output energy forms. For example, some piezoelectric materials can produce a current with an applied strain or can deform with an applied current. And if we look at the energy absorption characteristics of phase changing materials we find that it can be used in both directions either to release energy to the environment or to stabilize an environment depending on the direction of the phase changing. Also with shape memory alloys, the bi-directional characteristic can be used to produce multiple outputs, replacing components consisting of many parts. [15]

2.2.4. Size/location

One of the most primary characteristics that differentiate between traditional materials and smart materials, despite its class, is the distinct size and direct action of the material. Smart materials are smaller in size due to the elimination or reduction in secondary transduction networks, additional components, and, in some cases, even packaging and power connections. Components that are composed of a smart material are not just smaller in size compared to similar constructions composed of traditional materials but they also require less infrastructural support. The outcome is components that can be deployed in the most influential location. The smaller size characteristic combined with the directness characteristic of the Property change or Energy Exchange realizes these materials to act as effective sensors which mean they interfere less with the environment being measured, and they require less calibration adjustments. [15]

2.3. Type characterizations

After reviewing and discussing the main fundamental characteristics that recognizes Smart Materials from other conventional materials and classifying them into two main classes, in this coming section, we will distinguish between these two primary classes of smart materials discussed above by naming them Type 1 and Type 2 which are defined as follows:

- **Type 1**: a material that has the ability to change one of its properties (chemical, mechanical, optical, electrical, magnetic or thermal) in response to a change in the conditions of its environment and performs so without any external control.
- **Type 2**: a material or device that transforms energy from one form to another to affect a desired final state. [15]

Table 5: Types of Smart Material. [15]

TYPE OF SMART MATERIAL	INPUT		OUTPUT
Type 1 Property-changing			
Thermomochromics	Temperature difference		Color change
Photochromics	Radiation (Light)		Color change
Mechanochromics	Deformation		Color change
Chemochromics	Chemical concentration		Color change
Electrochromics	Electric potential difference		Color change
Liquid crystals	Electric potential difference		Color change
Suspended particle	Electric potential difference		Color change
Electrorheological	Electric potential difference		Stiffness/viscosity change
Magnetorheological	Electric potential difference		Stiffness/viscosity change
Type 2 Energy-exchanging			
Electroluminescents	Electric potential difference		Light
Photoluminescents	Radiation		Light
Chemoluminescents	Chemical concentration		Light
Thermoluminescents	Temperature difference		Light
Light-emitting diodes	Electric potential difference		Light
Photovoltaics	Radiation (Light)		Electric potential difference
Type 2 Energy-exchanging (reversible)			
Piezoelectric	Deformation	⟷	Electric potential difference
Pyroelectric	Temperature difference	⟷	Electric potential difference
Thermoelectric	Temperature difference	⟷	Electric potential difference
Electrorestrictive	Electric potential difference	⟷	Deformation
Magnetorestrictive	Magnetic field	⟷	Deformation

2.3.1. Type 1: Property Changing

2.3.1.1. Chromics or Color-Changing Smart Materials

Fundamental characteristics of chromics:

A color-changing material group is a class of smart materials that are invariably amazing to any designer and it includes the following:

- Photochromics : materials that change color when exposed to light.(Fig 47)
- Thermochromics : materials that change color due to temperature changes.
- Mechanochromics : materials that change color due to imposed stresses and/or deformations.
- Chemochromics : materials that change color when exposed to specific chemical environments.
- Electrochromics : materials that change color when a voltage is applied.

Other related "change color" or "transparencies" technologies when electrically activated include liquid crystals and suspended particle devices. [15]

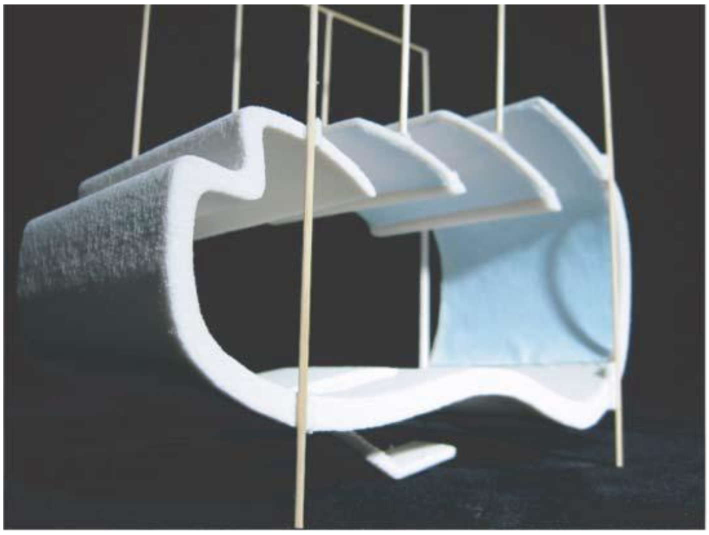


Figure 47 Design Experiment: Cool house project proposes interior panels that are covered with photochromic cloth which changes its color from a white base color to blue upon exposure to sunlight. The shown panel shapes are designed for a particular solar orientation and timing during the summer during which the interior turns into a cool blue. In winter, the cloth is not exposed to sunlight and so the Interior stays white. (Addington, M. and Schodek, D., 2005)

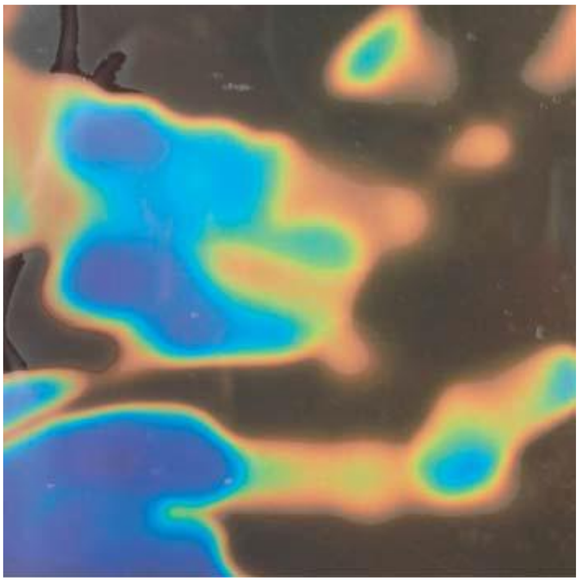


Figure 48 Thermochromic film (liquid crystal) calibrated for 25–30 ºC. Different temperature levels in the film are indicated by different colors where blue is the highest temperature level and black is the lowest. *(Ibid)*

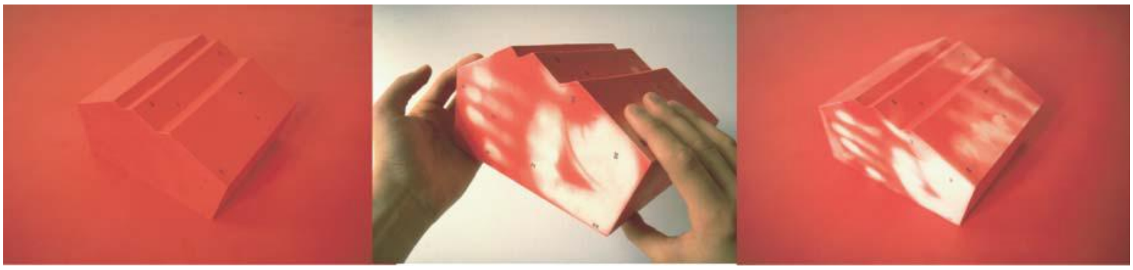


Figure 49 Memories of touch via thermochromic materials. *(Ibid)*

The researcher reviewed the Chromics Smart Materials briefly because it is not in the scope of study since the thesis concentrates more on materials that reacts thermally not chromically.

2.3.1.2. Phase Changing Materials PCM

2.3.1.2.1. History

Since the 1970s, number of researchers has attempted several trials to improve the thermal comfort of lightweight constructions, especially to overcome overheating problems in summer, using phase-change materials (PCMs) in buildings. They integrated the PCM using techniques such as immersion processes or macro-capsules. But each approach has different disadvantages, so for example, PCMs that are not encapsulated may react with the building structure and results in changing the properties of the matrix materials, or causes leakage that may occur throughout the years and forms a problem. Macro-capsules have several problems such as that they need to be protected against any destruction while the building is in use (no drilled holes or nails in the walls/ceiling). It also often requires much more work at the construction site for it to be integrated into the building structure, consequently making these systems relatively expensive. Another problem with macro-capsules when PCMs like paraffins are used is the decreasing heat transfer rate during the solidification process. This may prevent complete discharging of the system overnight.
Due to the above mentioned drawbacks, none of the PCM products had a big market impact. Recent advances in the micro-encapsulation technology may change this situation. [16]

2.3.1.2.2. Phase change theory

A lot of materials exist in several different physical states – gas, liquid or solid – that are known as phases. A material can undergo what is termed as phase change or change from one state to another when exposed to a change in the temperature or pressure. Phase change processes invariably involve the absorbing, storing or releasing of large amounts of energy in the form of latent heat. At precise temperatures, a phase change from a solid to a liquid or liquid to a gas, and vice versa, occurs. Phase-changing materials deliberately seek to take advantage of these absorption/release actions. While most materials undergo phase changes, there are several particular compositions, such as inorganic hydrated salts, that absorb and release large amounts of heat energy.
PCM's go through the following process: large amounts of energy are absorbed as the material changes from a solid to a liquid state, and then subsequently to a gaseous state then large amounts of energy are released when the material reverts from a gaseous to a

liquid state, and then to solid state. These processes are reversible where phase-changing materials undergo an unlimited number of cycles without degradation. (Fig. 50). [15]

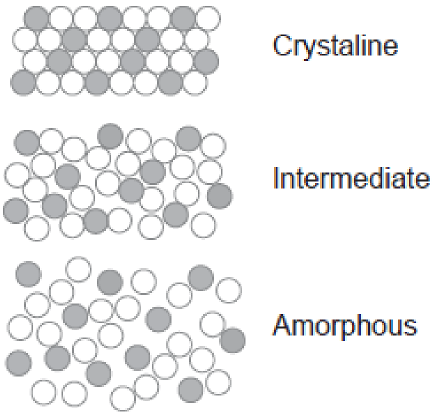


Fig. 50 Phase change transformation (Addington, M. and Schodek, D., 2005)

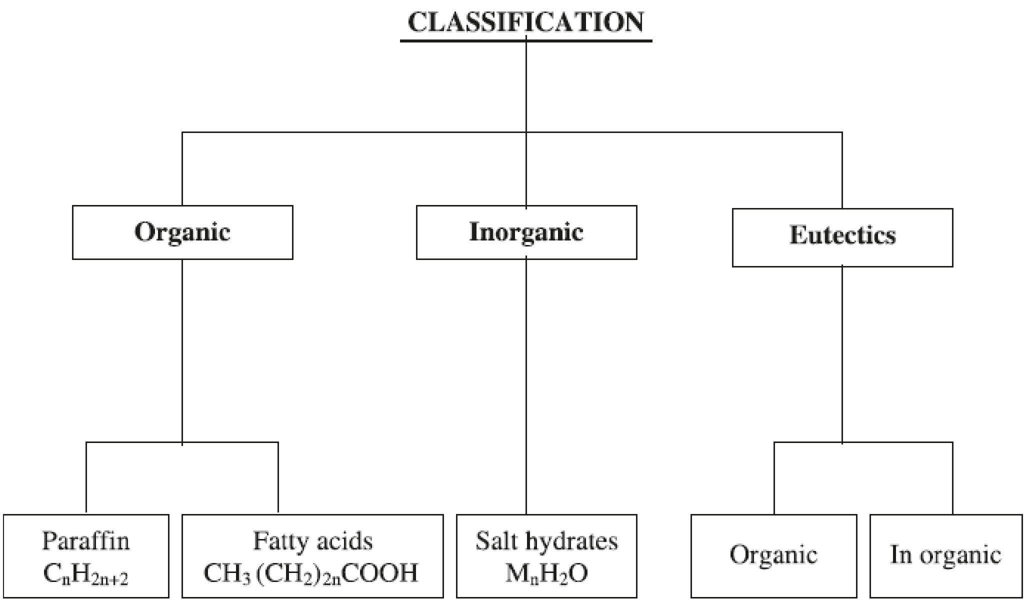


Chart 3: Classification of phase change material (Pasupathy, A. et al., 2006)

2.3.1.2.3. Applications

Phase-changing materials have naturally been exploited in architecture as a way of dealing with the thermal environment in a building since they have the ability to absorb or release energy at predictable temperatures. One of the first applications of Phase change materials was the development of so-called phase change wallboard which depended on embedding different materials to transfer phase change capabilities like salt hydrates, paraffins and fatty acids. The paraffin and fatty acids were integrated into the wallboard initially through direct immersion. Subsequently, filled plastic pellets were used. Transition temperatures were designed to be around 18–22 ^{o}C for heating dominated climates with primary heating needs, and 22–26 ^{o}C for climates with primary cooling needs. Direct immersion based products technologies faced a lot of problems that were associated with the exposure of paraffin and fatty acids (including problems with animals eating the wallboard products). And so researchers directed their efforts to seal phase changing materials into small pellets which worked better. This resulted in widespread use of Pellet technologies, for example, in pellets used in radiant floor heating systems (fig 57). In many climates, radiant floor systems installed in concrete slabs is a desirable option because it provides quite comfortable heating, but the problem with this system is it being subjected to undesired cycling and temperature swings since it needs to keep the slab temperature at the desired level, which in turn requires a high initial temperature. Embedding phase-changing materials in the form of encased pellets came as a good solution that could help level out these undesirable temperature swings.
Phase-changing materials didn’t stop at buildings but successfully extended to outdoor clothing and so we find patented technologies exist for embedding microencapsulated phase-changing materials in a textile. The size of the encapsulations within textiles is microscopic and these capsules are designed to be in a half-solid, half-liquid state near normal skin temperature. So as a person starts exercising and generates heat, the materials go through a phase change and absorb excess heat, thus cooling the body and as the body cools down, and heat is needed, the phase-changing materials begin to release heat warming the body. [15]

We briefly reviewed the possible applications of PCMs either in buildings or in textiles but in the coming section we’ll focus on the products in the market incorporating PCMs that could function mostly in architecture for the foreseeable future, which are mainly products that store latent heat and regulate temperature:

2.3.1.2.3.1. Microencapsulated PCM

- Plastic-encapsulated paraffin-based PCMs could be used in internal walls and ceilings.(Fig. 51)
- Resistant to mechanical damage like cutting and could be made in large quantities also could be incorporated into different construction materials.
- Only approved end products can be used but cannot be used alone because of inadequate fire resistance (fire safety). [17]

2.3.1.2.3.2. Plaster with PCM

- Micro encapsulated paraffin-based PCMs, for passive climatisation, could be used in internal walls and ceilings as conventional plaster (Fig. 52).
- Could be coloured by the application of paint or the addition of pigments which is easy to apply.
- Relatively expensive compared with conventional plasters. [17]

2.3.1.2.3.3. Gypsum Plasterboard with PCM

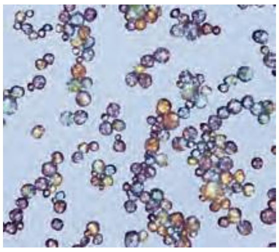
- Currently available in the form of boards 2000 mm x 1250 mm x 15 mm, and it is handled and fixed the same way as conventional plasterboard or fibre-cement boards. (Fig. 53).
- Relatively expensive compared with conventional plasterboard.[17]

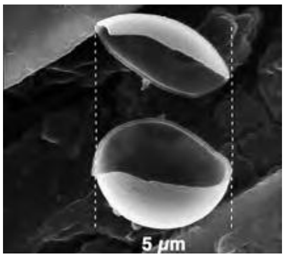
2.3.1.2.3.4. Light Directing Insulation Glazing System with PCM

- It is an insulation glazing system that consists of four panes positioned one behind the other with external integrated light-directing prismatic plastic panels and internal integrated transparent plastic containers filled with salt hydrate. The system provides passive climatisation of the facade and can be used in almost the same way as conventional insulation glazing systems (Fig. 54).
- Could be made in large quantities, can be used next to conventional glazing.
- Rather expensive to replace defective panes and PCM containers, relatively heavy which reflects on installation costs also higher manufacturing and installation costs compared with conventional insulation glazing. [17]

2.3.1.2.3.5. Aluminium Foil Bags with PCM

- Aluminium foil bags contain salt hydrates or salt hydrate mixtures for passive climatisation and could be incorporated in suspended ceilings to improve thermal conductivity when placed adjacent to components with good conductivity (e.g. made from metal). (Fig. 55).
- Could be made in large quantities, since it is not solid so it will not cause any damage to cladding materials and it is easy to apply.
- Any leakages are hazardous to health and may cause property damage which requires additional laminar components. [17]





- Fig. 51 Microscopic-scale photograph of micronal microcapsules with diameters of 2 µm to 20 µm. (Ritter, A., 2007)
- Fig. 52 Microscopic scale photograph of an individual Micronal microcapsule. *(Ibid)*
- Fig. 53 Dispersion with Micronal microcapsules. *(Ibid)*
- Fig. 54 Plaster pattern with Micronal microcapsules. *(Ibid)*
- Fig. 55 Aluminium composite bag with salt hydrate filling. *(Ibid)*

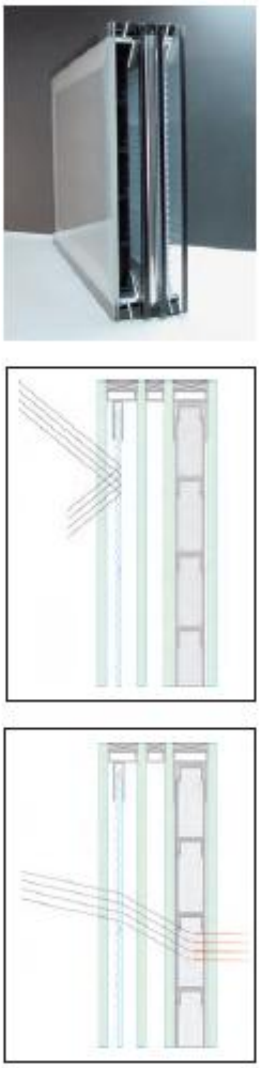


Fig. 56 Section through light-directing insulation glazing system with salt hydrate PCM. Operating principle at high and low solar positions. *(Ibid)*

Fig. 57 Pellets containing encapsulated phase-changing materials. They are used in radiant heating floor systems. (Addington, M. and Schodek, D., 2005)

2.3.1.2.4. Advantages and disadvantages

Table 6: Merits and de-merits of PCMs. [18]

Organic	Inorganic	Eutectics
Merits		
1. Availability in a large temperature range 2. Freeze without much super cooling 3. Ability to melt congruently 4. Self nucleating properties 5. Compatibility with conventional material of construction 6. No segregation 7. Chemically stable 8. High heat of fusion 9. Safe and non-reactive 10. Recyclable	1. High volumetric latent heat storage capacity 2. Low cost and easy availability 3. Sharp melting point 4. High thermal conductivity 5. High heat of fusion 6. Low volume change 7. Non-flammable	1. Eutectics have sharp melting point similar to pure substance 2. Volumetric storage density is slightly above organic compounds
Demerits		
1. Low thermal conductivity in their solid state. High heat transfer rates are required during the freezing cycle 2. Volumetric latent heat storage capacity is low 3. Flammable. This can be easily alleviated by a proper Container 4. Due to cost consideration only technical grade paraffins may be used which are essentially paraffin mixture and are completely refined of oil	1. Change of volume is very high 2. Super cooling is major problem in solid-liquid transition 3. Nucleating agents are needed and they often become imperative after repeated cycling	1. Only limited data is available on thermo physical properties as the use of these materials are very new to thermal storage application

3.1.3. Smart Gels -Hydrogel

Smart Gels are another Property changing smart materials that has the ability to change one of its properties. As an example of Smart Gels is the Aerogel, where the liquid component of the gel has been replaced with gas, which resulted in a material that insulates well yet still transmits light; it can maintain its shape although it is extremely lightweight. The density of the Aerogel is only three times that of air, yet can support significant weights. Aerogels were discovered in 1931 but were not explored until the 1970s (Fig. 58).

In case of Shape-changing gels or crystals, we find that they increase their volumes by hundred-folds because they have the capacity to absorb huge amounts of water. These same materials recover their original sizes when left to dry out (although often in a deformed way). Applications are found in everything from dehumidification devices and packaging through to baby diapers and plant watering spikes. One of the main examples of the shape changing gels that already has applications in architecture is the Hydrogel.

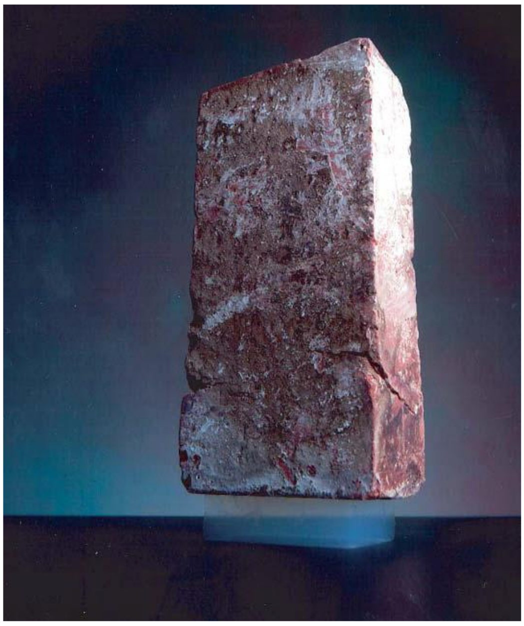


Fig.58 Aerogel with a mass of only 2 g supports a 5 Kg brick.
(Addington, M. and Schodek, D., 2005)

2.3.1.3.1. History

Around 1900, the term ‘hydrogel’ first appeared in scientific literature when it was used to describe a colloidal gel of inorganic salts. In 1960, Wichterle and Limwere the first to report on hydrogels as we know them nowadays, e.g. as water-swollen crosslinked macromolecular networks, in their landmark paper about poly (2-hydroxyethyl methacrylate) (pHEMA) gels for use as soft contact lenses. In the two decades following this discovery, hydrogel research remained essentially focused on relatively simple, chemically crosslinked networks of synthetic polymers with applications mainly in ophthalmic and drug delivery research. [19]

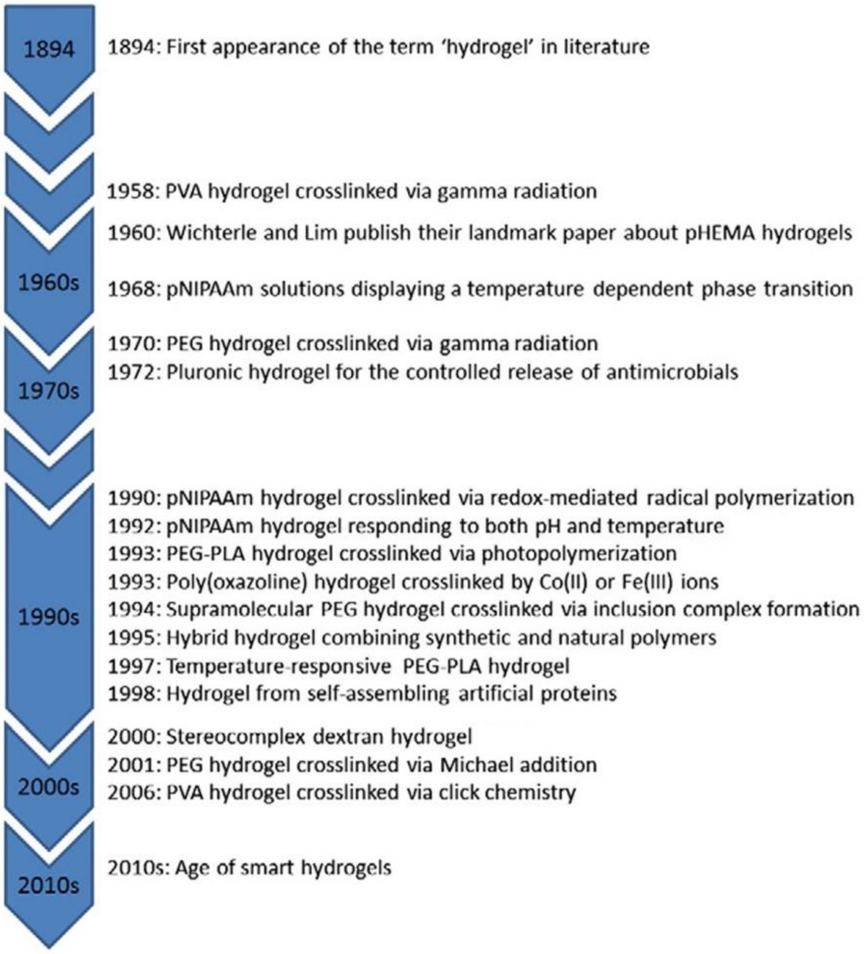


Fig. 59 Timeline presenting the most important events in the history of hydrogel research (Buwalda, S. et al, 2014)

2.3.1.3.2. Hydrogel theory

Hydrogels are three-dimensional polymer networks that are able to retain a large amount of water in their swollen state. Hydrogels may be classified as natural, synthetic or hybrid, depending on the source of the constituting polymers. Hydrogels can be chemically crosslinked by covalent bonds, physically crosslinked by non-covalent interactions or crosslinked by a combination of both. The interactions responsible for the water sorption include capillary, osmotic and hydration forces, which are counterbalanced by the forces exerted by the crosslinked polymer chains in resisting expansion. [19]

2.3.1.3.3. Applications

2.3.1.3.3.1. Intelligent window using a hydrogel layer for energy efficiency

The hydrogel used in this window is a special type of hydrogel intelligent material which undergoes phase transition with the ability of reversibility by utilizing solar energy and sensing changes in environmental temperature. The window panel using this intelligent material was called the Affinity Intelligent Window (AIW).

This laminated structure consists of the following:

- Hydrogel layer laminated on a conventional type of substrate glass sheet, and sealed with a composite structure using materials that suppresses water vaporization.
- A spacer used inside in addition to the sealing part.
- The substrate used within the structure is a glass sheet, not a plastic sheet that may allow permeation of water molecules.
- The hydrogel thickness should be between 0.05 and 2 mm.

As shown in Fig. 62, at low temperature, the transparency is water-clear, whereas at a high temperature, the optical scattering within the window panels causes the glass to be paper-white. In Fig. 60, it shows the two states (water-clear and paper white) of the AIW. Since Hydrogel is highly viscous, the properties are not affected by convection due to differences in temperature.
The hydrogel used in AIW consists primarily of water and other materials such as a water-soluble polymer with hydrophobic groups, an amphipathic molecule and sodium chloride. Fig. 61 shows a conceptual diagram of the hydrogel phase transition. At low temperature, the isotropic aqueous solution is dissolved homogeneously, with the water-soluble polymer and amphipathic molecules dissolved on the molecular level due to hydration of the hydrophilic groups, so that a water-clear state is achieved. Conversely, at high temperature, the hydrophobic groups of the water-soluble polymer and the amphipathic molecules undergo hydrophobic bonding with the structural change in the water component, by which the molecules are aggregated due to the weak bridging structure inside and between the molecules, so that a phase transition to the gel state occurs. Light scattering is caused by the difference in the refractive indices of the molecule aggregation domain and free water domain. As shown in the diagram, in this gel state, the amphipathic molecules inside the polymer aggregates undergo hydrophobic bonding together with the water molecules and are converted into a conjugate aggregate body. The resultant aggregate structure has an appropriate water content, but the free water is separated microscopically and retained inside the aggregate network, providing a homogeneous macrostructure without undergoing phase separation. The sodium chloride promotes separation of the free water, so the phase transition commencement temperature could be controlled with the amount of sodium chloride added. [20]

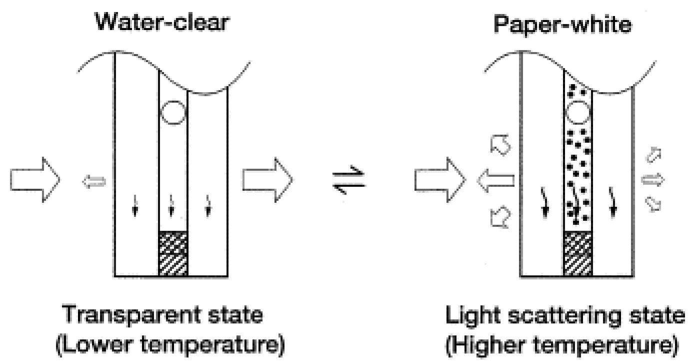


Fig. 60 Section in the structure of AIW showing the two states with homogeneous reversibility between water-clear and paper-white. (Watanabe, H., 1998)

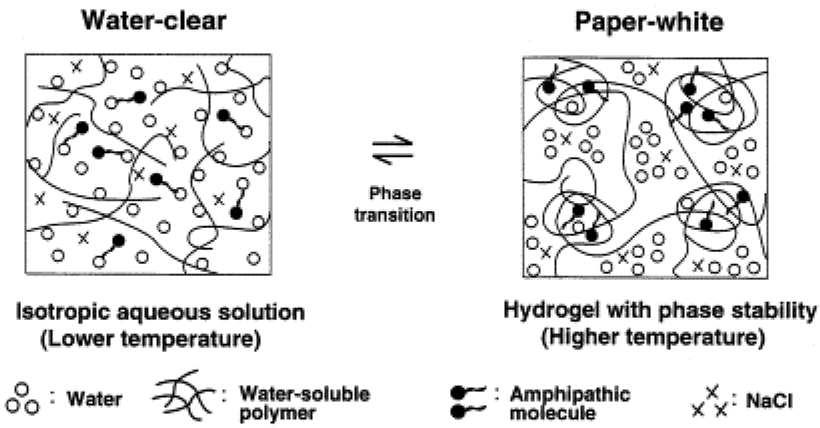
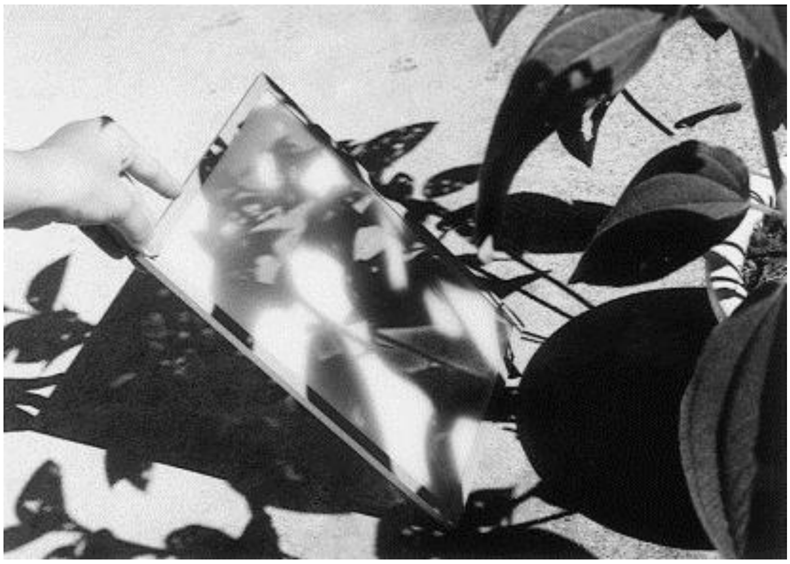


Fig. 61. The concept model of phase transition from the isotropic aqueous solution to the hydrogel with phase stability. *(Ibid)*

Fig. 62 The AIW has changed to paper white when exposed solar energy. The size of AIW was A4. *(Ibid)*



2.3.1.3.3.2. Hydrogel-filled ceramics for cool buildings

In 2014, a new type of building material known as "Hydroceramic" was developed by the Institute for Advanced Architecture of Catalonia (IAAC), this Hydroceramic responds to external temperature variations and automatically switches from insulating to cooling and vice versa. Nowadays we are all familiar with combined technologies that are responsible for warming or cooling our homes and workplaces and although these systems are designed to reach highest efficiency in their energy consumption, they still involve considerable costs, both for users and for the environment. This is why continuous research in this area is still highly required and luckily sometimes researches reach extremely promising results, as in the case of "Hydroceramic" which is a material that contains countless hydrogel bubbles that interact with the environment. Not to mention that hydrogels are materials capable to absorbing and retaining 500 times their weight in water.
The hydrogel bubbles in Hydroceramic are filled with water, and in high temperatures the liquid in each ball starts to evaporate. While evaporating, the temperature of the

hydrogel decreases. This results in cooling down organically the actual materials of the building when the sun is shining, which is typical to the way sweat cools the skin when it evaporates. This process is reversed when it rains, the hydrogel bubbles are refilled again with water, insulating the building once more. And so we conclude that it needs to be supplied with water regularly either naturally by rain or by other mechanical tools.
The final Hydroceramic prototype proved to be capable of decreasing the indoor environment temperature by between 5 and 6 degrees. Its performance is directly proportional to the outdoor environmental temperature due to the passive intelligence embedded, i.e. it cools more when temperatures are high and stops cooling when evaporation stops. These results were the outcome of an experiment set up to test the effect of hydrogel in reducing the temperature of a closed environment; it also concluded that the best material to house the hydrogel is the clay after testing other materials like Aluminum and Acrylic, and the results showed that the cooling properties of hydrogel requires the porous nature of clay which makes it the best option.
After these experiments, saving in the overall electricity consumption caused by traditional A/Cs was calculated and it reached up to 28 % using Hydroceramic in buildings. Another advantage of this material is being a cheaper alternative building technology, since it depends on using low cost clay and hydrogel. In other words, this new technology succeeded to redefine and embed ‘intelligence’ into a building’s environment by using responsive materials in hope to change this built environment to behave like a living entity, as part of nature and not isolated from it. Just then when buildings could start functioning like living organisms, with its biological systems including direct relations between the building and its surroundings. [21]

Fig. 63 Hydrogel filled ceramics
(IMA LAB, 2014)

2.3.1.3.3.3. Hydrogel that makes buildings sweat

A similar idea was made by Wendelin Stark and his colleagues at the Swiss Federal Institute of Technology in Zurich who produced a layer of thermoresponsive hydrogel, 3-millimetre in thickness. The gel undergoes a phase transition from a wet state to a dry state and releases water when heated to roughly 32 °C through evaporation, and with loosing water, a great amount of building’s heat is lost too. Just as mammals sweat to reduce their body temperature, it is the same concept applied here through using a coating of heat-sensitive hydrogel that could sweat to cool buildings. [22]

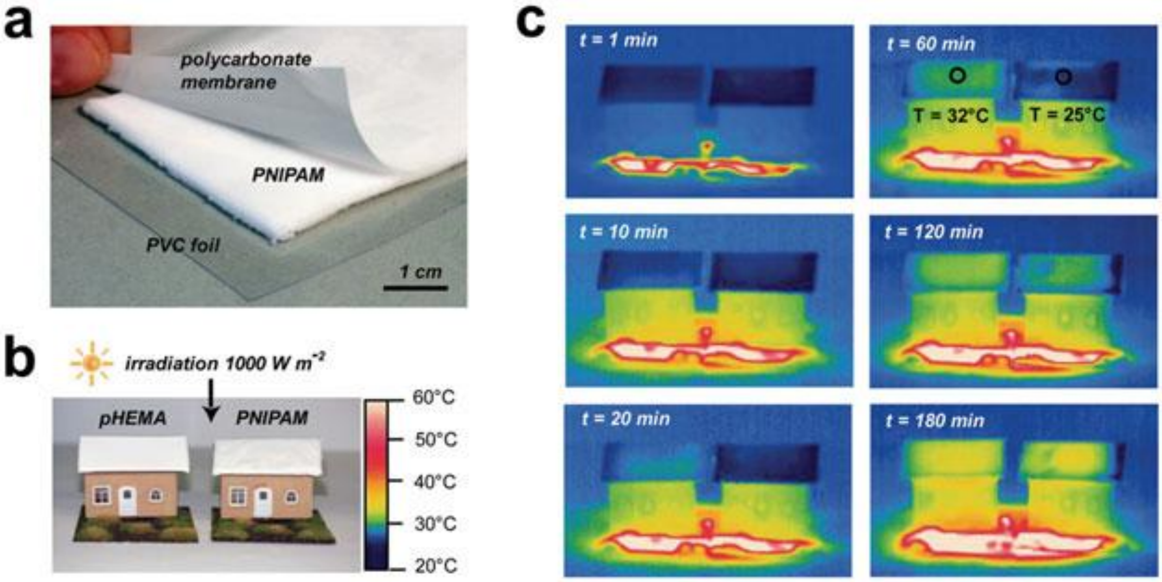


Fig. 64 shows slow sweating rate from a thermoresponsive PNIPAM hydrogel (right) which keeps a building cooler than conventional Phema hydrogels (left).
(Royal Society of Chemistry/ Chemistry World, 2012)

This thermoresponsive hydrogel was poly (*N*-isopropylacrylamide) (PNIPAM) and with a 5% crosslinker content, the polymer balanced robustness and thermal switching behavior. The two types of polymers (PNIPAM and Phema) were tested using simulation model. The PNIPAM polymer is able to store 90% of its weight in water, which results in keeping the polymer's surface temperature in simulated sunlight at around 35°C until the water starts to evaporate. After that, the temperature of the model roof quickly rises to 60°C. On the other hand, the temperature of a roof covered with Phema polymer rose rapidly to 45°C, then more slowly to 60°C.

These results were taken by researchers to study emission reductions, where they compared the energy consumed by air conditioning to keep the internal house temperature at 20°C in the two cases: first with the bare roof where the temperature reached 60°C, and second with the hydrogel covered roof where the temperature reached only 35°C. The results came out as follows: the building with the bare roof would emit 220 kg/CO2/year if the electricity was generated by a gas-fired power station, while the building with a hydrogel coated roof would emit just 80 kg/CO2/year. [23]

2.3.2. Type 2: Energy Exchanging

The definition of Equilibrium is: "When the energy state of a given material is equivalent to the energy state of its surrounding environment, hence no energy can be exchanged". If the material is at a different energy state, then there is a potential for an energy exchange. All of the energy exchange materials involve atomic energy levels – the input energy raises the level, then the output energy returns the level back to its ground state. We'll take photovoltaic materials as an example, when solar radiation hits the photovoltaic material; the photon energy is absorbed by the atoms of the material. But since energy must be conserved, atoms are forced to move to a higher energy level due to the excess energy of the atoms. The atom must release a corresponding amount of energy, since it is unable to sustain this level. Photovoltaics are able to capture this released energy –thereby producing electricity using semi-conductor materials. Note that all materials –traditional as well as smart – must conserve energy, and by conserving energy, the energy level of the material will increase whenever there is an energy input or addition. For most materials, however, this increase in energy is manifested by increasing the internal energy of the material, most often in the form of heat. Energy exchange smart materials are materials that are distinguished by their ability to recover this internal energy in a more usable form. Many of the energy-exchanging materials are also bidirectional where the input energy and output energy can be switched. The major exceptions to these energy exchanging materials are materials that exchange radiation energy – the high inefficiency of radiant energy exchange increases thermodynamic irreversibility.
Furthermore, the energy-exchange materials are almost always composite materials, exceptions include magnetostrictive iron and naturally occurring piezoelectric quartz, unlike most (although not all) of the property changing materials. [15]
The currently available energy-exchanging materials can be differentiated according to their triggering stimuli; the following are examples of commonly used energy exchange materials:

- **LIGHT-EMITTING MATERIALS**
- **SEMICONDUCTORS-THERMOBIMETALS**
- **PHOTOVOLTAICS, LEDS, TRANSISTORS,THERMOELECTRICS**
- **SHAPE MEMORY ALLOYS**
- **SHAPE MEMORY POLYMERS**

Out of which the researcher will focus on temperature triggered materials such as: Thermobimetals and Shape Memory Materials due to their great potential of application in architecture.

2.3.2.1. Thermobimetals

2.3.2.1.1. History

In the eighteenth-century, clockmaker John Harrison invented the earliest surviving bimetallic strip. His earliest examples had two separate metal strips joined together by rivets but he also invented another joining technique by directly fusing molten brass onto a steel substrate. This type of strip was fitted to his last timekeeper, H5. Harrison's invention is honored in his memorial at Westminster Abbey, England. [25]

2.3.2.1.2. Thermo bimetal theory

Thermo bimetals (TB) are laminated composite materials and consist of at least two components, usually bands or strips, made from metals with different thermal expansion coefficients, which are permanently bonded to one another, for example by plating. The thermo bimetal component with the lower thermal expansion coefficient is called passive; the one with the higher coefficient is called active.
The composite forms a curved shape and can be used for various applications and purposes depending on the components used, shape of components and the way the temperature changes over time. In Europe, the terms used to describe TBs refer to the composition of the active component alloy, whilst in America; it is the passive component that is being referred to.
TBs have been around since the beginning of the industrial revolution and so they are considered relatively old smart materials. Today they are mainly used in control and measurement systems, such as thermostats, and they are also used with electrical control systems as the mechatronics' components.
TBs can be resistant to corrosion by plating it with copper and chrome, and by incorporating a layer of copper between the two components, their electrical conductivity for active heat gain can be improved.
Characteristics like: good platability, high melting point, hot and cold ductility, high strength and predictable behaviour, a high modulus of elasticity (Young's modulus), should be possessed by components for the manufacture of TBs. Specific dimensional relationships needs to be maintained. [17]
As an Energy Exchange material, a thermo bimetal strip converts a temperature change into mechanical displacement and this process takes place as follows:
The different expansions of the two strips of the thermo bimetal composite material force the flat strip to bend in a certain direction when heated, and bend in the opposite direction when cooled below its initial temperature. The metal with the higher thermal expansion coefficient is found on the outer side of the curve when the strip is heated and is found on the inner side when cooled. The sideways displacement of the strip is much larger than the small lengthways expansion in either of the two metals and a range of mechanical and electrical devices used this effect. Some applications use the bimetal strip in the flat form while others use it wrapped into a coil for compactness. [24]

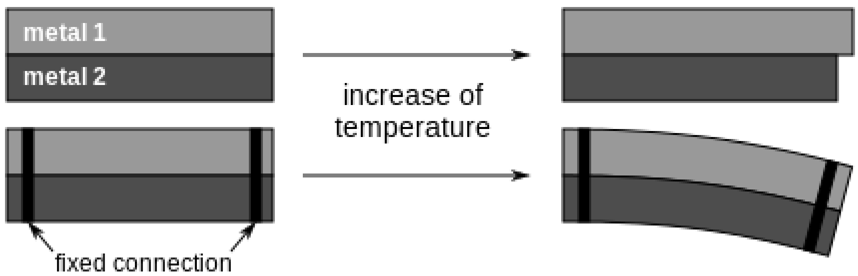


Fig. 65 Diagram of a bimetallic strip showing much larger sideways displacement of the strip due to the difference in thermal expansion in the two metals.
(Wikipedia, 2016, https://en.wikipedia.org/wiki/Bimetallic_strip)

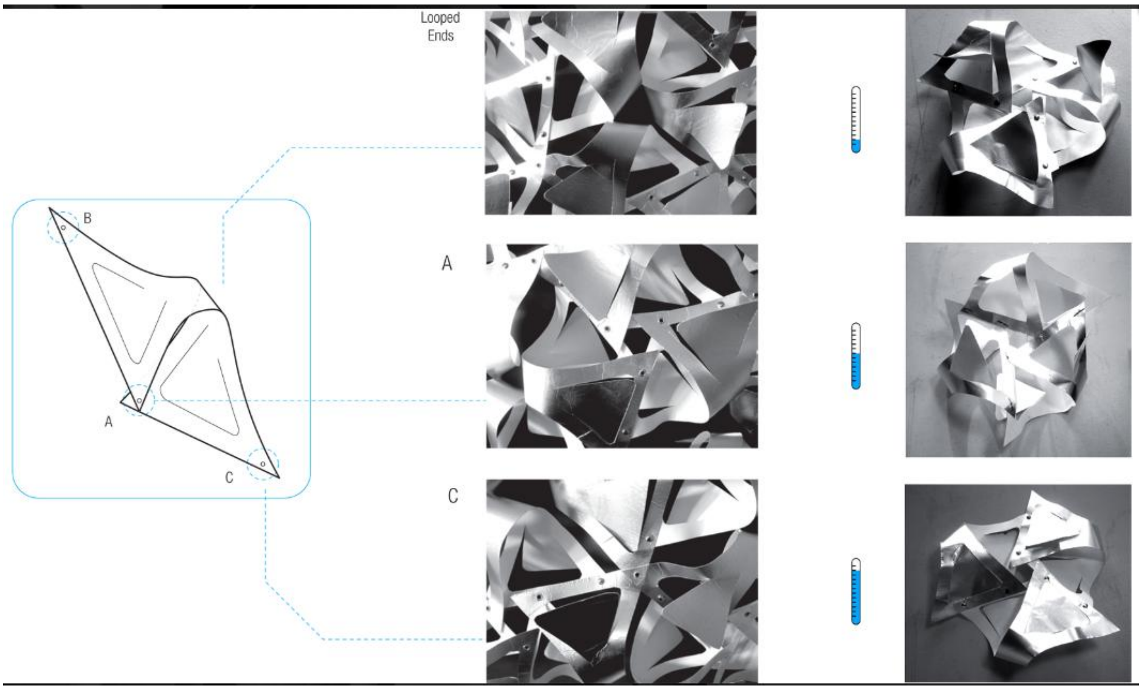


Fig. 66 Shapes of Thermo bimetal that responds and start changing its shape according to temperature.
(Erin Ceuvas, 2015, http://erincuevas.com/204274/2193626/main/thermal-bimetal)

2.3.2.1.3. Application

1. Thermostats
2. Circuit breakers in electrical devices
3. Actuators

2.3.2.2. Shape Memory Materials

Shape memory materials (SMMs) are characterized by the ability to recover their original shape from a significant and seemingly plastic deformation when a particular stimulus is applied and this is known as the Shape Memory Effect (SME). Superelasticity (in alloys) or visco-elasticity (in polymers) is also common characteristic observed under certain conditions. The SME can be applied in many fields, starting from aerospace engineering (e.g., in deployable structures and morphing wings) to medical devices (e.g., in stents and filters). [25] In this section the researcher will discuss the two shape memory materials which are: Shape Memory Polymers and Shape Memory Alloys.
And will start with introducing a brief background to Polymers and the main types of polymers in order to understand to which type does Shape Memory polymer belongs to help us understand its behavior.

2.3.2.2.1. Shape memory polymers

An introduction to Polymers:

Often polymers are classified by how they behave when heated. If they have softened when warmed, they are called thermoplastic polymers. However, if they never become soft but only char after intensive heating, they are known as thermosets.

3.2.2.2.1.1 Common Synthetic Polymer Types:

3.2.2.2.1.1.A Thermoplastic polymers

Thermoplastic polymers, such as vinyls, are made by joining monomers together to form long chains. This can be done by means of a catalyst, such as benzoyl peroxide. The catalyst causes one of the bonds in the double bond in the monomer to open and form a free radical. A free radical is an unstable, reactive kind of a molecule. In this polymerization reaction these radicals link together to form long chains of repeated polymeric units. Each molecular chain may have a molecular weight of from several thousands to a million.

In figures 67, 68 and 69 the dashes on either end of the polymeric units represent electron-pair bonds. These bonds connect adjacent polymeric units (not shown) together. The brackets deliberately cut the dashes into two pieces. This is to show that half of the bond (one electron) came from the adjacent polymeric unit (not shown). The degree of polymerization is represented by the letter *n*, which stands for the number of polymeric units in the polymer.

Figure 67 shows the polymerization of vinyl chloride to form the poly (vinyl chloride) polymer. As illustrated in this figure, when one of the electron-pair bonds (of the double bond of vinyl monomers) is broken, one electron goes to each end of the monomer, forming a free radical. Each of these electrons might be pictured as an electron “hand” groping for the free electron hand of another monomer radical. The clasped hands represent a new electron-pair bond that holds the two radicals together. Thus monomer radicals become forked and grow into a tangled mass rather than a very long chain.

To limit the chains to the desired length, monomers with only one functional group (chain stoppers) are used in small amounts to terminate any chain they join.

Many thermoplastic polymers can be decomposed if they are heated to a high temperature because a monomer unit breaks off. Most of these monomers have a distinctive aroma. This is one way to identify a polymer.

Structural diagrams of other monomers which join to form thermoplastic polymers are shown in figure 68. These unite with one another stepwise, to form the chain of carbon atoms known as addition polymers or chain-growth polymers. The *n* shown in fig. 68 indicates the number of repeating units in the final chain. Each of these polymers can be to almost any specification that is needed. Polyethylene is an illustration. As normally polymerized, ethylene forms a polymer with tangled much-branched chains which are not well-packed. This form of the polymer is known as low density polyethylene. With different catalysts, ethylene can be polymerized to form a polymer with straighter and more closely aligned chains, which, being more closely packed together, are more dense. This high density form of polyethylene has a higher melting point and more than double the tensile strength of the low-density polymer.

Whether a monomer would be predicted to form a thermoplastic or thermosetting polymer depends on the number of double bonds or functional groups in the monomer. One double bond or two functional groups in a monomer can produce a thermoplastic (linear) polymer. If long enough, these linear chains form a solid polymer which, when heated, will soften and flow as the chains slide over one another. [26]

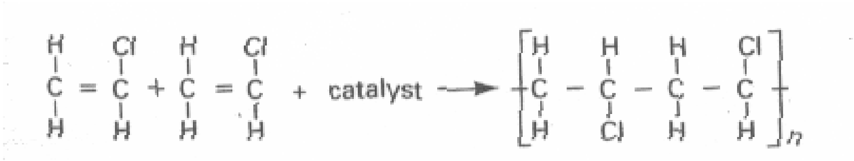
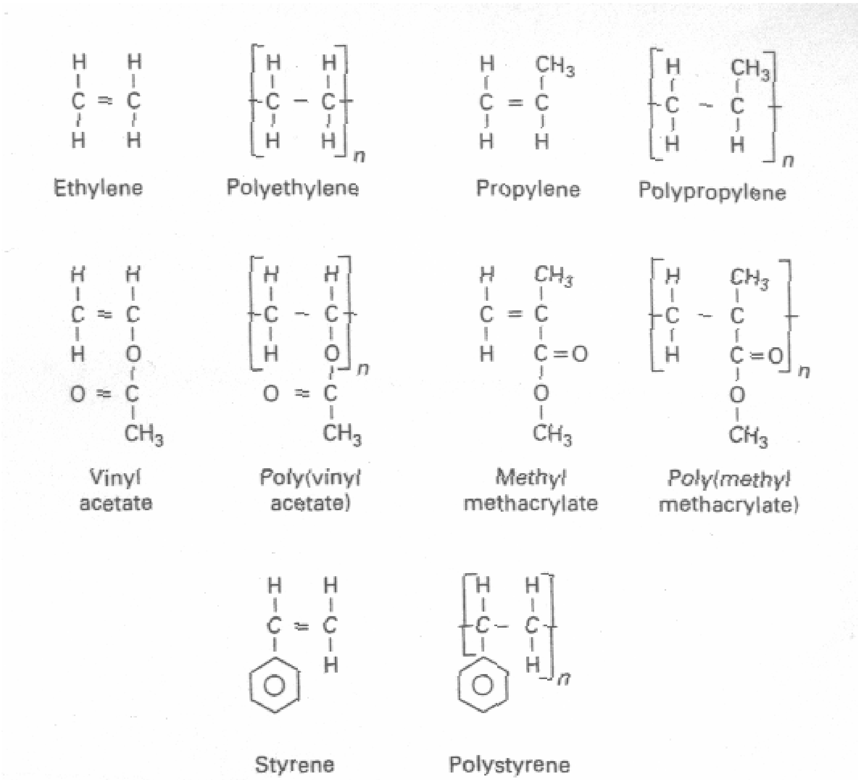


Fig. 67 Polymerization of vinyl chloride. (Brantley, L. and Brantley, R., 1996)

Fig. 68 Common polymers and their monomers. *(Ibid)*



3.2.2.2.1.1.B Thermosetting or cross-linked polymers

Thermosetting polymers, formed by monomers with two or more double bonds or functional groups, form cross-linkage between chains. These polymers, unlike the previous thermosetting polymers do no soften, but they do char after intensive heating.

Figure 69 shows the formation of a phenolic thermosetting resin. The reaction also represents a condensation polymerization reaction since the two chemicals react together (condense) to form the start of a polymer and split off a small molecule, in this case water. Made from phenol and formaldehyde, this phenolic (phenol formaldehyde) resin was discovered by Bakeland in 1907 and named Bakelite. It is a good illustration of a common three-dimensional cross-linked thermosetting polymer.

Another important thermosetting polymer (resin) is the epoxy class of polymers. The epoxy (epoxide) resin is well established in the building industry. This resin is used as an adhesive, a protective coating, and a general-purpose bonding agent.

Progress in the development of new types of polymers has been rapid in the last few decades. For example, a mixture of two different monomers polymerizes to form a polymer, called a copolymer. Glass fibers can be added to monomers to form a reinforced polymer (composite) with increased strength. Research in the nature and methods of formation of old and new composites has expanded to concrete, mortar, metals, glass ceramics, and polymers. [26]

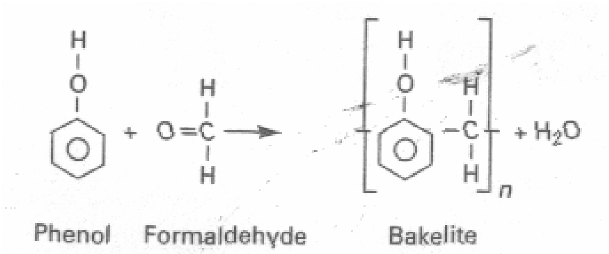


Fig. 69 Phenolic resin formation *(Ibid)*

After reviewing a brief background on polymers we go back to Shape Memory Polymers which is classified as "Thermoplastic" type of polymers, and discuss its history, theory and application.

3.2.2.2.1.2 History

The first shape memory polymer, a poly(norbornene) based polymer, was reported by CdF Chimie Company, France, in 1984 and was available commercially in the same year by Nippon Zeon Company of Japan under the trade name Norsorex. This polymer has a Tg of between 35^{o}C and 40^{o}C but applications have been limited by its processibility.
The Kurare Corporation, Japan, developed a second commercial SMP, Kurare TP-301, in 1987. It is poly(trans-isoprene) based , has a Tg of -68 ^{o}C and a melting temperature (Tm) of 67 ^{o}C, but like poly(norbornene) has limited processibility.
A third commercial SMP, Asmer, was introduced by Asahi Company, Japan and is poly(styrene-butadiene) based with Tgs in the 60^{o}C to 90^{o}C range.
Diisocyanate/polyol based polyurethane SMPs were developed by Mitsubishi Heavy Industries in the late 1980s. Poly(urethane) based SMPs are available under a number of trade names including Diary MM-4510, a polyester polyol based poly(urethane) and Diary MM-4520, a polyether polyol based poly(urethane). The advantage of the poly(urethane) SMPs is the flexibility where the chemistry of the polyurethane provides with a wide range of Tgs in designing materials and therefore wide range of temperatures where the shape memory effect can be invoked. In addition, these poly(urethanes) are thermoplastic polymers which provides a significant improvement in processibility. Nippon Zeon has produced a series of polyester based SMPs that are marketed under the trade name Shable.
Through the nineties, most of the development and applications of SMPs discussed in the literature concerned thermoplastic poly(urethane) based SMPs. There are a number of reasons for this. The most important is the ability to control the structure and therefore properties of poly(urethanes). In particular, the ability to vary the glass transition temperature of this SMP over a wide temperature range increases the potential applications. The thermoplastic nature of poly(urethanes) renders them

amenable to processing by techniques such as extrusion, injection or blow molding or by solution casting. Poly(urethanes) also have good chemical and ultraviolet resistance and biocompatibility compared to other SMPs.
In 1997, Liang et. al. proposed the use of shape memory composites to address the low strength and stiffness of SMPs. They investigated the preparation of poly(urethane) SMPs composites using chopped glass, unidirectional Kevlar, and woven fibreglass. More recently, the properties of SMP composites fabricated using resin transfer molding and preimpregnation of fibre tows (Elastic Memory Composite) have been reported. The matrix resin was an epoxy based thermoset resin that, by controlling the degree of cross-linking, can have Tgs ranging from –13^{o}C to 95 ^{o}C. [27]

3.2.2.2.1.3 SMP Theory

Shape Memory Polymers (SMP) are dual-shape materials which belong to the group of thermoplastic polymers and can actively change from a shape A to a shape B where shape A is a temporary shape obtained by mechanical deformation and followed by fixation of that deformation and shape B is the permanent shape which is accomplished by applying a stimulus.
In shape-memory polymers, the stimulus reported to be used so far are: heat or light. Other indirect actuation of the shape memory effect were also realized using irradiation with infrared light, application of electric fields, alternating magnetic fields, or immersion in water. The shape memory effect does not require a specific chemical structure in the repeating units but it only relies on the molecular architecture. Therefore, intrinsic material properties, such as mechanical properties, can be adjusted to the need of specific applications through the variation of molecular parameters, such as the comonomer ratio or the monomer type.
The shape-memory effect is not an intrinsic property, which means that polymers do not display this effect by themselves instead, shape memory results from a combination of polymer morphology and specific processing and can be understood as a polymer functionalization.
Formation process from shape B to shape A and back to B again is explained as follows:
The polymer is formed into its initial permanent shape B by conventional processing such as extruding or injection molding, followed by a process called Programming, where the polymer sample is deformed and fixed into the temporary shape A. When an external stimulus is applied, the polymer recovers its initial permanent shape B again. This cycle of programming and recovery can be repeated several times, with different temporary shapes in consecutive cycles (Fig 70).
Heat stimulus is the most stimuli used by the shape-memory polymers reported so far. If the additional cross-links are based on physical interactions, a further distinction in *T*trans can be made, which can be either a glass transition *T*g or a melting temperature *T*m. The shape-memory technology is extended to use light as a stimulus if the cross-links are functional groups that are able to undergo photoreversible reactions. Material could be heated indirectly by using other stimuli like electrical currents or electromagnetic fields. [28]

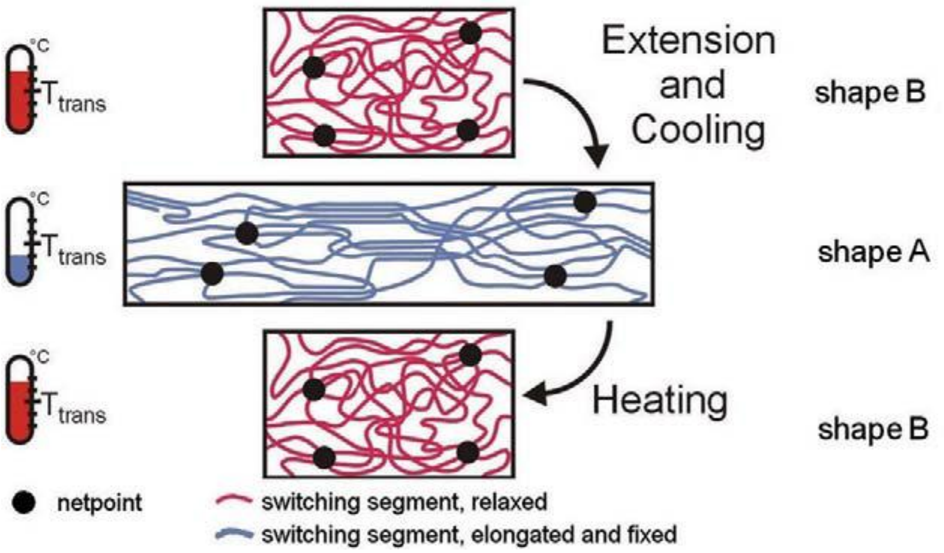


Fig. 70 Molecular mechanism of the thermally induced shape-memory effect.
(Behl, M. and Lendlein, A., 2007)

3.2.2.2.1.4 Shape Memory Polymer Composites

Polymer composites are a combination of a polymer matrix and micro/nano-sized fillers such as particles, fibers, platelets, or tubes. The polymer matrix can be an amorphous or crystalline thermoplastic material or a crosslinked three-dimensional polymer network. By distributing any stress through the whole specimen, the matrix is able to hold or bind the fillers together and protects them from damage. Polymer composites have received considerable attention over the last decade because of their potential to enhance dramatically properties relative to the neat polymer matrix, where we find small amounts of filler incorporated leads to an improvement in material properties, such as strength ,modulus, flame retardancy, heat resistance, , and lowered gas permeability. In addition, new functions including electrical, magnetic, optical, as well as biofunctionality could also be introduced by polymer composites. The material properties' enhancement and novel functions creation has been connected to the interfacial interaction between the polymer matrix and fillers as well as the formation of a network of interconnected filler particles. Heat and electrical current could be conducted by this network of interconnected particles. Tailoring and development of polymer composites opens the possibility to promote their application in automotive, biomedical, aerospace, building, optoelectronic, and electrical applications. Micro-/nanostructural parameters such as distribution, dimension, shape, alignment, volume fraction, and packing arrangement of fillers can control the novel functions and properties enhancement of polymer composites. Physical properties of polymers with randomly distributed particles are isotropic whereas anisotropic properties could be obtained from fiber filled composites, except for the very short, randomly distributed fibers. Furthermore, composites filled with macro-sized fillers had different properties compared to those with nanometer-sized fillers. By using higher macro-sized filler concentration, some of the properties of nanocomposites, such as increased tensile strength, may be achieved at the expense of increased weight and decreased gloss but other properties of nanocomposites such as improved barrier or optical clarity properties could not be achieved by high concentration of macro- sized fillers. Critical filler volume fraction is the filler concentration required for substantial improvement in the overall material properties. The fillers could be classified either by their size or by their geometry. Three different categories of filler materials could be found:

- Particles (e.g., metal, POSS, silica and other organic and inorganic particles),
- Layered materials (e.g., layered silicate and graphite),
- Fibrous materials (e.g., single-walled and multi-walled nanotubes and nanofibers).

The surface area/volume ratio of the fillers is a morphological characteristic, which is of fundamental importance to the understanding of the structure–property relationship of nanocomposites. As shown in Fig.71, the change in layer thickness, particle diameter, or fibrous material diameter from micrometer to nanometer changes the surface area/volume ratio by three orders of magnitude. There is often a distinct size dependence of the material properties at this scale. In addition, when the interfacial area drastically increased, the properties of the composite became dominated by the properties of the interface or interphase.

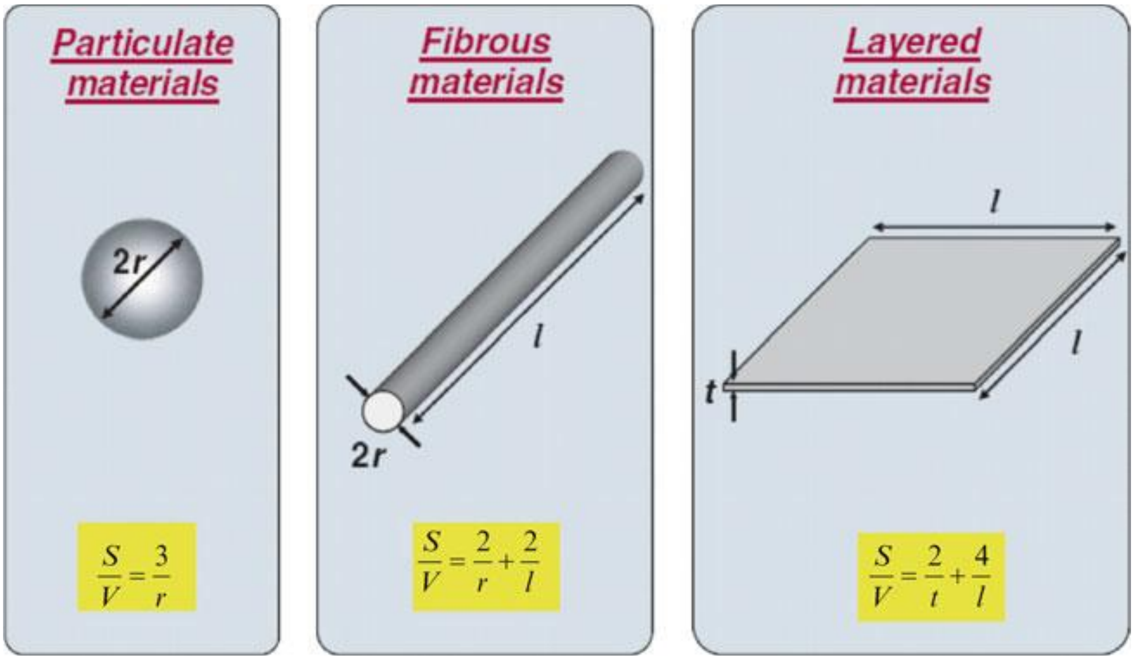


Fig. 71 Surface/volume (*S/V*) ratios for varying filler geometries, *r* is the radius, *l* is the length, and *t* is the thickness of filler. (Lendlein, A., 2010)

Major challenges in fundamental understanding and design of polymer composites are related to the following: dispersibility of fillers, complexity of the composite structure, and the relationship between dispersion and optimal properties. The first step in the processing of nanocomposites is the uniform dispersion of nanoparticles and nanotubes against their agglomeration due to van der Waals bonding. Exfoliation of clays and graphitic layers are essential. Well-dispersed fillers in polymer matrix has been achieved through studying several strategies, including melt processing, in-situ polymerization and solvent casting method (often with surface functionalization and/or sonication pretreatment). As for the melt processing, it often led to limited filler dispersion in the polymer matrix but the blending polymer and fillers in solvent or in-situ polymerization, resulted in a better dispersion. The modification of the filler surface by grafting of macromolecules onto its surface is preferable. The filler is highly compatible to the polymer matrix in this case which is often desirable because it allows for optimal transfer of stress from the matrix to the fiber and provides the best possible adhesion. [29]

Thermally induced shape-memory polymers can be heated by illumination with infrared light instead of increasing the environmental temperature. This concept has been demonstrated in a laser-activated polyurethane medical device. Heat transfer can be enhanced in such devices by incorporation of conductive fillers, such as conductive ceramics, carbon nanotubes and carbon black (Fig. 72). The mechanical properties are also influenced by this incorporation of particles: stiffness is increased and strain levels are recoverable due to incorporation of microscale particles and can be further enhanced by the incorporation of nanoscale particles. The molecular structure of the particles has to be considered in order to achieve an enhanced photothermal effect. Polyesterurethanes reinforced with carbon nanotubes or carbon black of similar size display increased strain and fixity. Carbon-black-reinforced materials show limited shape recovery of around 25-30%, while carbon-nanotube-reinforced polymers, observed an *R*r (Recovery rate) of almost 100% which has been attributed to a synergy between the crystallizing polyurethane switching segments and the anisotropic carbon nanotubes.

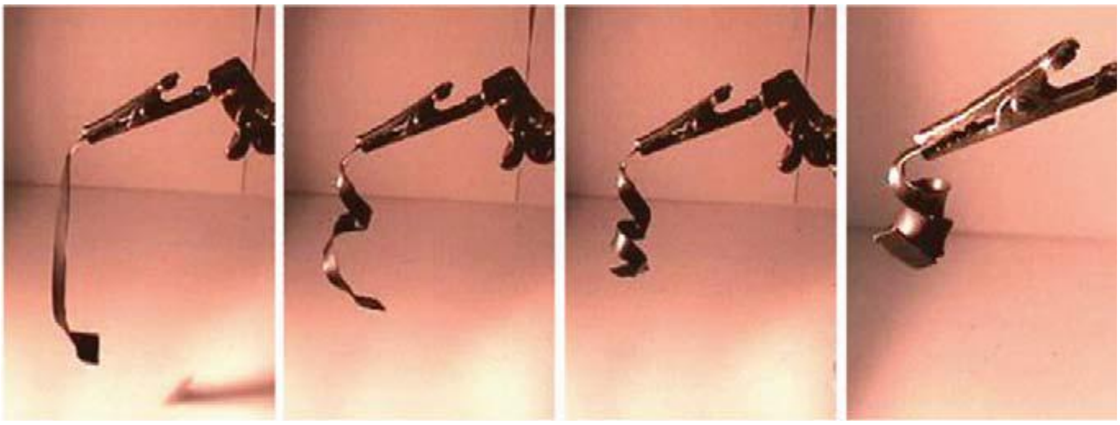


Fig. 72 Strain recovery under infrared radiation (exposure from the left).
(Behl, M. and Lendlein, A., 2007)

Infrared absorption, nonradiative energy decay, and resulting local heating is limited to the near-surface region of a stretched ribbon, resulting in strain recovery of the near-surface region and curling of the ribbon within 5 seconds toward the infrared source. [28]

All the previous section on Shape Memory Polymers was discussing the One Way conventional SMP and the ability of adding fillers to form Composite SMP to enhance its thermal, optical and physical properties, but the problem with the One Way SMP is that it is not a repeated cycle, i.e. after recovering its permanent shape, it needs mechanical interference to go to back to its temporary programmed shape, but this problem was solved through recent researches and the researcher will review one of the most recent research.

3.2.2.2.1.5 Two Way Shape Memory Polymers

"The shape memory effect in SMPs is due to heat energy, which causes the polymers in the reversible phase to move freely as polymer molecular chains. Therefore, two-way shape memory effect with an SMP material is considered to be impossible, but it is possible if two different shape memory effects are used, such as:

The shape memory effects of an SMA (Shape Memory Alloys) and an SMP (Shape Memory Polymers) or the shape memory effects of two kinds of SMPs. In the following section, it is the latter solution which is proposed through two operating methods which are:

- The first operating method is the double SMP layer method where one shape memory effect generates displacement and the other shape memory effect cancels the generated displacement.
- The second operating method is the single SMP layer method where the thermal deformation of an SMP cancels the generated displacement caused by the shape memory effect.

In the double SMP layer method, the shape memory effects of two kinds of SMPs with different glass transition temperatures (Tg1 and Tg2, Tg1 < Tg2) are used. The two kinds of SMPs have reverse shapes of the memory with respect to each other. When heating these two kinds of SMPs, the memory shape related to Tg1 appears first, and then it disappears around Tg2 because the memory shape related to Tg1 is canceled by the memory shape related to Tg2.

In the single SMP layer method, the shape memory effect and thermal contraction of a single kind of SMP is used and the mechanism for the two-way behavior in this method takes place as follows:

The SMP is cooled below the Tg after a memory shape appears above Tg. Then, the SMP shrinks thermally especially near the Tg. This is used to return the SMP from the generated memory shape to the pre-memory shape (the shape prior to the memory shape). Thus, this method is effective only when the SMP undergoes tensile deformation in the memory shape. However, this method simplifies the actuator structure.

The advantage of these two operating methods is that it only needs for activation a temperature cycle of heating and cooling. Also the proposed methods are considered to be suitable for small actuators such as Microelectromechanical Systems (MEMS). The two proposed methods could be implemented using other shape memory materials such as SMA but the structure and fabrication would be more complicated than those of SMPs.

The SMPs of the polyurethane series Diary were chosen for being able to tailor the Tg to an arbitrary temperature and their applications have been investigated.

Fundamental experiments were conducted by using the cantilever beam prototype actuators to examine the effectiveness of the proposed methods and the characteristics of the actuators using these methods. By applying the temperature cycle, the relationship between the displacements of the actuators and the temperature of the SMPs was measured. The experiments concluded that the actuators could reproduce the specified displacements. [30]

Operating Principle

3.2.2.2.1.5.1. Operating principle of double SMP layer method

As mentioned before, the double SMP layer method uses two kinds of SMPs with different glass transition temperatures (Tg1 and Tg2, Tg1 < Tg2). To begin with, the memory shapes related to Tg1 and Tg2 must be imparted to the two SMP layers. The memory shape is determined by the shape acquired when the SMP stiffens (are dried). The memory shape of Tg2 must be set to be the reverse of that of Tg1.
Then follows the steps from (a) to (d) which are carried out to conduct the behavior of the two way actuator. Those steps are also shown in the upper part of Fig. 73 using the example of a cantilever beam actuator. Curves shown in the lower part of Fig. 73 demonstrates the relationship between temperature and elastic modulus of the two SMPs.
The steps of the method are as follows:
(a) The actuator is heated from a glassy state.
(b) The actuator produces the memory shape-1 related to Tg1 above Tg1.
(c) When temperature becomes around Tg2 (>Tg1) by further heating, the actuator produces the memory shape-2 related to Tg2. Then the actuator cancels the memory shape-1 by superposing the two memory shapes since the memory shape- 2 is the reverse of the memory shape-1. Then the beam returns to the flat configuration, which is the same shape as in the glassy state.
(d) The actuator is cooled below Tg1 (in the glassy state) to maintain the flat configuration.

The double SMP layer method could be applied for any memory shape. However, this method requires fabricating the two SMP layers and imparting the two memory shapes. The polyurethane SMPs is the material chosen for fabrication due to the following reasons:

- The SMPs can set the glass transition temperature to an arbitrary specific value (–40 to 120 ^{o}C) which is a wide range of temperature.
- The liquid type is suitable for spin-coating.

The *T*gs of the used SMPs were determined to be 35 and 55 ^{o}C since their glass transition region is about 10 ^{o}C. [30]

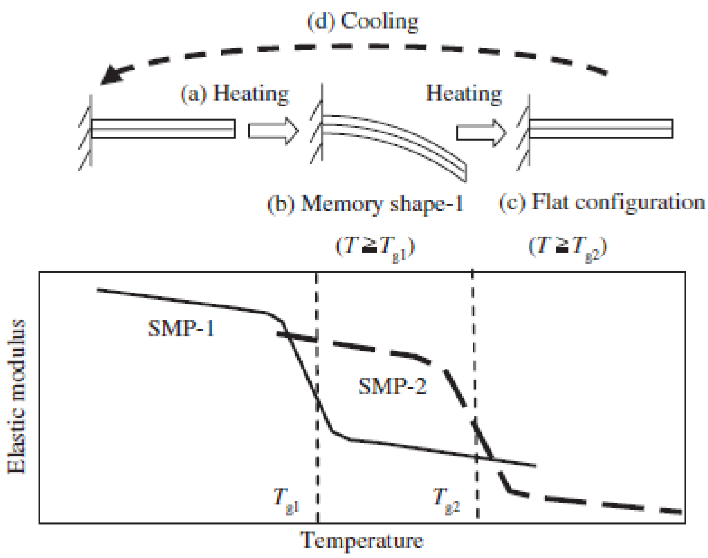


Fig. 73 upper part shows steps of operating method. Lower part shows the relationship between elastic modulus and temperature of the double SMP layer method actuator (curves).

3.2.2.2.1.5.1.2 Operating principle of single SMP layer method

Also as mentioned before, this method uses the thermal contraction and the shape memory effect of a single type of SMP. The thermal contraction is used to return the generated memory shape to the pre-memory shape. This method was applied to a cantilever beam actuator.

The cantilever beam actuator consists of a substrate with an SMP layer coated on the substrate. The shape in the glassy state of the SMP is the flat configuration and the imparted memory shape is the bent configuration.

The actuator conducts two-way behavior as shown in Fig. 74 and the steps are as follows:

(a) The beam is the flat configuration in the glassy state.

(b) When the actuator is heated above *T*g, the memory shape appears. The figure indicates that the SMP layer is formed in the convex (tensile) side of the beam.

(c) Then, the actuator is cooled by natural heat radiation. When the temperature of the SMP decreases to near *T*g, the SMP layer gradually stiffens and shrinks thermally. This is because the Young's modulus and coefficient of thermal expansion (CTE) of the SMP a little below *T*g are larger than those above *T*g.

(d) The thermal shrinkage of the SMP makes the memory shape returns to the flat configuration, i.e. the pre-memory shape.

Hence, accomplishing the two-way behavior using single SMP layer.

The single SMP layer method is only effective when the SMP undergoes tensile deformation when the memory shape appears (Fig. 74 (b)), while the double SMP layer method, which was previously described, is effective for any memory shape. However, this method is distinctive with its simple structure and ease of actuator fabrication.[30]

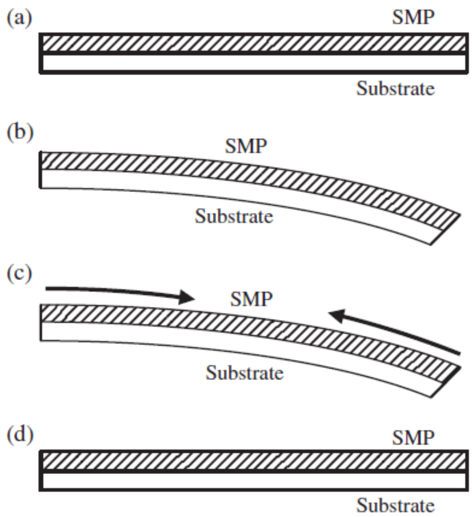


Fig. 74 Mechanism to return the generated memory shape to prememory shape in the actuator of the single SMP layer method

Conclusions

In the previous section the researcher reviewed recent research that provided a two way operating SMP which was not possible up till then. Two operating methods for two-way behavior SMP actuators were developed. First one was based on using the shape memory effects of the two kinds of SMPs with the different glass transition temperature where the memory shape generated around *T*g1 is canceled by the memory shape generated around *T*g2 (>*T*g1). The second one was based on using the thermal contraction and the shape memory effect of the single kind of SMP where the generated memory shape is canceled by the thermal contraction of the SMP when the SMP is

cooled near *T*g. The effectiveness and the fundamental characteristics of these methods were examined experimentally by using the cantilever beam actuators with spin-coated polyurethane SMP. The proposed methods used only shape memory effect which was heating and cooling the actuator for activation while conventional SMP actuators used shape memory effect and an external force for two-way actuator behavior. These simple operating methods are considered to be suitable for small actuators, particularly for MEMS". [30]
These two operating methods succeeded to dispense the use of any external force, resulting into an actuator that works automatically by itself which could promote it to take part in numerous applications.

3.2.2.2.1.6 Applications

The past decade has witnessed remarkable advances in stimuli-responsive shape memory polymers (SMPs) with potential applications in several fields such as: aerospace, biomedical devices, energy, textiles, civil engineering, bionics engineering, household products and electronic engineering.

List below shows present and potential applications for SMPs

1. Aneurysm occlusion devices
2. Assembly/disassembly tools
3. Bio-MEMs
4. Bone defect fillers
5. Cardiac valve repair
6. Cells manipulating and capturing
7. Chemical feeding in chemical reactions
8. Clot removing devices
9. Controlled drug release
10. Crease and pattern retention finishing
11. Damping fabrics
12. Damping materials
13. Deodorant fabrics
14. Electroactive shape memory hinge
15. Embolic devices
16. Endoscopic surgery suture
17. Erasable Braille
18. Fashion design
19. Flexible light-emitting diodes
20. Hair treatment
21. Heat and moisture management
22. Heat shrinkable packages for electronics
23. Hot shrinkage micro-tags
24. Kidney dialysis needles
25. Light-modulators and display devices
26. Measuring tools in complex cavities
27. Memory foam mattress, pillow and insoles
28. MEMs applications
29. Microtweezers in medicine

30. Micro-valves in microdevices
31. Morphing of aircraft wings and helicopter rotor blades
32. Novel Mckibben artificial muscles
33. Ophthalmic applications
34. Orthodontic
35. Orthopedic cast
36. Orthopedics Morphix structure anchor
37. Packaging
38. Pharyngeal mucosa reconstruction
39. Phase change fabrics
40. Physiological monitoring
41. Post-surgical treatment of mitral insufficiency
42. Pressure garments
43. Recordable and erasable memories
44. Study of cell proliferation
45. Selective desalination material
46. Self-healing
47. Self-peeling dry adhesive
48. Shape changing nanofibers
49. Shape memory fibers
50. Smart mandrels for composite tooling
51. Shape memory neuronal probe
52. Skin-care products
53. Soft lithography
54. Surface wetting
55. Microfluidic devices
56. Surface wrinkle and micro-patterns
57. Switchable information carriers
58. Temperature sensors
59. Toys
60. Treatment of esophageal stenosis
61. Vascular stents
62. Surgery inside living cells
63. Vehicle active air dams and other aerodynamic surfaces
64. Weight reducing agent
65. Wound dressing
66. Wrinkle free finishing of cotton fabrics [31]

2.3.2.2.2. Shape Memory Alloys

2.3.2.2.2.1 History

Adolf Martens discovered martensite in steels in the 1890s and it was a major step that led eventually to the discovery of shape memory alloys. The martensitic transformation was probably the most widely studied metallurgical phenomenon during the early 1900s. The martensitic transformation, as observed in the Fe-C system, was established as an irreversible process. Kurdjumov and Khandros introduced in 1949 the concept of thermoelastic martensitic transformation, which explained the reversible transformation of martensite based on experimental observations of the thermally reversible martensitic structure in CuZn and CuAl alloys. The concept of thermoelastic martensitic transformation was demonstrated in other alloys such as InTl and CuZn by 1953. Up till 1963 the reversible martensitic transformation and the alloys that exhibited them remained unutilized. With the discovery of NiTi by Buehler and coworkers, the breakthrough for engineering applications occurred while investigating materials useful for heat shielding. It was noticed that the material also possessed a shape recovery capability in addition to its good mechanical properties, compared to some common engineering metals. Following this observation, the term Nitinol was coined for this NiTi material in honor of its discovery at the Naval Ordnance Laboratory (NOL). The term Shape Memory Effect (SME) was given to the associated shape recovery behavior. The discovery of Nitinol led to active research interest into SMAs. Wide investigations on the effects of heat treatment, microstructure and composition were held and started to be understood during this period.
Studies showed in 1965 that the addition of a third alloying element such as Co or Fe to the existing NiTi system led to a dramatic decrease in the SMA transformation temperatures. The new alloys inspired the first commercial SMA application, known as Cryofit, where SMA material was used for pipe couplings in F-14 fighter aircraft. The transformation temperatures for Cryofit were so low that in order to prevent actuation from occurring before the assembly, the pipe couplings were transported in liquid nitrogen. In 1989, continued research to address this issue resulted in the development of the NiTiNb system, this system was easier to handle due to its larger temperature hysteresis, and found widespread applications in repairs for nuclear reactors and in battle damage repairs. In the early 1970s, *High Temperature SMAs* (HTSMAs), such as TiPd, TiPt and TiAu (with transformation temperatures greater than $100^{o}C$), were also developed. Meanwhile in 1978, while Melton and Mercier were studying the fatigue properties of NiTi it showed that alloying the material with Cu did not change the transformation temperatures considerably, but narrowed the stress hysteresis. Miyazaki showed improved fatigue life for NiTiCu alloys later in 1999. The low cost associated with this material system in addition to the improved fatigue life promoted it for a wide variety of engineering applications. [32]

2.3.2.2.2.2 SMA Theory

Surprisingly if we take a look at the following devices, we’ll find that they all share a common material technology, those devices are: tiny actuators that eject disks from laptop computers, eyeglass frames that are amazingly bendable, medical stents used for opening arteries that are implanted in a compressed form and then expand to the right size and shape when warmed by the body and small microvalves. The interesting behavior of each of these devices relies upon the shape memory effect that refers to the

ability of a particular kind of alloy material to revert, or remember, a previously memorized or preset shape.
The characteristic derives from the phase-transformation characteristics of the material. A solid state phase change – a molecular rearrangement – occurs in the shape memory alloy that is temperature-dependent and reversible. For example, at high temperature the material can be shaped into one configuration, while at low temperature the material is deformed dramatically, and then returns to its original shape upon the application of heat in any form, including by an electrical current. The phenomenon of superelasticity, which is the ability of a material to undergo enormous elastic or reversible deformations, is also related to the shape memory effect.
One of the most commonly used alloys in shape memory applications is Nickel–titanium (NiTi) alloys, although many other kinds of alloys also exhibit shape memory effects. These alloys can exist in final product form in two different temperature-dependent crystalline states or phases, those two states are:
The Austenite state which is the primary and higher temperature phase.
The Martensite state which is the lower temperature phase.
The physical properties of the material in the austenite and martensite phases are quite different. The material in the Martensite phase is soft and ductile while in the Austenite state is strong and hard. The Martensite crystal structure has a complex rhombic structure while the Austenite crystal structure is a simple body-centered cubic structure. When we take a look at the stress–strain curve of the higher temperature austenite, we'll find that it is similar to most metals while the stress–strain curve of the lower temperature martensitic structure almost looks like that of an elastomer in since it has plateau stress-deformation characteristics where large deformations can easily occur with little force. In this state, it behaves like pure tin, which can (within limits) be bent back and forth repeatedly without strain hardening that can lead to failure. The material in the lower temperature martensite state has a twinned crystalline structure, which involves a mirror symmetry displacement of atoms across a particular plane.
Twin boundaries are formed that can be moved easily and without the formation of microdefects such as dislocations. Unlike most metals that undergo deformations by slip or dislocation movement, deformation in a twinned structure occurs by large changes in the orientation of its whole crystalline structure associated with movements of its twin boundaries.
The thermally induced shape memory effect is associated with these different phases. The material is in the austenite phase in the primary high temperature environment, and becomes martensitic upon cooling. No obvious shape change is observed upon cooling, but now the material is able to be deformed mechanically. It will remain deformed while it is cool but when heated, the austenitic structure reappears and the material returns to its initial shape. Superelasticity can also take place. A phase transformation from the austenite phase to the martensite phase (which is highly deformable) is induced by the application of stress to a deformed shape memory alloy, this stress causes martensite to form at temperatures higher than previously and there is high ductility associated with the martensite. When the applied stress level is removed and the material reverts back to austenite, the associated strains or deformations are reversible. High deformations, on the order of 5–8%, can be achieved. For the superelasticity phenomenon to occur, changes in the external temperature environment are not necessary.
Why these phenomena occur is fundamentally a result of the need for a crystal lattice structure to accommodate to the minimum energy state for a given temperature. There are many different configurations that a crystal lattice structure can assume in the

martensite phase, but there is only one possible configuration or orientation in the austenite state, and all martensitic configurations must ultimately revert to that single shape and structure upon heating past a critical phase transition temperature. The process described is repeatable as long as limits associated with the transition phases are maintained. A form of fatigue failure can occur after repeated cycles under high stress or deformation levels.

Both of the two primary phenomena associated with shape memory effects which are: thermally induced effects and mechanically induced effects have direct applications. In the shape memory effect associated with the thermal environment, a material having an initial shape while in its high temperature austenite phase can subsequently be deformed while in a lower temperature phase martensite phase. The alloy reverts back to its initial shape when reheated to the high temperature austenite phase by a heat stimulus, such as an electric current (but any heat source will work). A high force is generated by the phase-changing material during this process. The material can thus be used as an actuator in many different applications. Usually the material provides the actuating movement as part of a larger device. Devices using it are often very simple as compared to more traditional mechanical actuators because the force and movement occur within the material itself. Heat which could be induced by electrical current is easily applied and electronically controlled and accordingly, the use of shape memory alloys in release latches and a host of other devices are widely spread.

In the shape memory effect associated with the mechanical environment, or superelasticity, the material can undergo an elastic deformation (caused by an external force) that can be as high as twenty or more times the elastic strain of normal steel. Superelastic materials thus exhibit incredible abilities to deform and still spring back to their original shape. Eyeglass frames was an initial consumer application of superelastic materials that could seemingly be tied in knots, but revert to their original shape upon release. [15]

Fig. 75 Desired shape (austenite) Deformed shape (martensite) Original state (austenite)

For Shape memory alloys. (Addington, M. and Schodek, D., 2005)

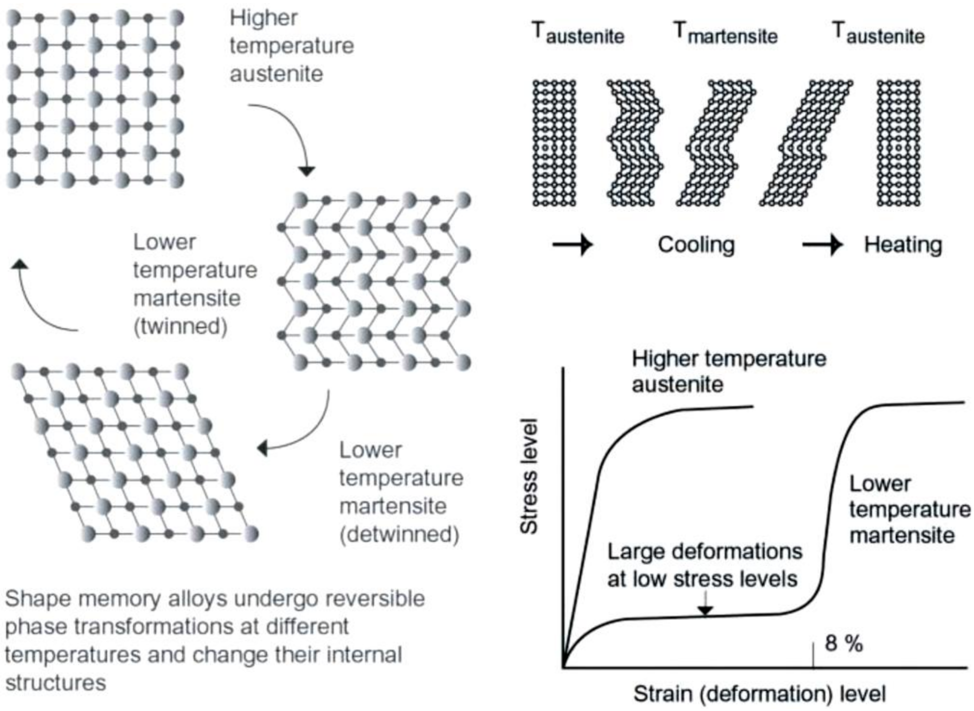


Fig. 76 Shape memory alloys (e.g., Nitinol) that exhibit thermally induced shape memory effects. *(Ibid)*

2.3.2.2.2.3 Applications

1. Aircraft and spacecraft
2. Automotive
3. Robotics
4. Sense cracks and contract to heal macro-sized cracks in reinforced concrete.
5. Piping

6. Smart phones
7. Osteotomies
8. Orthopaedic surgery
9. Dental braces
10. Eyeglass frames

2.3.2.2.2.4 Shape-memory polymers vs. shape-memory alloys

There are major differences between Shape-memory polymers (SMPs) and Shape memory alloys (SMAs) of which is their glass transition or melting transition from a hard to a soft phase which is responsible for the shape-memory effect. Martensitic/Austenitic transitions are responsible for the shape-memory effect in shape-memory alloys. SMPs are characterized with a lot of advantages that make them more attractive than shape memory alloys. For example, they have a high capacity for elastic deformation (up to 200% in most cases), lower density, much lower cost, easy processing, a broad range of application temperatures which can be tailored, potential biocompatibility and biodegradability, and probably exhibit superior mechanical properties than SMAs as shown in table 7. [33]

Table 7: A summary of the major differences between SMPs and SMAs. [33]

SMPs and SMAs		
	SMPs	**SMAs**
Density (g/cm^3)	0.9–1.2	6–8
Extent of deformation	up to 800%	<8%
Required stress for deformation (MPa)	1–3	50–200
Stress generated upon recovery (MPa)	1–3	150–300
Transition temperatures (°C)	−10..100	−10..100

Recovery speed	1s – minutes	<1s
Processing conditions	<200 °C low pressure	>1000 °C high pressure
Costs	<$10/lb	~$250/lb

Conclusion

After reviewing five types of Smart Materials and after discussing their properties and applications, whether in architecture or in other fields, the researcher chose to work with the Shape Memory Polymers for several reasons:

1. Shape Memory Polymer is a flexible smart material that could respond to different stimulus such as temperature, light and PH.

2. It reacts to a wide range of temperature, from very low to high temperatures.

3. It could be shaped into different shapes, and also reshaped hundreds of times which indicate its ease of handling.

4. It is a transparent material.

5. It could be treated to tolerate direct sunlight and with stand exterior climatic conditions.

6. It is already an industrial product that is manufactured by a number of companies, and so it could be easily purchased, these companies also sell it in a form of raw material so that an individual can process and program it.

7. Less expensive compared to other smart materials.

8. It could be applied through different elements in architecture such as:
-Windows in internal and external walls
-Solar chimneys
-Openings in domes

-Skylights

And so therefore and for the above mentioned reasons, the researcher chose to work with SMP sheets and try to apply it within architecture.

But before going to the experiments section and the work done with the selected material, the researcher will review projects that adopted the Biomimetic concepts in architecture and also different smart building materials in order to learn how to combine between biomimetic design and smart materials in architecture to reach a building that can respond to climatic conditions and save energy consumption without mechanical interference.

3. EXAMPLES OF PROJECTS AND RESEARCHES IN BIOMIMETIC ARCHITECTURE AND SMART MATERIALS

This part will review the most related project examples that demonstrate and shows how Biomimicry was translated in architecture through design and through using smart materials.

3.1. Self-Activated Building Envelope Regulation (SABER)

A new type of thin film building membrane was created by UCBerkeley Professors Luke Lee in Bioengineering and Maria-Paz Guttierez in the architecture department where they reached a material structured at the nano and micro scale that can help minimize energy consumption used for climate control in buildings. They proposed recently a project to the National Science Foundation, this project is focusing on developing a building's skin that mimics nature's skins, a skin that is able to control humidity, heat and light in buildings the same way our skin does, without using any electrical or mechanical elements. Professors Luke Lee and Maria-Paz Guttierez prototype lense reacts to changes in the building's atmosphere by triggering microscopic openings in the membrane; this prototype lense is used in their biomimic "Self-Activated Building Envelope Regulation (SABER)". By this new structure "The material has become the system," says Guiterrez.

The film consists of two alternating rows of cells; these types of cells are passive devices that work depending on their material properties, not mechanical or electrical devices. These two rows of cells provide openings that are actuated by either humidity from the inside or light from the outside.

The first row of cells works as follows when the film is in sunlight:

It has micro-lenses embedded in the film; these micro-lenses direct light to tiny pockets that consists of photo-activated hydrogels which contract when subjected to light opening up elastomeric microventuri tubes, allowing more airflow into the building.
The second row of cells works as follows when the film is exposed to humidity:
It consists of hygroreactive polymer that expands when the level of moisture increases and opens up microvalves allowing more air into the building, which is the same way hydraulic mechanism, such as the turgor pressure in the guard cells of stomata in plants, acts in nature.
Then wraps the structure from the outside an external moisture barrier layer with a hydrophobic nano structure that mimics the lotus leaf surface which slides water off.
A layer of desiccant silica gels is placed on the inside in order to absorb moisture from the air inside and, this layer is integrated with the self-regulated ventilation system.
In conclusion, this project could be considered as a significant pioneering breakthrough that would minimize drastically energy consumed to run mechanical structures in order to supply heating, cooling and humidity control in buildings, not to mention that this energy used to help climate control in buildings is responsible for the burning of about a huge amount of fossil fuel. [34]

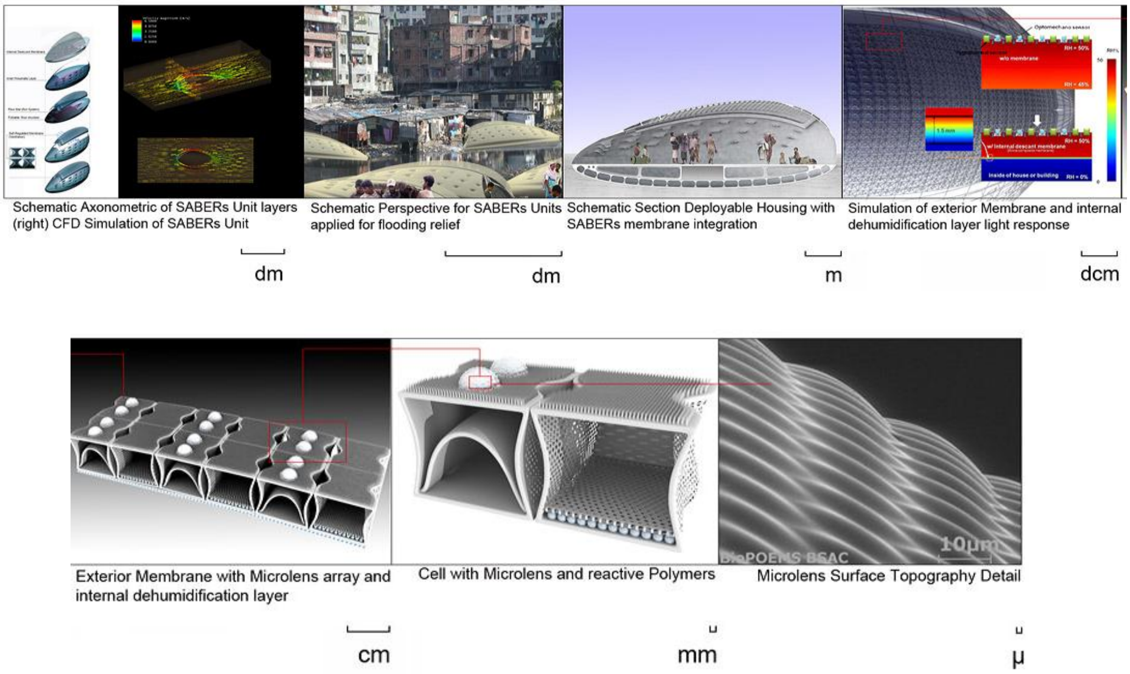
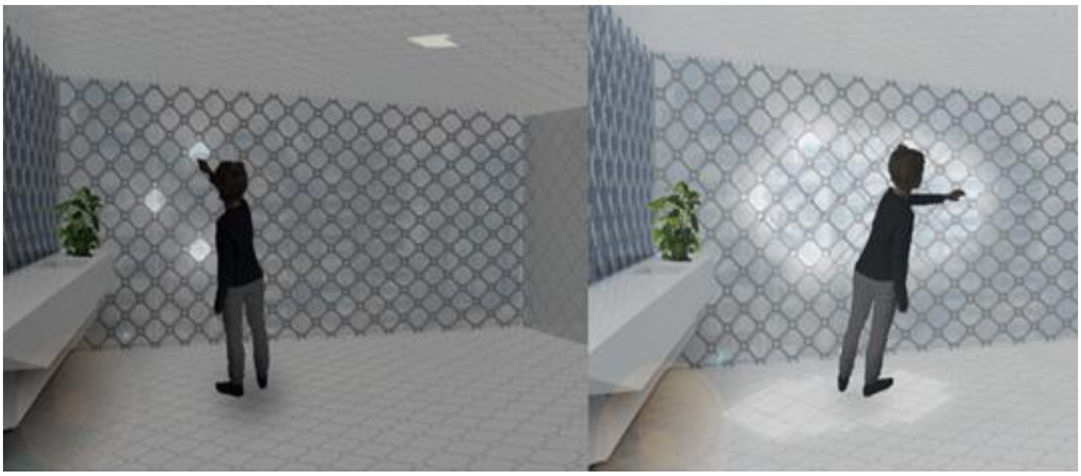


Fig. 77 SABER Project
(Clean Technica, 2010, http://cleantechnica.com/2010/05/14/clever-photosynthetic-breathing-building-skin-to-cut-need-for-energy/)

3.2. Habitat 2020

Following the lead of nature through Biomimicry which is one of the most effective ways to cut down the ecological footprint of buildings, Habitat 2020 is a an explicit future example of Biomimetic Architecture that has succeeded to merge basic cellular functions with high-tech ideas in order to create ‘living’ structures that operate like natural organisms. In this project, architects adopted a different approach which was a nature-inspired city living approach that looks at the urban landscape as a dynamic and ever-evolving ecosystem. With this perspective, and within this cityscape, buildings may open, close, breathe and adapt according to their environment exactly like nature. The Habitat 2020 building was designed for China, and came out to be extremely different to our perception of a structure's surface. In this building, the exterior structure has been designed to act as a living skin, rather than a system of inactive and inert materials that are used only for construction and shelter. The building's skin is supposed to act like a membrane that connects between the exterior and interior of the habitat. Taking the leaf surface as an example for biomimicry, it has several stomata, cellular openings that are responsible for gaseous exchange and transpiration in plants, and so the building's skin of this project will consider the function of the stomata guard cells and translate it within the project design. The building's skin would allow the entry of air, light and water into the building by automatically positioning itself according to the sunlight letting in light; thus minimizing electricity consumed for lighting during the day. The building also allow the entry of air and wind by channeling it into the building after filtering it to provide clean air and natural air-conditioning. In addition, this active skin would be capable of harvesting rain water where water would be purified, filtered, used and recycled. It could even absorb moisture from the air. The waste produced is also used by converting it into biogas energy which has a wide range of use in the habitat. [35]



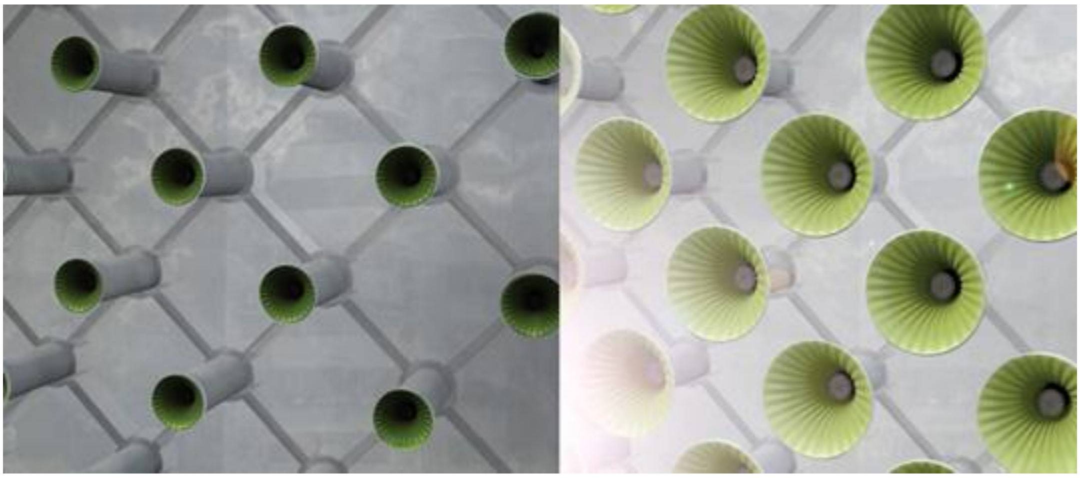


Fig. 78 Habitat 2020 Building
(INHABITAT, 2008, http://inhabitat.com/habitat-2020-off-the-grid-future-abode/)

3.3. IHUB competition scheme

The microscopic pores (stomata) on plant leaves, control the rate of evaporation and the exchange of gases involved in photosynthesis. When temperatures increase, the stomata open wider, which causes more water to evaporate and allow the plant to stay cooler than its surroundings. The water in plants is transported through vascular bundles in a process known as transpiration, and this is driven by osmotic pressure and capillary action. Architects explored the potential of using transpiration in IHUB competition scheme (Fig. 79). The aim was to create a building that cools itself using water but without pumps. If Capillary action and an equivalent of transpiration pull could be harnessed to deliver the water, then the rate of evaporation would drive the process. The designs show a network of capillary tubes on the southern elevation through which air can be drawn and cooled by evaporation. [6]

Fig. 79 IHUB competition scheme (Pawlyn, M., 2011)

3.4. Astonishing water-sensitive building material acts just like pine cones

A revolutionary new building material that responds to the presence of water was developed by Royal College of Art design student Chao Chen. After observing and studying the hydro-sensitive behavior of pine cones, he found that it opens and closes depending upon their exposure to water, Chen has succeeded to develop a wood laminate material that acts the same as the pine cone, where it bends and flexes in response to rain, humidity or soil moisture. This technology could be applied in shelters that seal up when exposed to rain and to building cladding that opens up to allow more light on a dull, drizzly day but shuts off to block out heat when the weather is hot and dry.

Chen's inspiration for the Water Reaction Project grew from his past observations of pine cones: the cones are open when they are dry, but close up in the presence of water to prevent their seeds from rotting. As Chen explained to Fast Co Design, Each pine cone has two layers. When it gets wet, the outer layer elongates more than the inner layer and closes in on itself. This led to the development of the laminate product, which features sandwiched layers of fabric, thin film and wood veneer. The veneer absorbs water, expands across the grain and curves or flattens depending on the production technique. "Utilizing inherent properties, this bio-mimetic material detects humidity and changes its shape automatically without mechanical structures or electrical elements" states Chen.

So how this product could be used? Chen has developed three prototypes for starters. The first is a shelter covered in tiles made of the laminate. The tiles curl and open in dry weather to let in light and breezes, but when wet they flatten to shut out the rain and protect occupants. Conversely, the Water Reacting Architectural Surface is flat when it is dry and sunny, useful for keeping interiors cool in hot weather. When the laminate is exposed to moisture, however, it curls, opening up the surface to let in light. Chen has also adapted this design to reveal a brightly painted surface underneath the laminate, which creates a cheerful and colorful exterior treatment for drizzle-prone cities, such as London or Vancouver. The third application is delightfully simple: a splice of laminate serves as a moisture detector for plants, standing upright and showing a red indicator when the plant needs watering, and bending and showing a blue surface when water levels are optimal.

Chen is still studying for his Masters in Product Design at RCA and concedes there's more work to be done on the designs before they can go into production. "These three products are still in the stage of working prototypes. The material needs to be more durable. I need to test how many times it can get wet, how it can deal with heavy winds," he notes. [36]

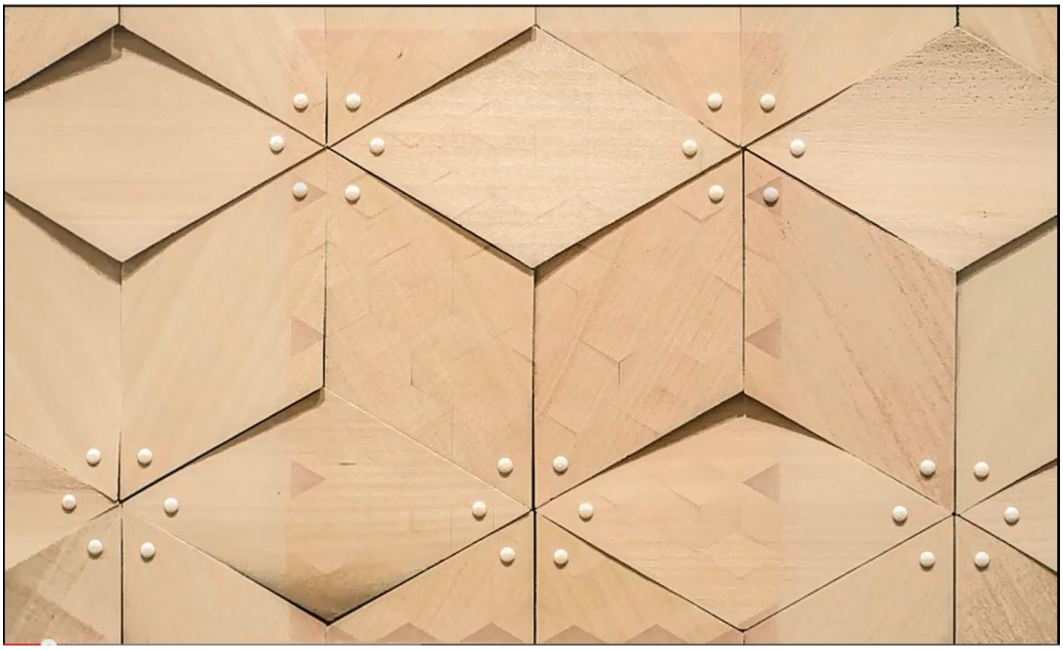


Fig. 80 Tiles when wet they flatten to shut out the rain (INHABITAT, 2015, http://inhabitat.com/astonishing-water-sensitive-building-material-acts-just-like-pine-cones/)

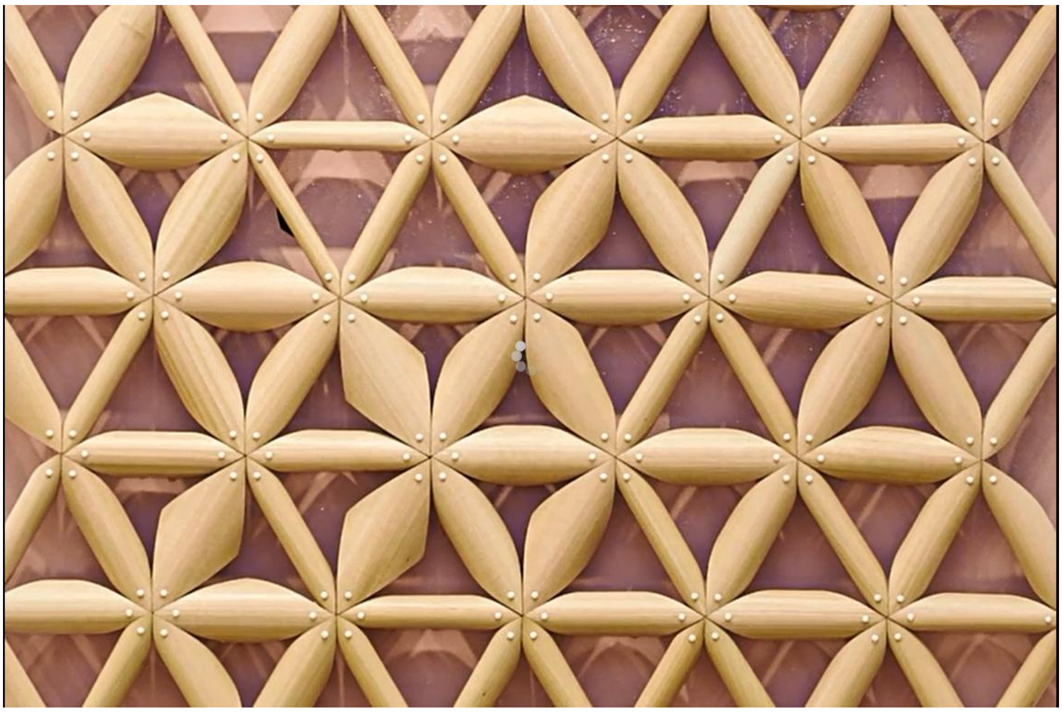


Fig. 81 Tiles curl and open in dry weather to let in light and breezes *(Ibid)*

3.5. Senior citizens apartments with a latent heat-storing glass facade, Switzerland (2004)

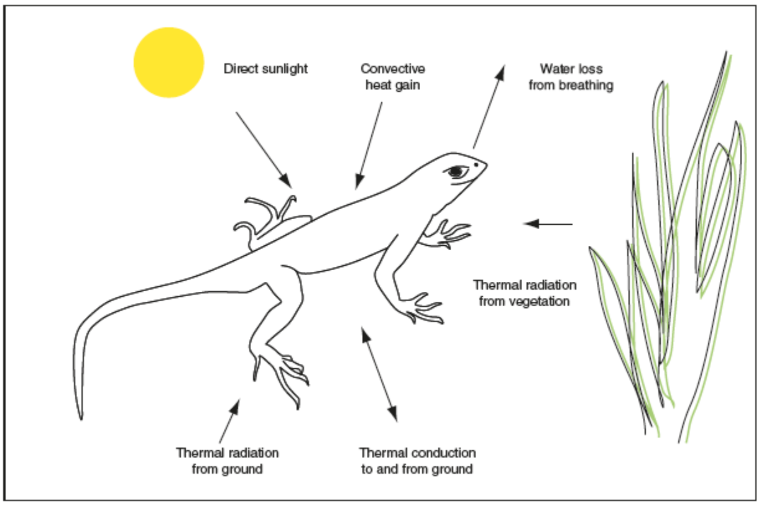
The PCMs, in addition to their "latent heat"-storing properties, has the ability to change their optical appearance which was used in several building facades designed by the Swiss architect Dietrich Schwarz. The idea first involved using pure paraffin placed in transparent hollow plastic blocks; this pure paraffin was used in the south facade of a zero energy house in Switzerland as latent heat storage facade elements. But during implementation, a salt hydrate was used as the PCM, for fire safety reasons.

The detailed structure of the south façade is as follows:
The architect installed a new glazing system called "GLASSXcrystal" which is a new design of a latent heat-storing insulation glazing system filled with salt hydrate covering an area of 148m^2. The GLASSXcrystal system is 78 mm in width and it is constructed like an ordinary triple insulation glazing unit, but the outer panel is a light-directing prism panel and the inside panel is a PCM panel, consisting of polycarbonate containers filled with a salt hydrate mixture, which is capable of storing heat at +26°C to +28°C. During summer the prismatic panels reflects the solar radiation back outside. In winter the solar radiation is allowed to pass almost undisturbed into the facade construction due to the lower sun angle, where it reaches the PCM panel, and gets converted into thermal radiation and stored by the melting of the salt hydrate. The salt hydrate crystallises and releases its stored heat energy into the room when the room temperature falls below +26°C, perhaps at night or on cloudy days.
The different phases of the salt hydrate dteremines the charge state of this latent heat-storing glass facade which can be observed directly from its optical appearance, where the following occurs:
The salt hydrate is uncharged if the facade looks opaque (seen from outside through the prismatic panels or from the inside). The salt hydrate is being charged or is fully charged if it appears translucent (seen from outside through the prismatic panels) or transparent (from the inside, with no printed pattern). [17]

Fig. 82 Facades using PCM panels. (Ritter, A., 2007)

3.6. S.C.A.L.E.S.

The common side-blotched lizard's physiology is optimized for efficiency in extreme temperatures and in water-scarce conditions as mentioned before in biomimicry section in details. The physiological strategies of the lizard's skin have inspired the house walls' design, while the lizard's behavioral adaptations have influenced the "smart" sun tracking system actuated by a hydraulic system and sensors.[9]



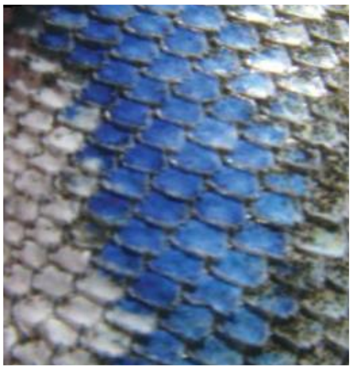


Fig. 83 Lizard's skin (Mazzoleni,I., 2013)

Fig. 84 Side blotched lizard. *(Ibid)*

S.C.A.L.E.S. "(smart – continuous – active – layered – environmental – system)" is the culmination of the observed efficient thermoregulation of the lizard; it combines the characteristics and behaviors that help it survive in the desert, and integrate it in the building envelope. It takes cues from survival skills of the lizard and makes the building, in essence; survive in the desert quite comfortably. [9]

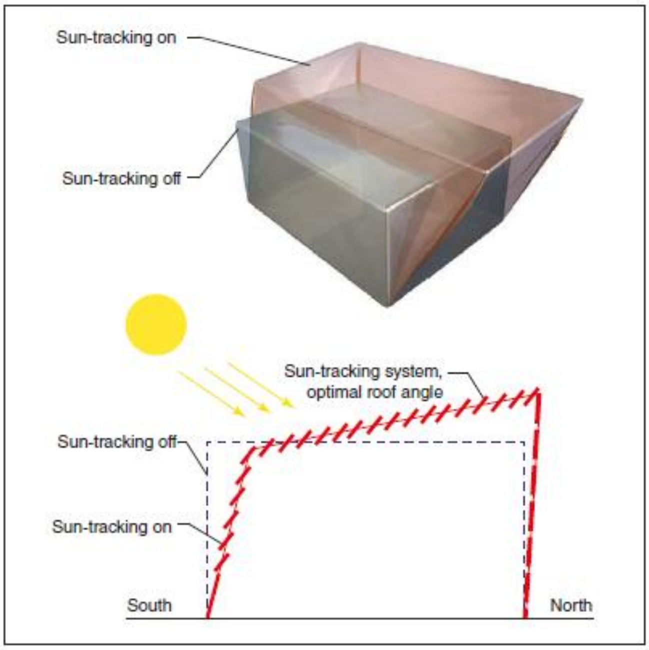


Fig. 85 The operable windows for the sun tracking system. *(Ibid)*

S.C.A.L.E.S. uses modular panels, distributed throughout the entire envelope, in different ways, depending on their functions. The south-facing wall is composed of three different types of panels: opaque insulative, photovoltaic, and operable window. The insulative panel uses phase change material to allow for a stable interior temperature throughout the day. The panel is hollow and filled with a bio-based phase change material. Heat gets stored during the day, while keeping the interior cool. The heat collected during the day is slowly released and heats the residence at night. The envelope's structural system is made up of a braced steel grid to which the panels attach. All façades follow a similar organizational strategy, while the panel composition may vary depending on their exposure. [9]

Fig. 86 The braced steel grid. *(Ibid)*

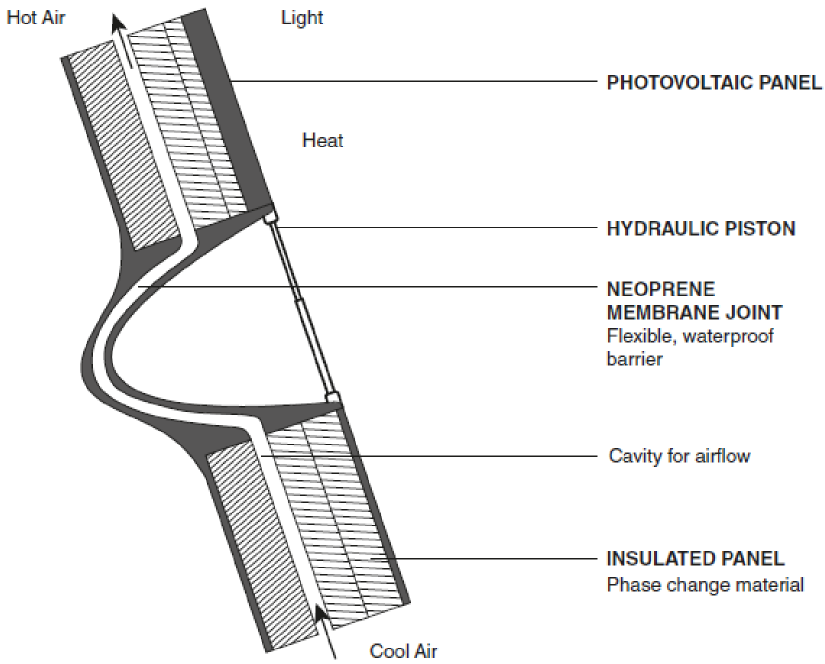


Fig. 87 The photovoltaic panel captures the sun's rays and converts them to the studio's electricity. The window panel allows for views and ventilation. These panels are strategically arranged to maximize their performance. Between the panels is a flexible,

foamed neoprene membrane that allows the panels a range of motion, controlled by sensors, while being continuous, insulative, and waterproof. *(Ibid)*

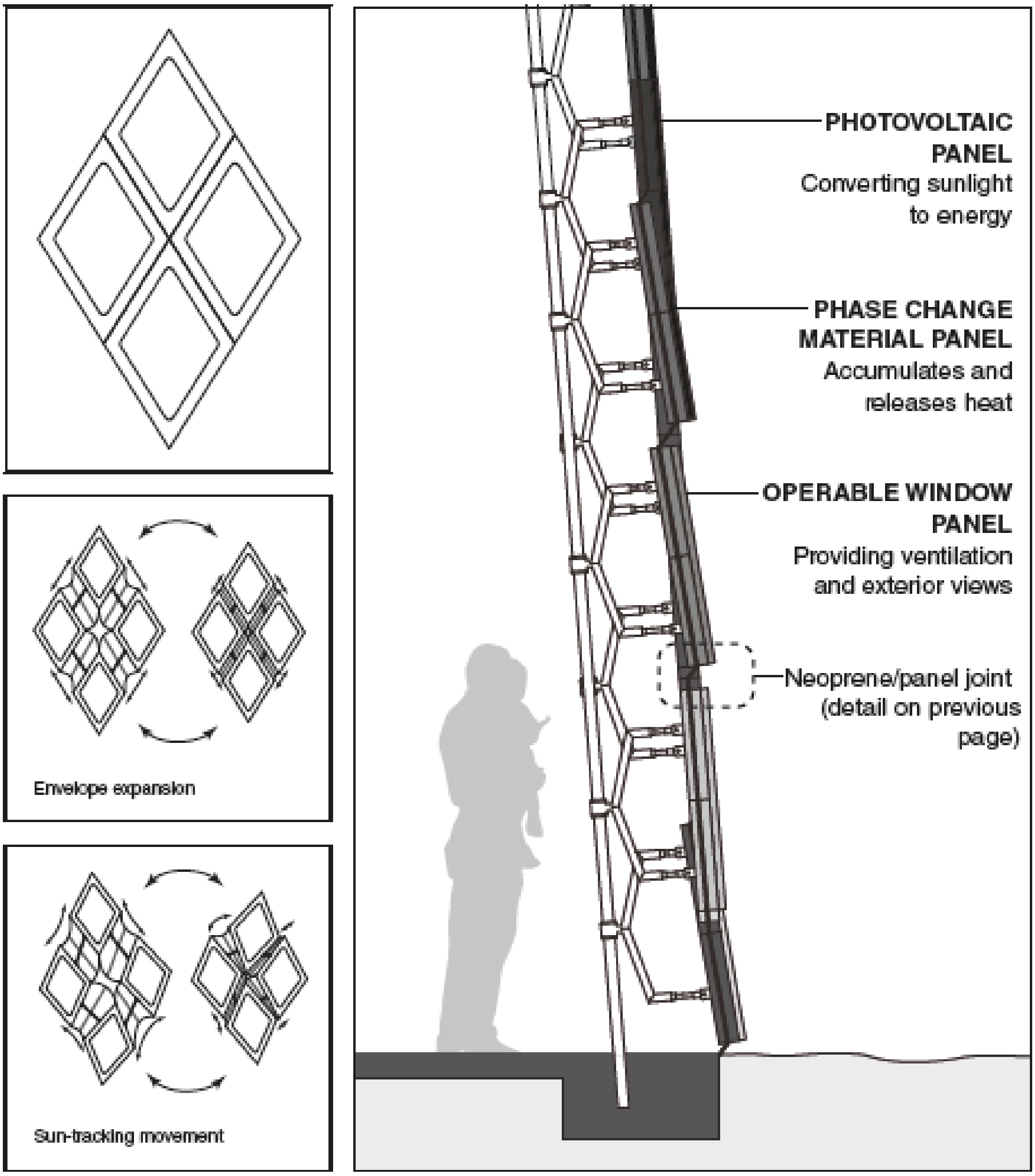
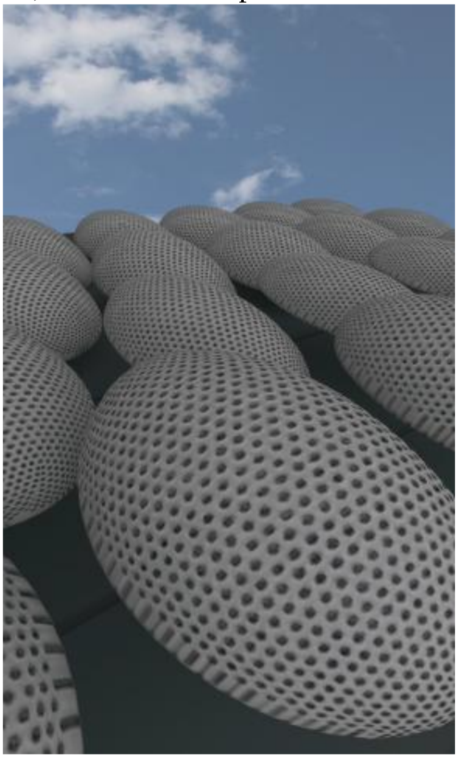


Fig. 88 The wall is composed of rhomboidal panels mounted on hardware that allows for a small range of movement. The scales are mounted on universal joints, gas springs, and rod ends. The universal joints allow for the panel to tilt horizontally and the gas springs move opposite to one another and allow for vertical tilt. *(Ibid)*

Fig. 89 The artist studio fixes itself directly on the desert floor, much like the lizard. The individual panels gleam in the sunlight while collecting heat and energy. The structure maintains a slight tilt in the roof and south façade in order to be optimally positioned to the sun angle. *(Ibid)*

3.7. Proto Project

The project, located in the Namib Desert, serves as a temporary residence for desert researchers. Taking cues from the beetles' ability to collect water from such an arid climate which we have also discussed previously in details in the biomimicry section, the building is positioned so that the largest sloped roof/façade is facing southeast toward the morning fog that sweeps up from the ocean, and burrows a portion of the building underground to regulate its thermal mass. The building envelope uses a series of mesh discs to capture moisture from the morning fog. Each disc is set on a pivot and tilts when enough water has accumulated.



The water rolls down the grooved roof membrane toward the water cistern at the base of the structure. The collected water not only provides a potable water source for the occupants but is a cooling mass to help regulate comfort within the space. Not only does the shape of the building mimic the "fog basking" water collection feature of the beetle, architecturally the form creates an interior volume (low to high ceilings) which optimizes air stratification and overall climate comfort. A portion of the roof discs are perforated to allow for the collection of water to sustain the interior plants. The plants allow for storage of water, food, aromatherapy, and help humidify the space through evapotranspiration. [9]

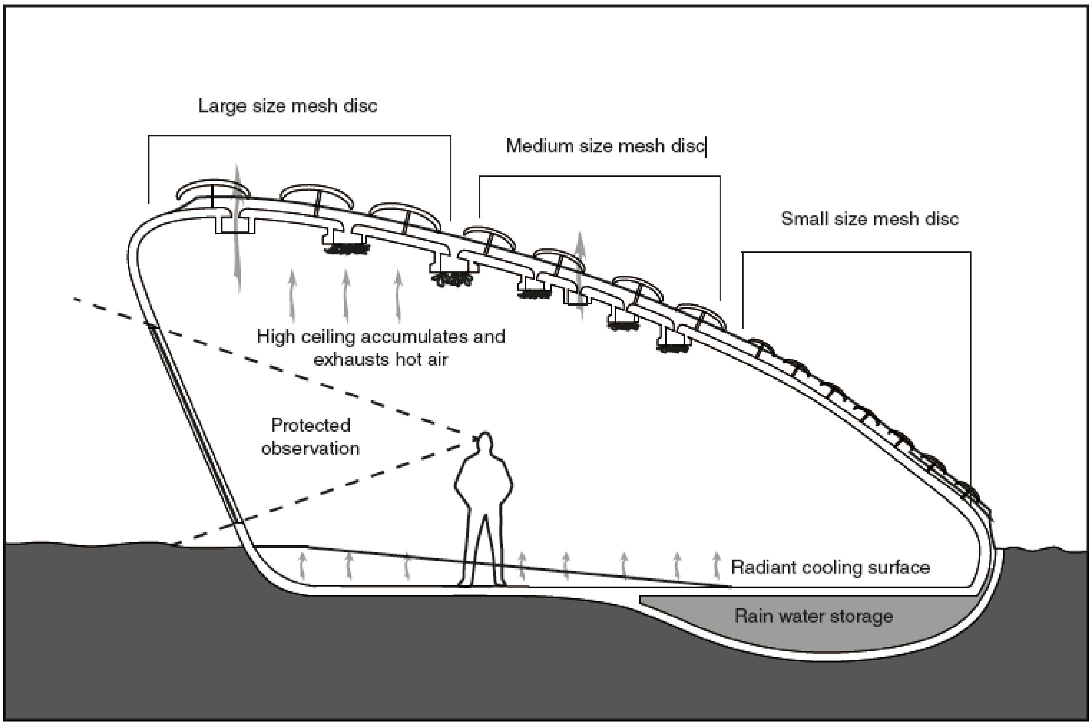


Fig. 90 The diagrams show the components of the mesh disc and how it collects water droplets. The schematic building section indicates the exterior positioning and decreasing sizes of the discs as well as delineating the interior space, slightly sunk into the sand to take advantage of its thermal mass. *(Ibid)*

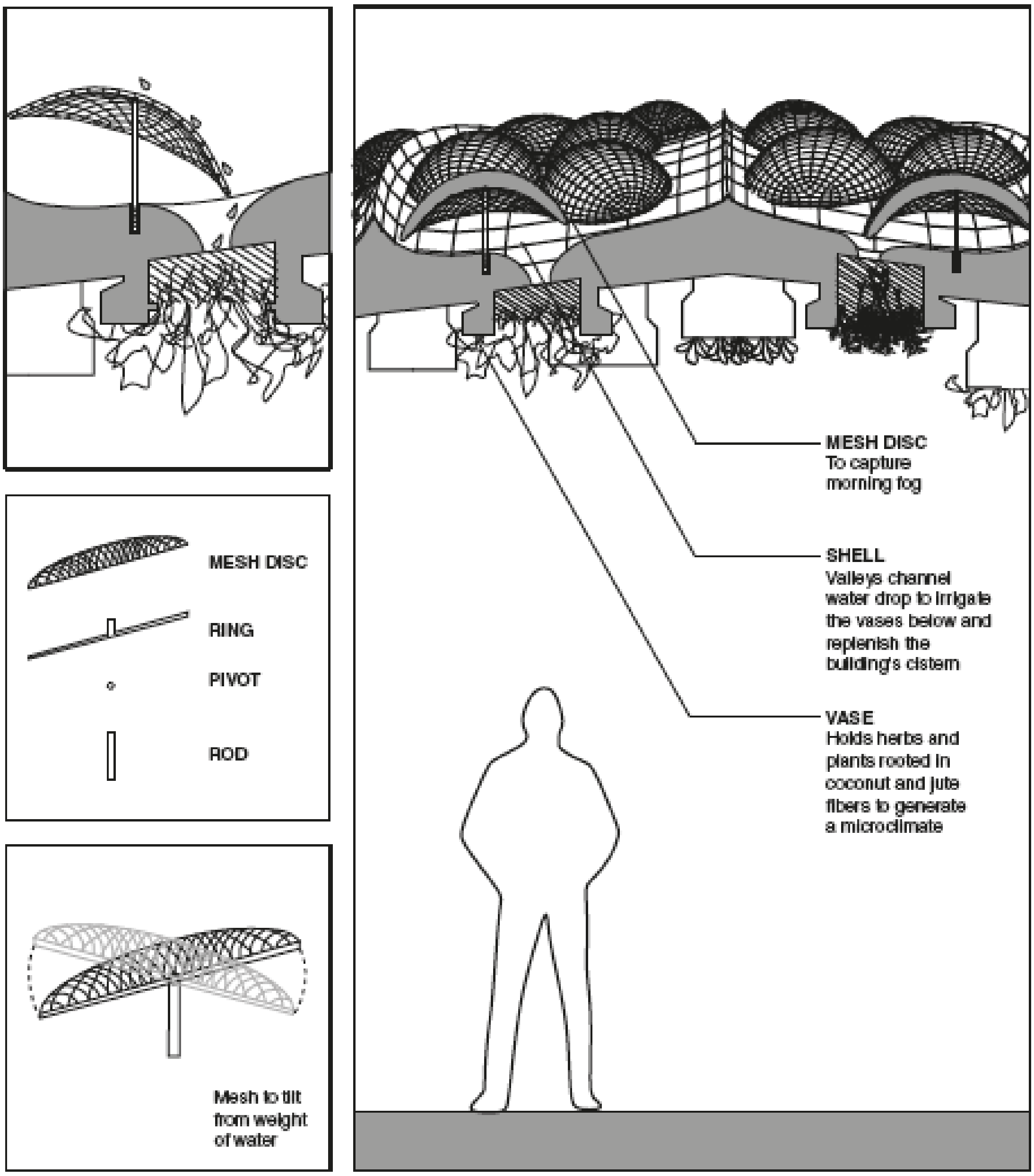


Fig. 91 The wall section and rendering demonstrate how water is captured through the discs made out of mesh. The water is then funneled into the channels by the geometry of the overall massing. The channels are connected to the upside down pots in the ceiling which grow a range of mixed herbal vegetation. The vegetation shown on the section creates a ceiling condition that is unexpected for a desert condition and provides a small quantity of edible greens. *(Ibid)*

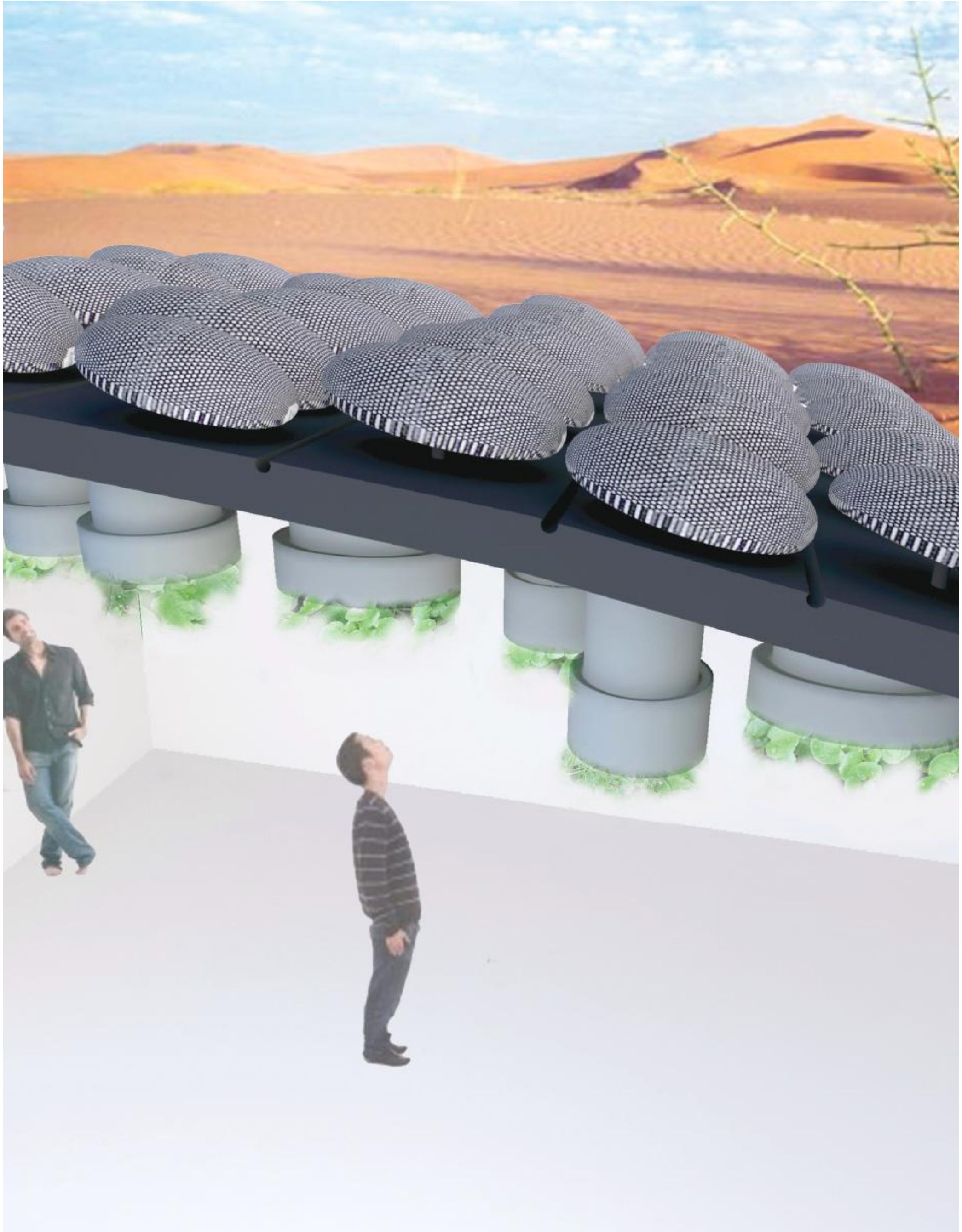


Fig. 92 In this hot, arid and typically deemed uninhabitable environment, the project provides an unexpected oasis for researchers. Furthermore, the dynamic system on the roof engages in water collection, transforming the interior with landscapes of edible vegetation, thus creating an environment that allows the researcher to thrive in such a severe climate. *(Ibid)*

3.8 Compass Termites and the Eastgate Centre

The termites' buildings use zero-waste construction methods, employ solar-powered air conditioning and even boast sustainable agriculture. The forms of the mounds vary according to location. Those of the African species *Macrotermes bellicosus* comprise multiple cathedral-like spires in the hot, dry savannah regions and lower, domed mounds in the cooler forest. According to contemporary biologist Judith Korb and the 1960s entomologist Martin Luscher, the forms of termite mounds can be explained as elaborate systems for thermal control in order to create optimum egg-laying conditions for the queen termite and ideal temperatures for fungus farming.

From an architectural perspective, perhaps the purest manifestation is the mound created by **compass termites** (Amitermes meridionalis) in Western Australia.

The compass termites' towers forms a flattened almond shape in plan, with the long axis aligned perfectly north-south. The long, flat sides present a large absorbing area, which catches the warmth of the morning sun after the cold night, while in the middle of the day the minimum surface area would be presented to the noontime sun. Ventilation tubes within the walls can be controlled by the termites, so that the interior mound is moderated by the steady temperature of the ground below the surface. Further tunnels extend all the way down to the water table, so that in extreme conditions termites can carry pieces of leaf down to pick up droplets of water and bring them back to spread on the internal walls to enhance evaporation cooling. Some commentators have claimed that temperature in the royal chamber is maintained within one degree of 31^{o} C even though the outside temperatures vary as much as 39^{o} C between night and day.

Termites were the primary source of inspiration for architect Mick Pearce when he designed the Eastgate Center in Harare, Zimbabwe, in conjunction with engineers at Arup (completed in 1996). This office building and shopping complex achieves remarkably steady conditions all year round without conventional air conditioning or heating, and uses only 10% of the energy of a standard approach. Pearce studied the mounds of the M. Michaelseni and M. Subhyalinus, which appear to use a combination of steady ground temperatures and wind induced natural ventilation as their means of thermo-regulation.

The building is of heavy masonry construction, with external shading devices that minimize solar gain. As in many locations to which termites are adapted, the night-time temperatures drop sharply in Harare and this cool night air is drawn into a plenum between the first and second floors with fans. The cool air is circulated into large floor voids, which contain a labyrinth of precast concrete elements that maximize heat transfer by having a large surface area. During the day, an induced flow system draws air from these cool voids out into the office space via grilles. Warmer air at soffit level, particularly from around the light fittings, is funneled into 48 masonry chimneys. On all but completely still days, the wind velocity at the top of the chimney is higher than the velocity at ground level and the effect, enhanced by the positive buoyancy of the warm air, is to draw air upwards. Low-speed fans provide back-up to ensure that there is always adequate ventilation. While outside temperatures typically range between 5^{o} C and 33^{o} C, the interior is maintained at 21^{o} C to 25^{o} C. [6]

Fig. 93 Compass termite mounds- zero waste construction with solar powered air conditioning. (Pawlyn, M., 2011)

Fig. 94 The Eastgate Center- a building inspired by termite mounds that maintain comfortable conditions close to the equator without mechanical cooling. *(Ibid)*

3.9 A Shape-Shifting, Heat-Sensitive BiMetal Lets Buildings Breathe

Doris Kim Sung, who was a biology student at Princeton before turning to architecture, said that "Skin is the first line of defense for the body, and our building skins should be more similar to human skin." Sung worked with the thermobimetal, which as we mentioned before, is a "laminated composite materials that consist of at least two components, usually bands or strips, made from metals with different thermal expansion coefficients, which are permanently bonded to one another, for example by plating". The two different sides expand at different rates, when it gets hot, causing the thermobimetal to curve.

Building with an exotic material is totally different than knowing and demonstrating its unique properties. Sung studied well the properties of the thermobimetals and came up with a project based on thermobimetal panels; each panel is perforated with a unique pattern, adjusted to the angle of the sun and its exact location on the structure. The thermobimetal panels operate as a shading device, but also as a ventilation system, since the surface curls when it's hot allowing more air to pass through.

Sung is also working on several more important tests such as:

- An entire facade made of thermobimetal designed for a home in China.
- Other simple thermobimetal building components like a window shade that consists of flower-like pieces of the metal embedded within windows which curl to provide natural sun shading.

Her studies of ventilation systems are based on the way crickets breathe, where she found that they pull in air from tiny holes all over their body rather than a single airway. She tried to mimick this ventilation system within her designs where thermobimetal curls or extends allowing airflow into thousands of tiny facade openings. "When you're tired of opening and closing the blinds, or there's a power outage," says Sung, "these thermobimetals will still be working—tirelessly, efficiently, and endlessly". [37]

Fig. 95 Sun shade canopy made from thermo bimetal. (CO.DESIGN, 2012, http://www.fastcodesign.com/1671279/a-shape-shifting-heat-sensitive-metal-lets-buildings-breathe)

Conclusion

After reviewing different examples of projects adopting Biomimetic Architecture and Smart Building Materials, researcher concluded that most of the projects dealt with the building envelope as a live and active envelope, most of them mimicked the skin of living organisms whether humans, animal or plants, which supported the Hypothesis of the researcher for the thesis that proposed the same idea, a living active skin that can respond to the surrounding environment and reacts to air, light and humidity and therefore minimizes the energy consumed on mechanical and electrical system to control the climate in buildings. In order to achieve this target the researcher will combine Biomimetic design with Smart Building Materials.

From second part in literature review, the researcher came to conclusion that the material that has the greatest potential to act as living skin is the Shape Memory Polymers, so it was the Smart Material chosen to work with, for this reason and other reasons explained in that section, and so the following chapter will review the experiments and studies conducted to reach the desired sample of SMP that could be incorporated within the building envelope and can perform the living skin performance.

CHAPTER THREE

RESEARCH APPLICATION and CASE STUDY

1. Researcher's experiments:

Out of all the Smart building materials that were discussed previously:
1. Phase Change Materials
2. Smart Gels
3. Thermo Bimetals
4. Shape Memory Alloys
5. Shape Memory Polymers

The Researcher chose the Shape Memory Polymers because of the following main reasons:
1. It reacts to low temperatures that range from 25 to 40 degrees Celsius.
2. Has various applications within architecture design
3. Less expensive
4. Transparent

The Researcher worked on the Shape Memory Polymer (SMP) sheets that worked as one way in order to act as an internal window within internal walls to enhance the internal air flow because the internal walls block the cross ventilation and hence block the air flow which affects the indoor thermal comfort.

Limitations:

The experiments were held in year 2015 with samples of Shape Memory Polymers (SMP) that were used internally within a model, it was not experimented externally or exposed to external climate conditions, it was not experimented on real scale internal window but on an internal window in a model with scale 1:20.
It is proposed to be placed in an internal window within an internal wall in North Coast area. The reason behind that is as follows:
1. Internal walls and partitions in housing units in North Coast block the natural ventilation and so create uncomfortable zones thermally and if this material is to be placed in internal walls it could allow natural ventilation within the rooms.
2. The Weather in North Coast is comparatively clean and is not loaded with dust and this material is not yet treated to deal with dust.

All Experiments and ANSYS Simulation were held in the Lab of Building Physics Department (Wind Tunnel Lab) at Housing and Building Research Center- Dokki-Egypt.

The researcher went through several experiments with different samples to understand the properties of this material and how it works, and so,bought 3 different samples from 2 countries: USA and Japan.
The American Company is called "Bendableplastic" and it has fixed samples with fixed dimensions and thicknesses but different temperatures of glass transition (Tg) where the sample starts to react, and it also has custom made samples upon order.
The Japanese Company is called SMP Technologies Inc. and it also has fixed samples with fixed dimensions with different temperatures of glass transition to choose from.
And so the researcher held the experiments over the three SMP samples.
The target of the experiments was to reach a SMP sheet that would bend when exposed to warm air heated up to 38- 40 degrees Celsius.

Tools used for experiments:

1. Blower that blows air at three different speeds and temperatures.

Fig. 96 Blower

2. Heat sensor that measures temperature and displays it.

Fig. 97 Heat sensor and reader

3. Wind sensor that measures wind velocity

Fig. 98 Air speed sensor and reader

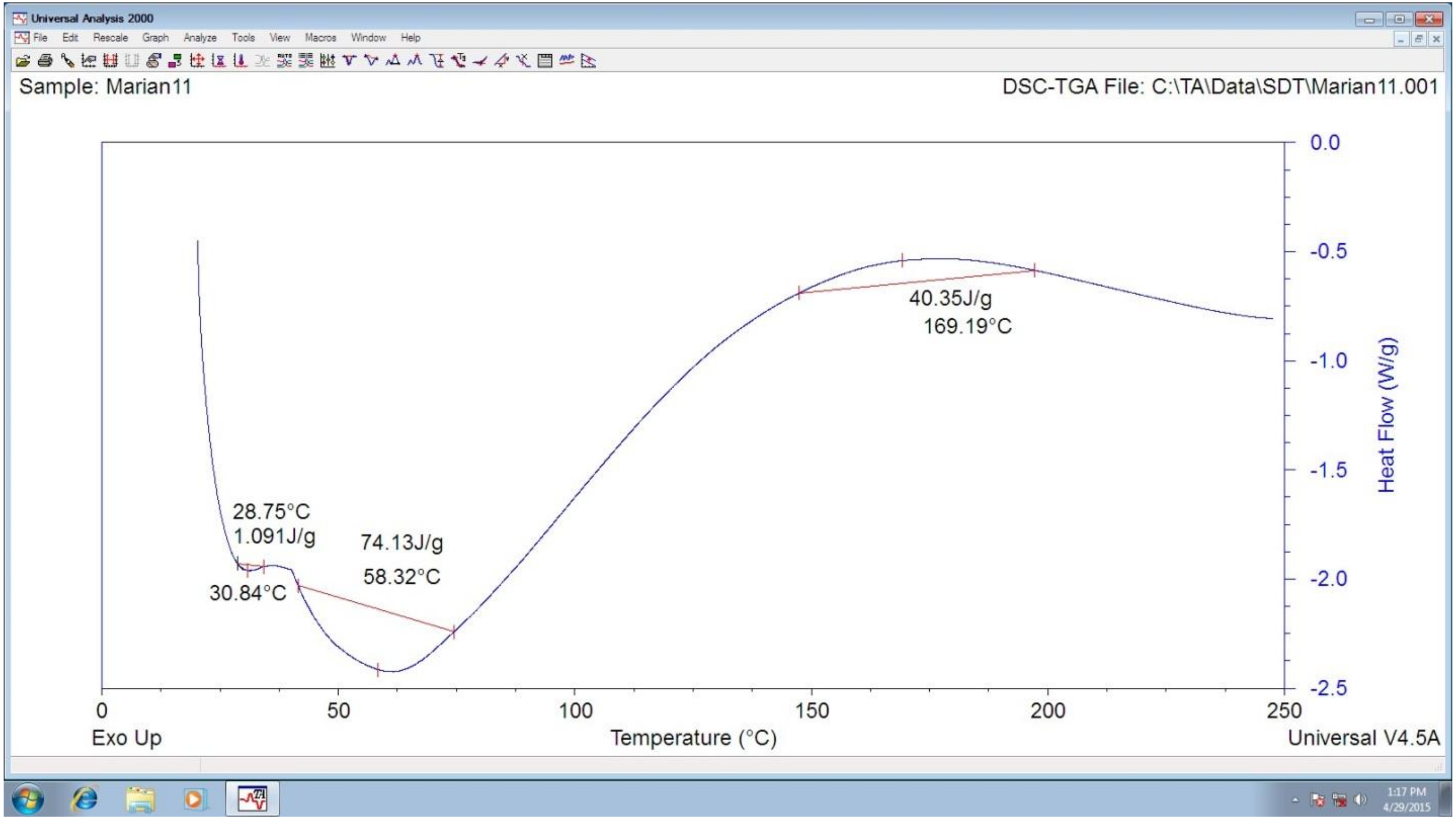
1.1 First sample:

- Thickness : 0.7mm thick Shape Memory Polymer
- Origin : Bendableplastic- United States of America
- Temperature of Glass transition: 37- 40 degrees Celsius
- The Sheet is programmed to be flat, and when warmed it becomes more elastic and it was bended by the researcher then exposed to air flow heated up to 40 degrees Celcius.
- Thermal Analysis of the SMP sheets was held by the "Differential Scanning Calorimetry" (DSC).

Start	Maximum	Stop
Tg °C	Tc °C	Tm°C
41.55	58.32	74.48

Tg: Glass Transition
Tc: Crystallization Temperature
Tm: Melting Temperature

Fig. 99 The thermal analysis graph for the 0.7mm thick SMP sheet showing the Tg and the Tc and the Tm.



Conclusion:

After bending the sheet in warm water, the sheet is then placed in cold water to maintain its new bended shape, then exposed to warm air that is heated up to 40 degrees Celsius, when the bended sheet is exposed to the hot air it retains its original flat shape.

But the problem with the 0.7mm thick SMP is that it was very light in weight and was affected by the wind pressure coming out of the blower and its shape was also deformed permanently beside that it did not reach the target of the experiment which is to bend when exposed to hot air.

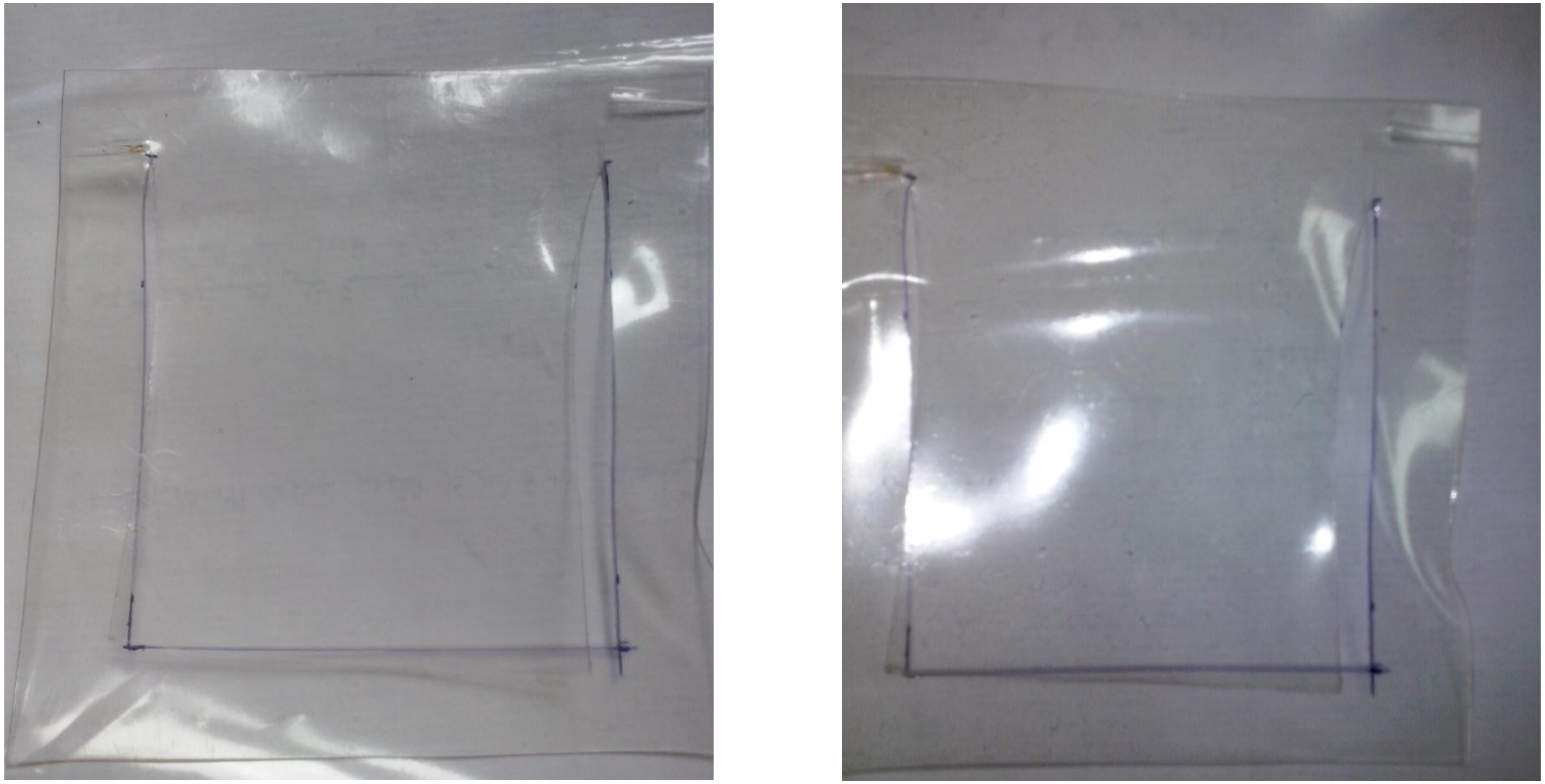


Fig. 100 Photos of the 0.7mm SMP sheets after exposure to air flow heated up to 40 degrees Celsius.

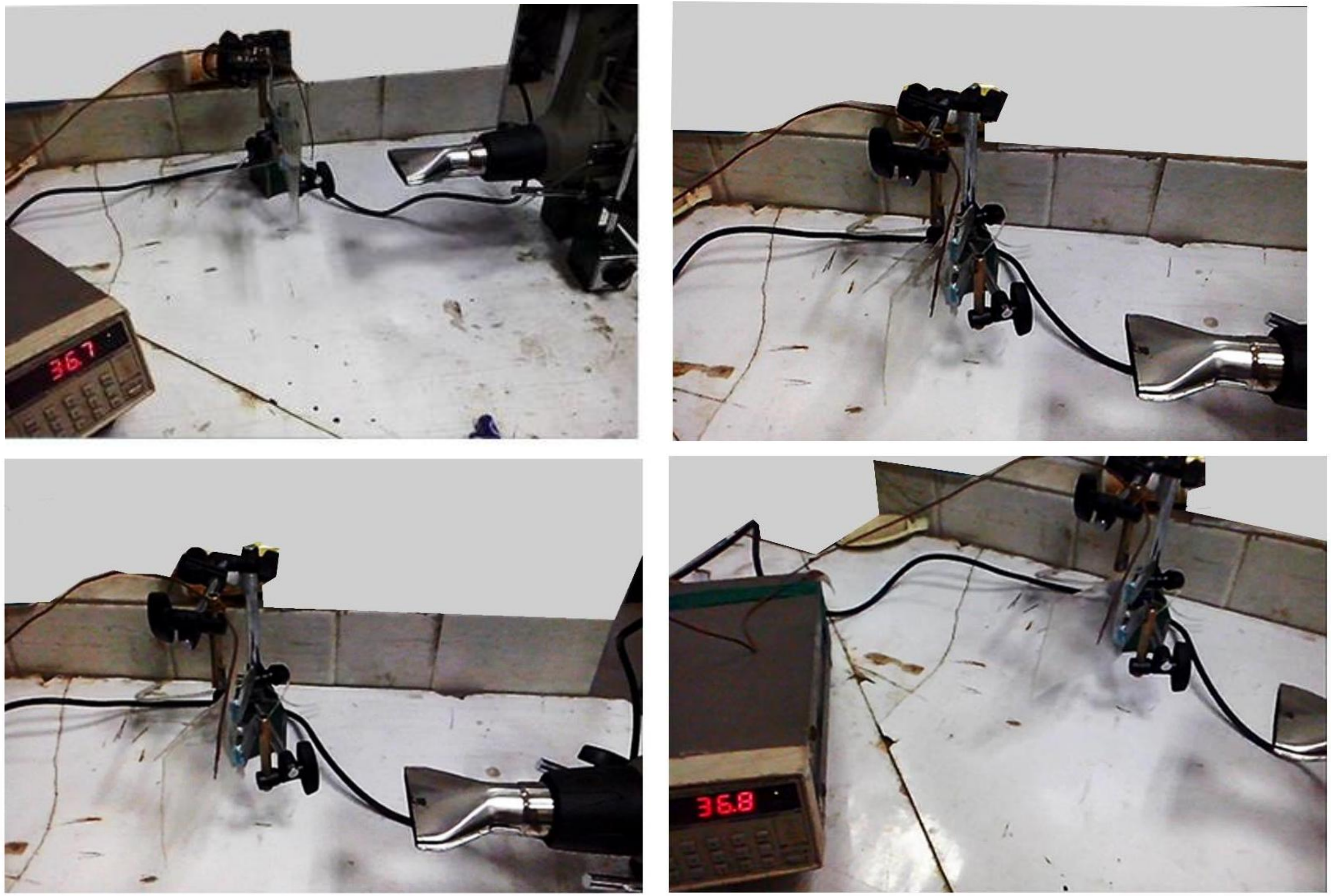


Fig. 101 Shows the steps of bending of 0.7 mm SMP sheet after exposure to hot air.

1.2 Second sample:

Thickness : 2mm thick Shape Memory Polymer
Origin : SMP Technologies Inc. Japan
Temperature of Glass transition: 35 degrees Celsius
The Sheet is programmed to be flat, and when warmed it becomes more elastic and it was bended by the researcher then exposed to air flow heated up to 35 degrees Celsius. Thermal Analysis of the SMP sheets was held by the Differential Scanning Calorimetry.

Start	Maximum	Stop
Tg °C	Tc °C	Tm°C
40.16	60.57	85.57

Tg: Glass Temperature
Tc: Crystallization Temperature
Tm: Melting Temperature

Conclusion:

After bending the sheet in warm water, the sheet is then placed in cold water to maintain its new bended shape, then exposed to warm air that is heated up to 35 degrees Celsius, when the bended sheet is exposed to the hot air coming out of the blower, it retains its original flat shape again.
The 2mm thick Shape Memory Polymer sheet showed a much better result than the 7mm regarding its stability facing the wind pressure, where the SMP sheets reacted to the temperature stimulus only and not to the wind pressure.
But still the SMP sheet moved into a flat shape and this is not the target of the experiment which is to bend when exposed to hot air.

Fig. 102 The thermal analysis graph for the 2mm thick SMP sheet showing the Tg and the Tc and the Tm.

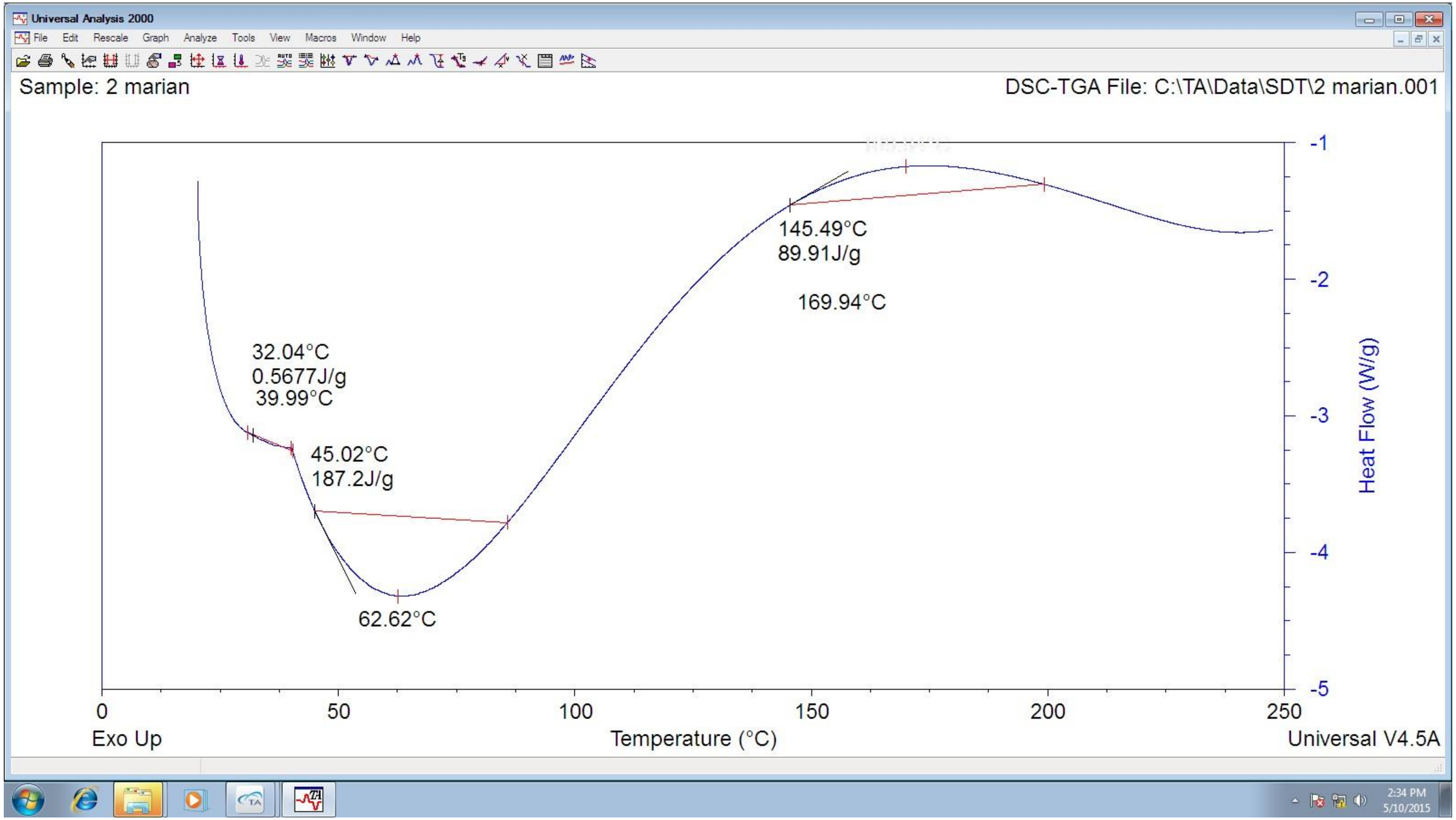
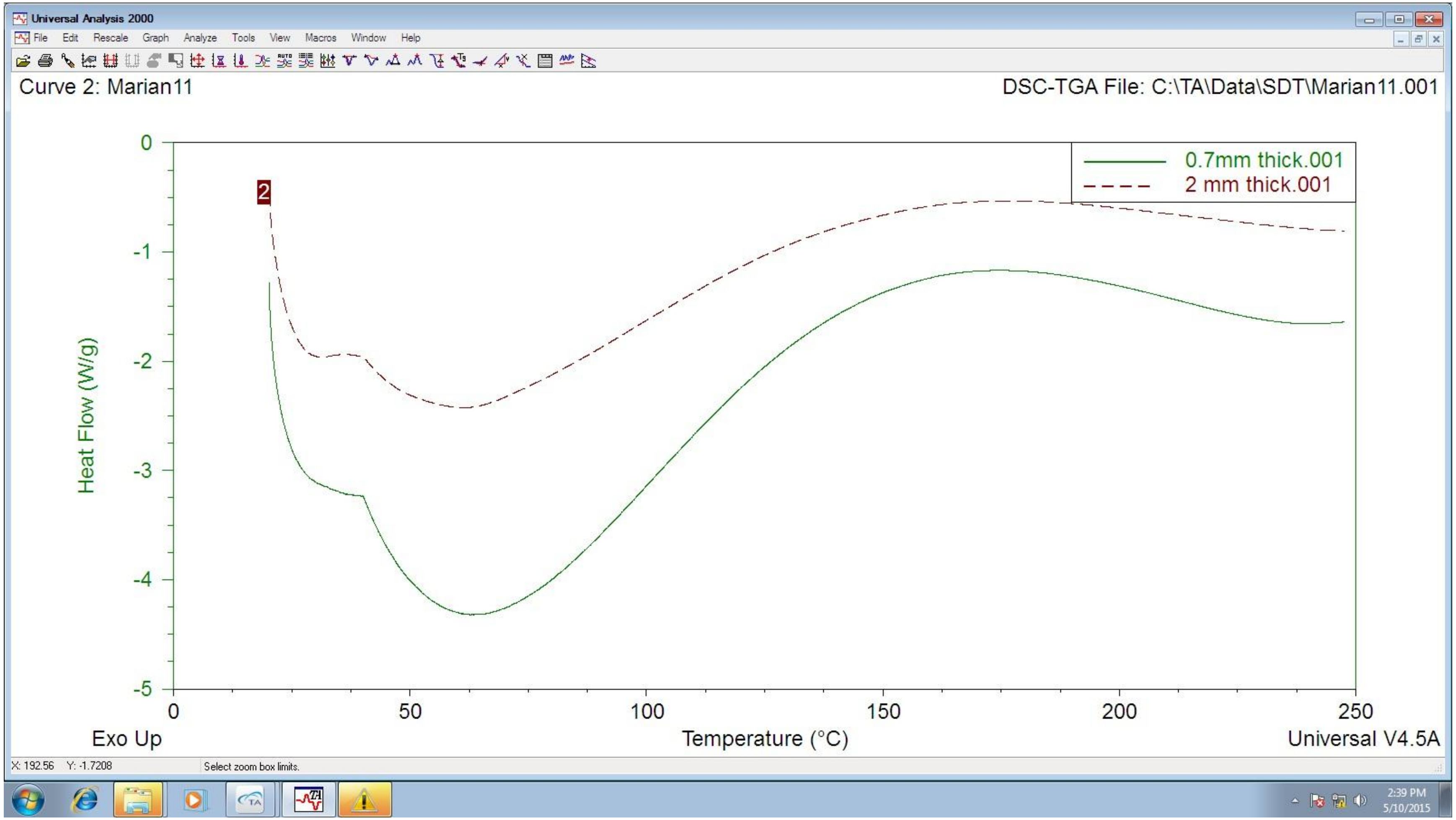


Fig. 103 Pictures taken for the 2mm thick SMP sheet after bending it by hand then exposing it to hot air heated up 35 degrees Celsius which made it retain its original flat shape again.

Fig. 104 The thermal analysis for the two sheets the 0.7mm and the 2mm thick SMP sheets together showing the Tg and the Tc and the Tm for both.



1.3 Third sample:

Thickness : 2mm thick Shape Memory Polymer
Origin : Bendableplastic- United States of America
Temperature of Glass transition: 35- 40 degrees Celsius
The Sheet is programmed to be bended, and when warmed it becomes more elastic and it was flattened by the researcher then exposed to air flow heated up to 35 degrees Celsius.
Thermal Analysis of the SMP sheets was held by the Differential Scanning Calorimetry.

Start	Maximum	Stop	Area
Tg °C	Tc °C	Tm°C	J/g
30.79	57.61	91.19	652.2

Tg: Glass Temperature
Tc: Crystallization Temperature
Tm: Melting Temperature

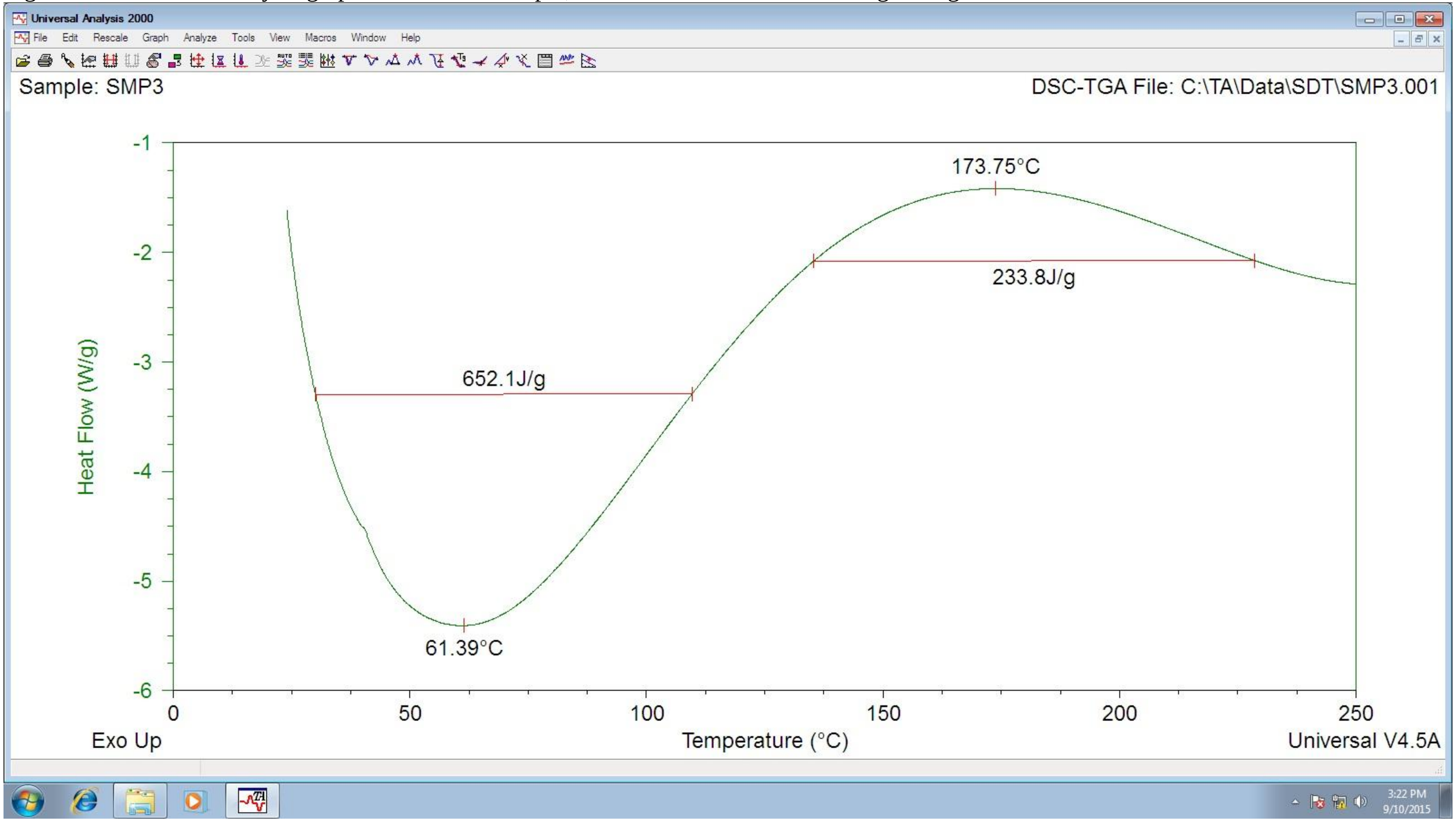
Conclusion:

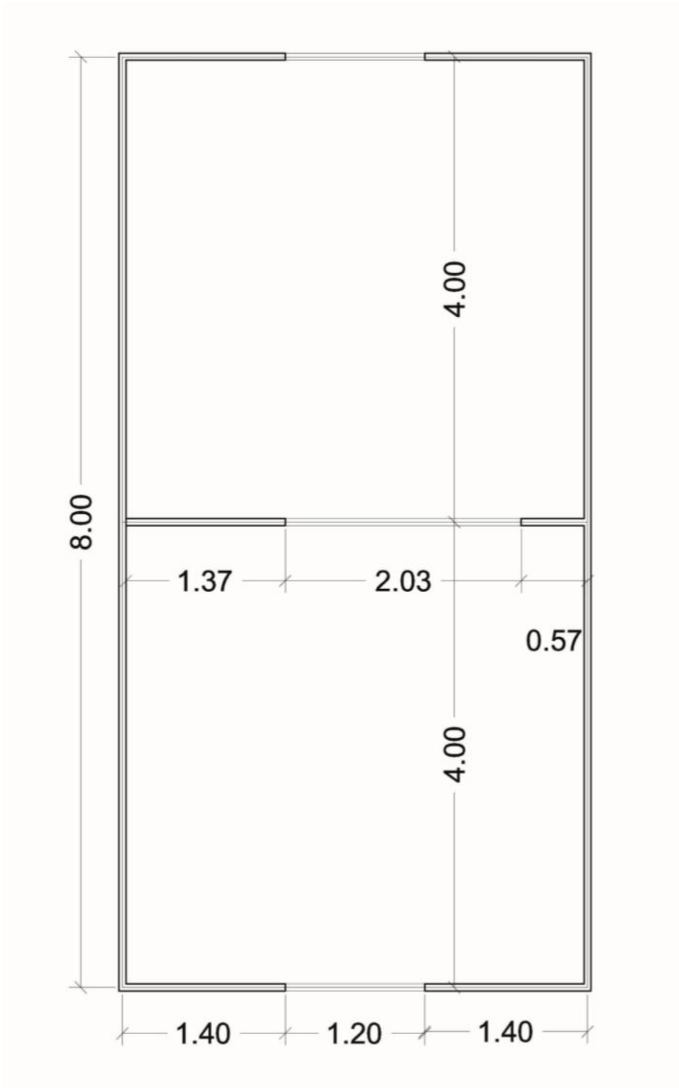
After flattening the sheet in warm water, the sheet is then placed in cold water to maintain its new flat shape, then exposed to warm air that is heated up to 35-40 degrees Celsius, when the flattened sheet is exposed to the hot air coming out of the blower, it retains its original bended shape again.

This 2mm thick Shape Memory Polymer sheet achieved the target of the experiments because the sheet was stable facing the wind pressure, and it was bended gradually when exposed to the hot air heated up to 40 degrees Celsius and so it allowed the air to flow.

And so therefore this sample sheet was placed into a simple model and the internal temperature and air flow was monitored.

Fig. 105 The thermal analysis graph for the third sample, 2mm thick SMP sheet showing the Tg and the Tc and the Tm





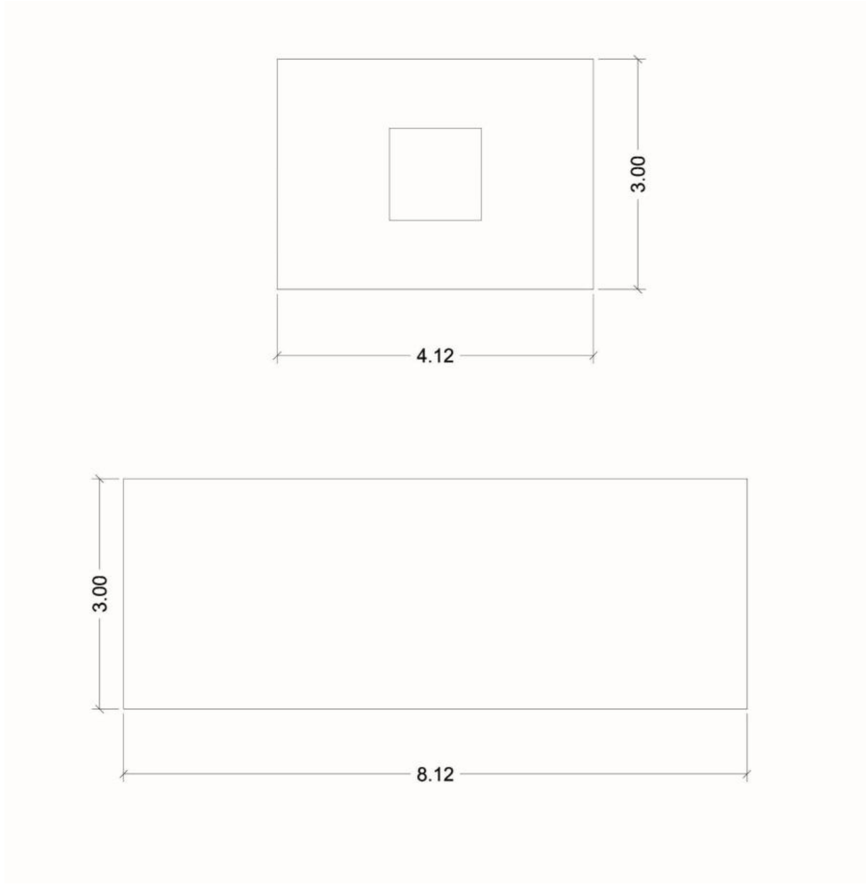
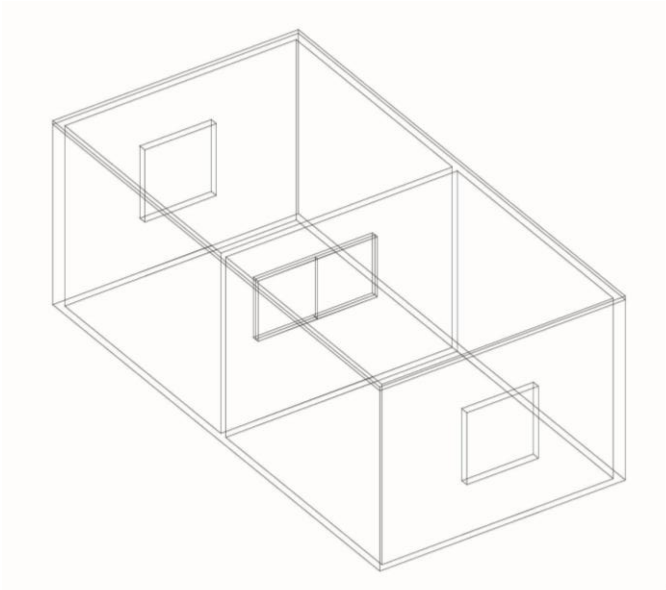


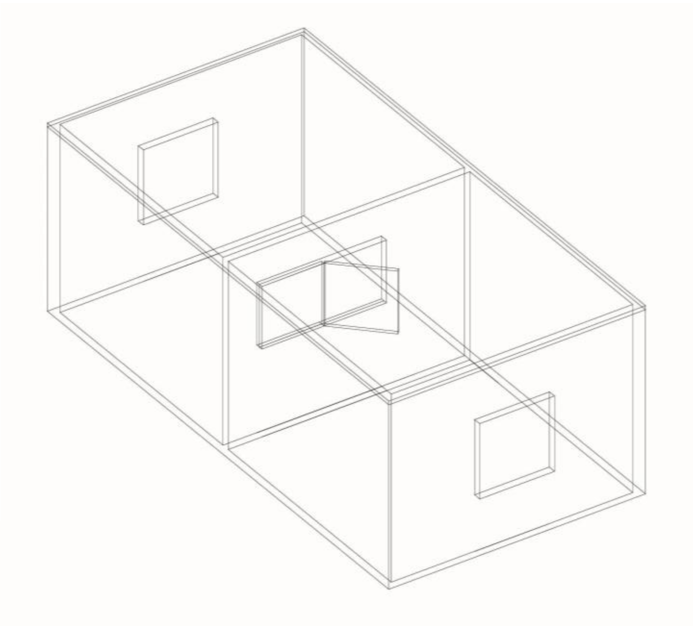
Fig. 106 Plan and elevations for the model where the sample was placed in.

Fig. 107 Three models with three positions of the SMP sample: 1. 180 degree   2. 45 degree   3. 90 degree

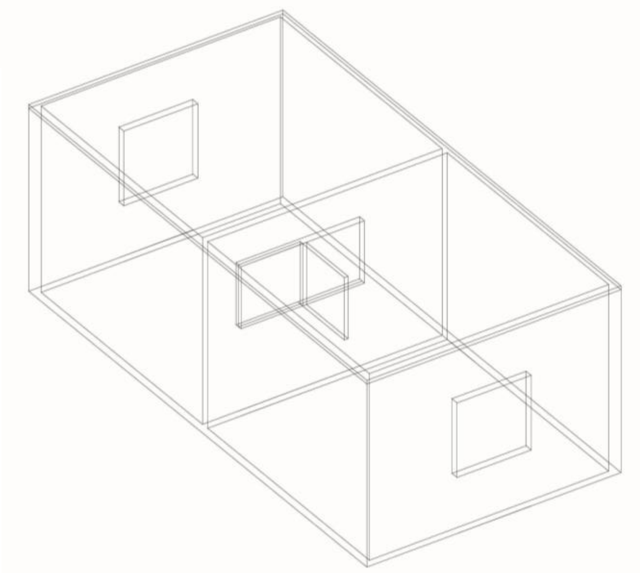
1.

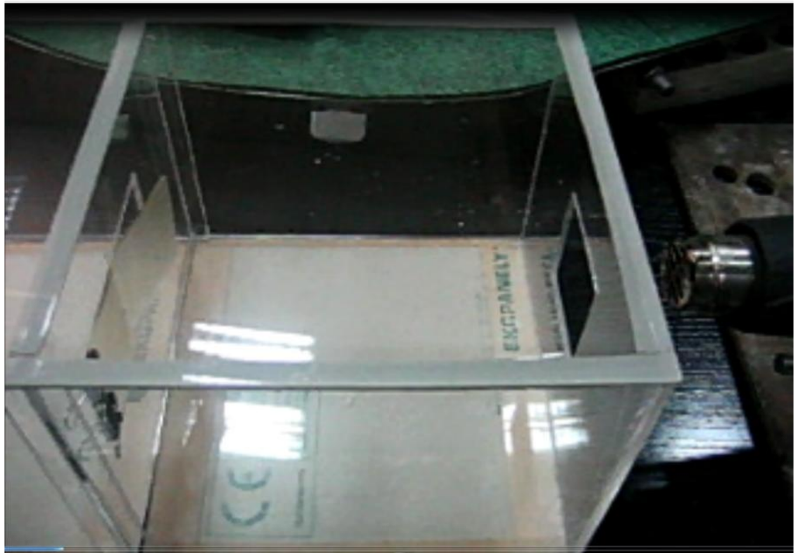
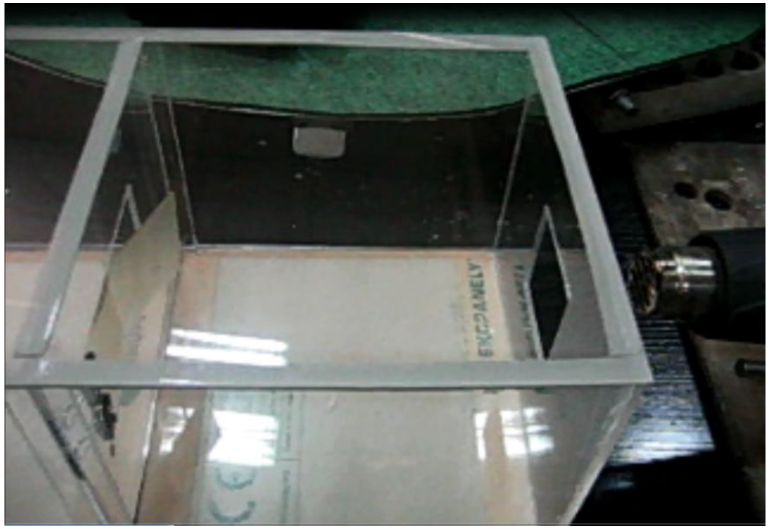


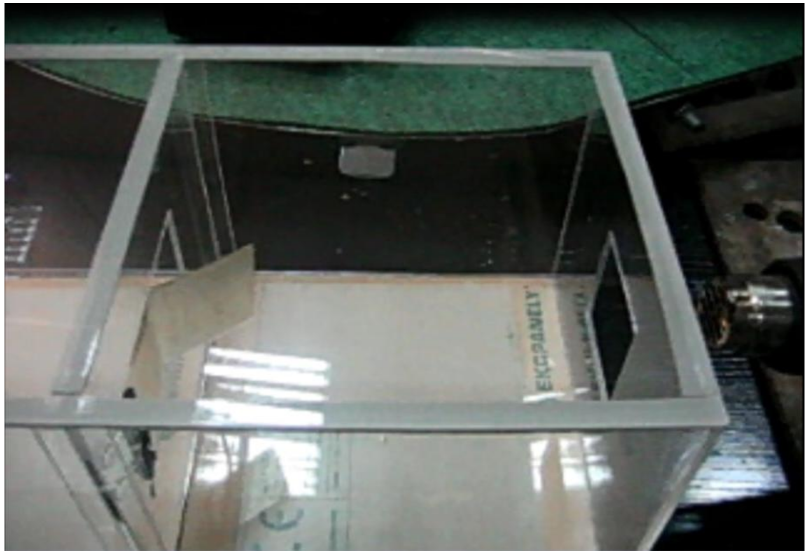
2.



3.



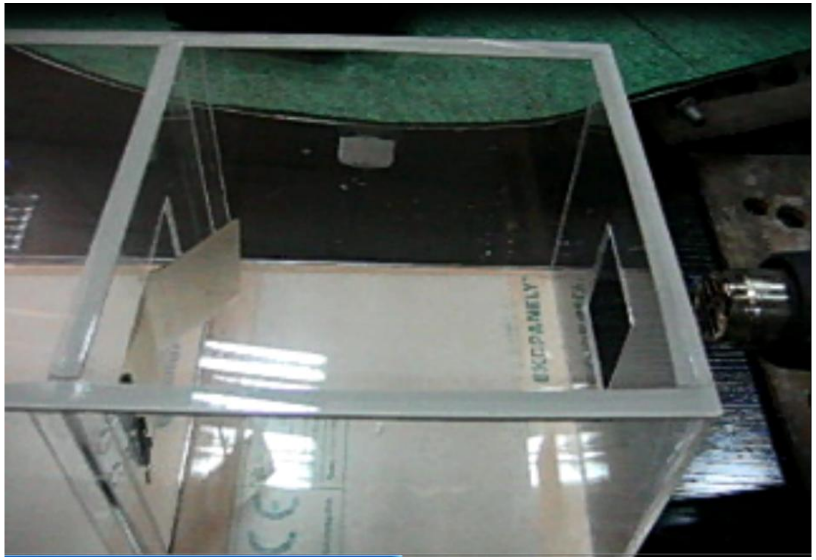


Fig. 108 Pictures taken for the last 2mm SMP sheet placed in the internal window within the model and exposed to hot air heated up to 37 degrees celsius, and the pictures show the movement of the sheet from 180 degree to 45 degree to 90 degree, allowing the air to flow in the model.

1.4 Results:

1. With the Shape Memory Polymer sheet in first position which was flat 180 degrees, i.e. the window was closed, there was no air flow.

2. ANSYS analysis showing the air flow and speed in the model with the second position: SMP sheet opens to 45 deg

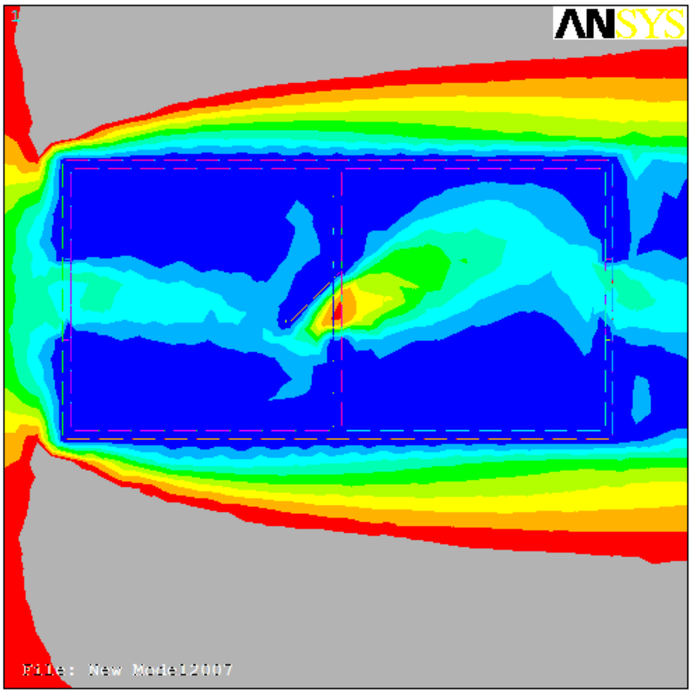


Fig 109 Shows air speed calculated by ANSYS

Air Velocity, (m/s)

0.12
0.24
0.36
0.46
0.60
0.72
0.84
0.96
1.09
> 1

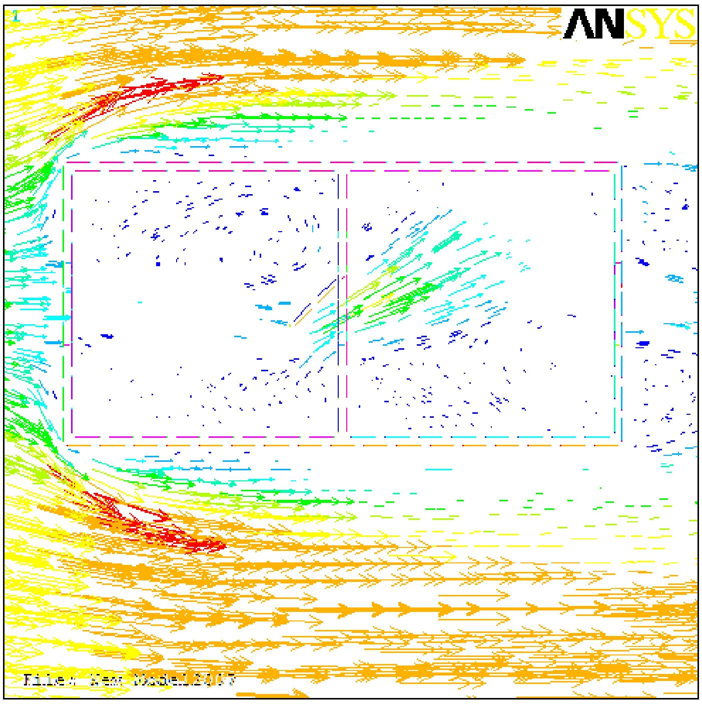


Fig 110 Shows air speed and flow direction and turbulences calculated by ANSYS

3. ANSYS analysis showing the air flow and speed in the model with the third position: SMP sheet opens to 90 deg.

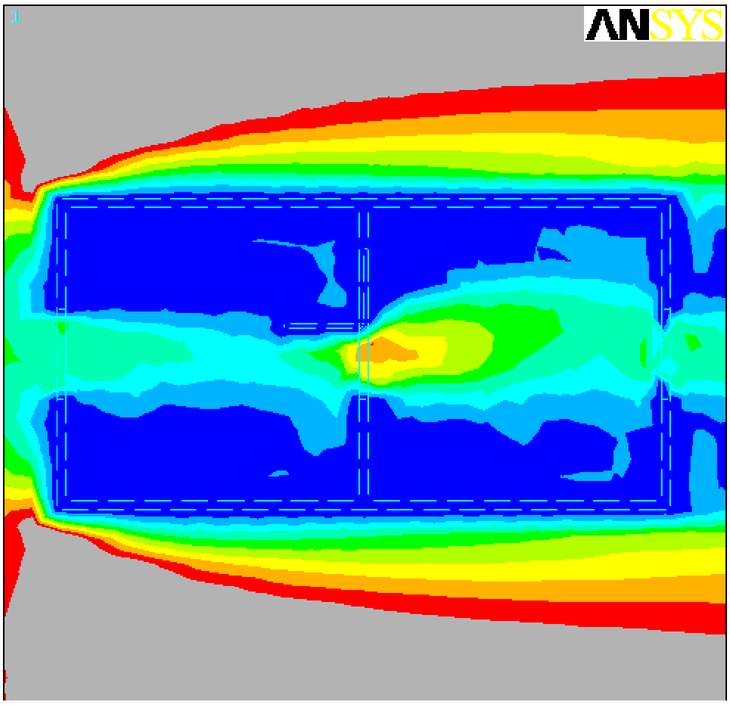


Fig 111 Shows air speed calculated by ANSYS

Air Velocity,(m/s)

0.12
0.24
0.36
0.46
0.60
0.72
0.84
0.96
1.09
> 1

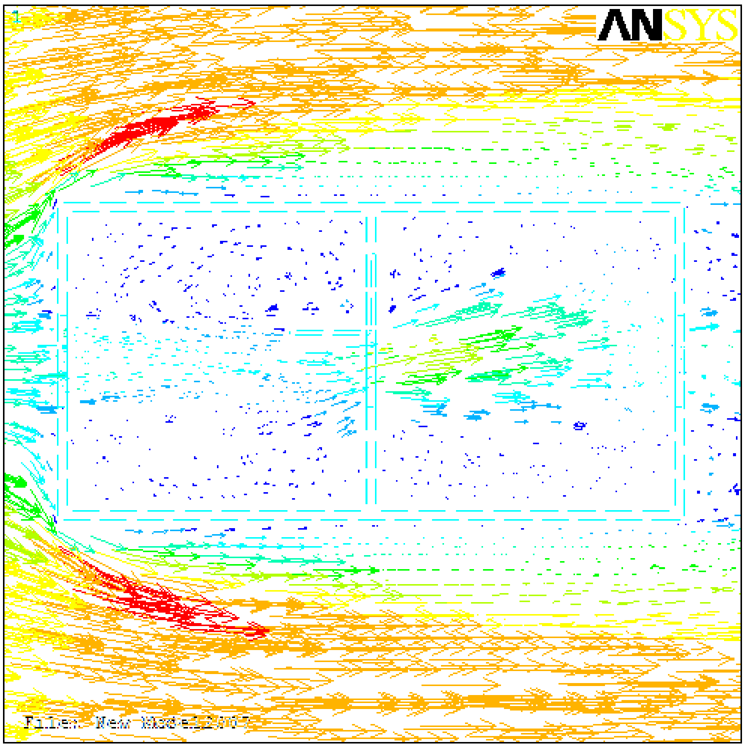


Fig 112 Shows air speed and flow direction and turbulences calculated by ANSYS

When the sample was heated and opened to 45 degree, air flow started moving through the internal space. Then it opened to 90 degree which was the maximum opening thus allowing greater air flow in internal space. By the opening of the shape memory sheet in the model, it allowed the flow of air in the internal space thus reducing the internal temperature which will lead to reducing cooling loads.

1.5 Thermal analysis conducted on an apartment 63 m^2

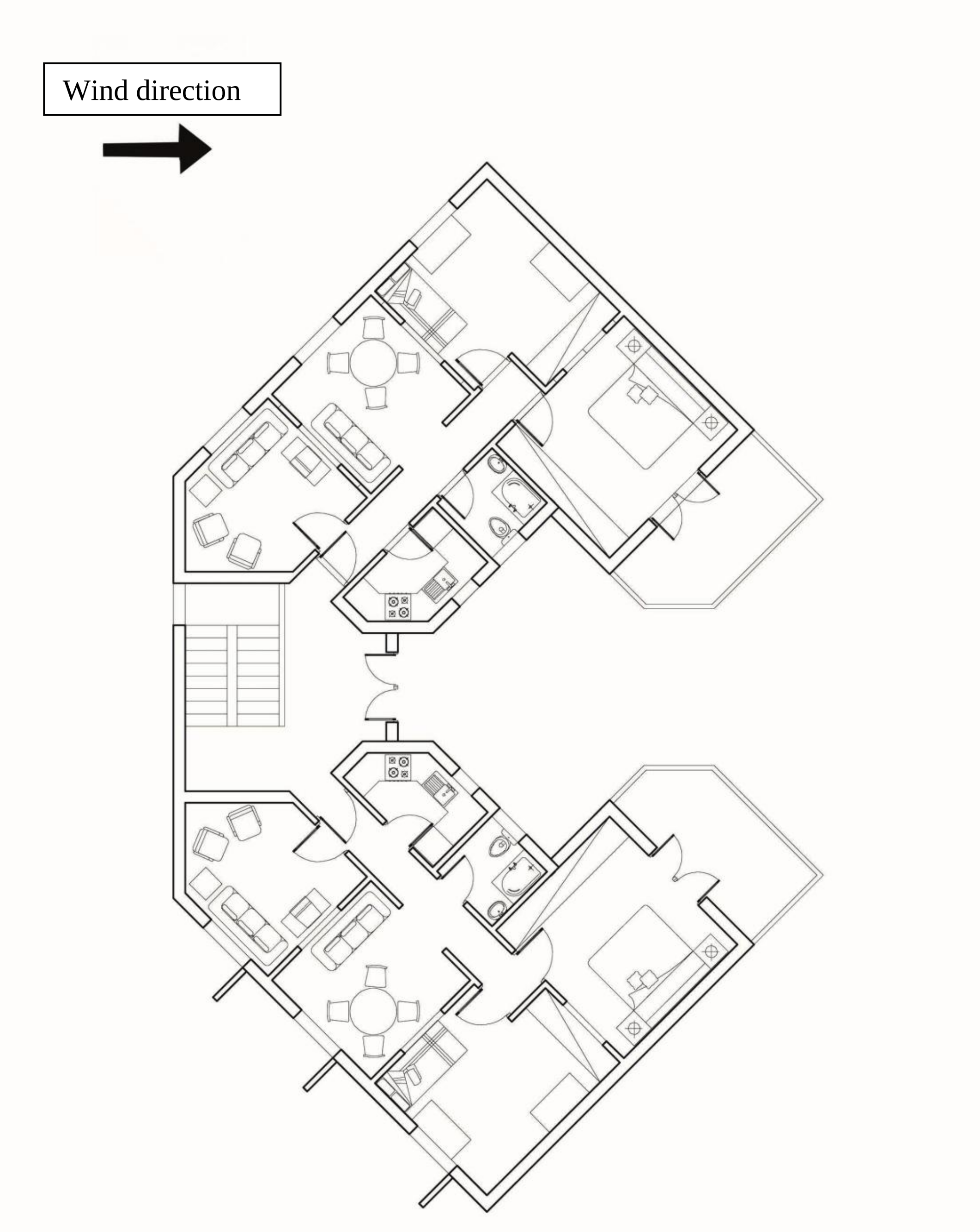


Fig. 113 Plan for a building with apartments 63 m^2 in area, this type of housing was designed for youth.

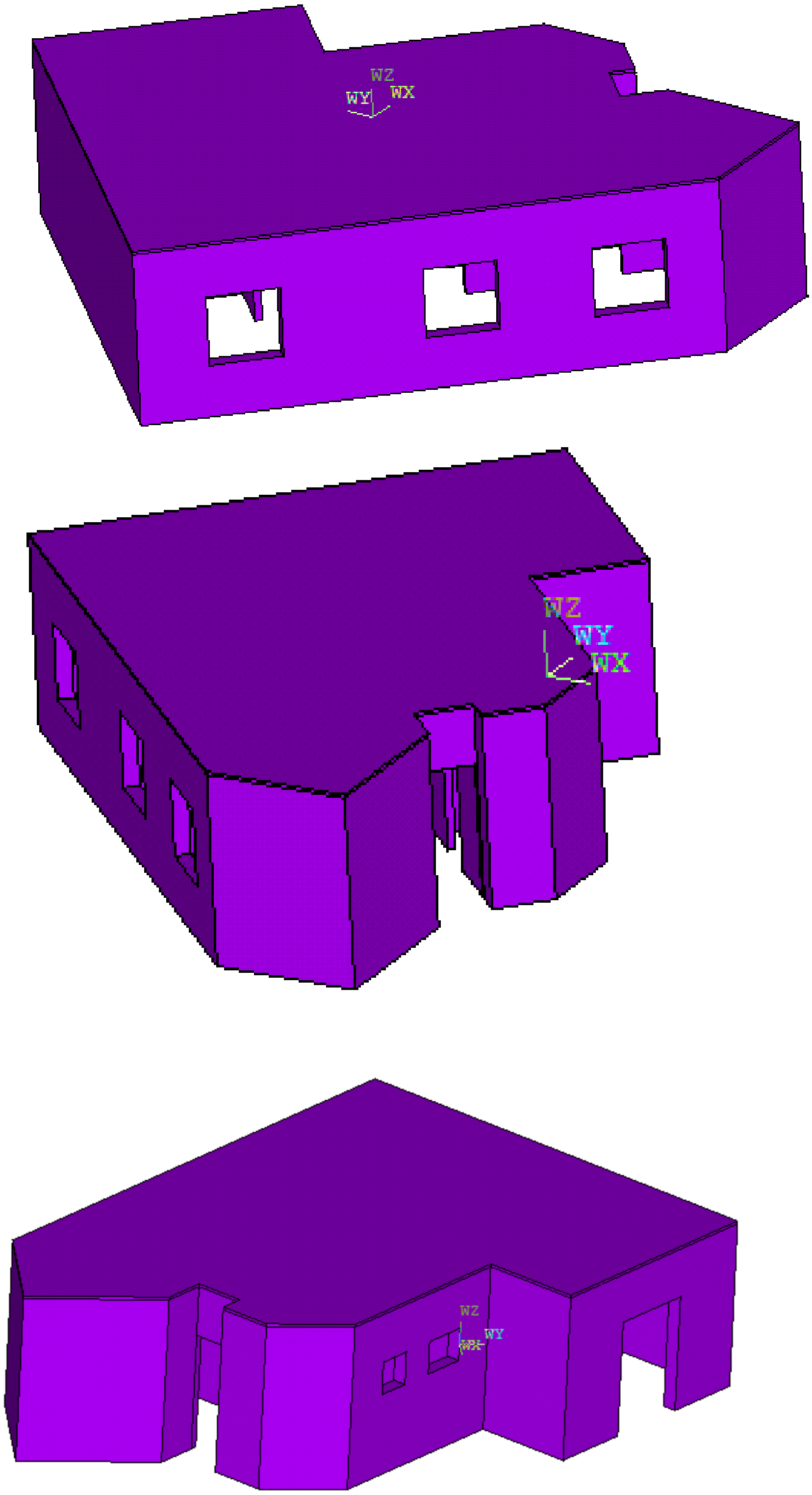
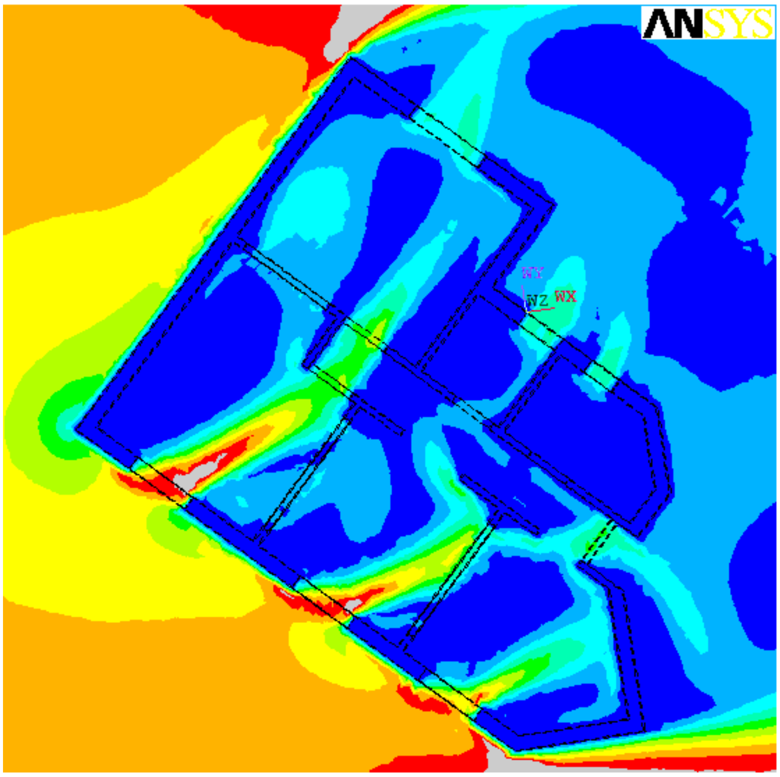


Fig. 114 Showing the 3D model for the apartment



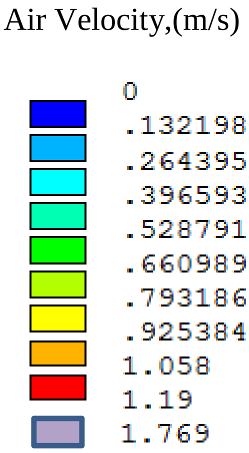


Fig. 115 Plan that shows air speed calculated by ANSYS

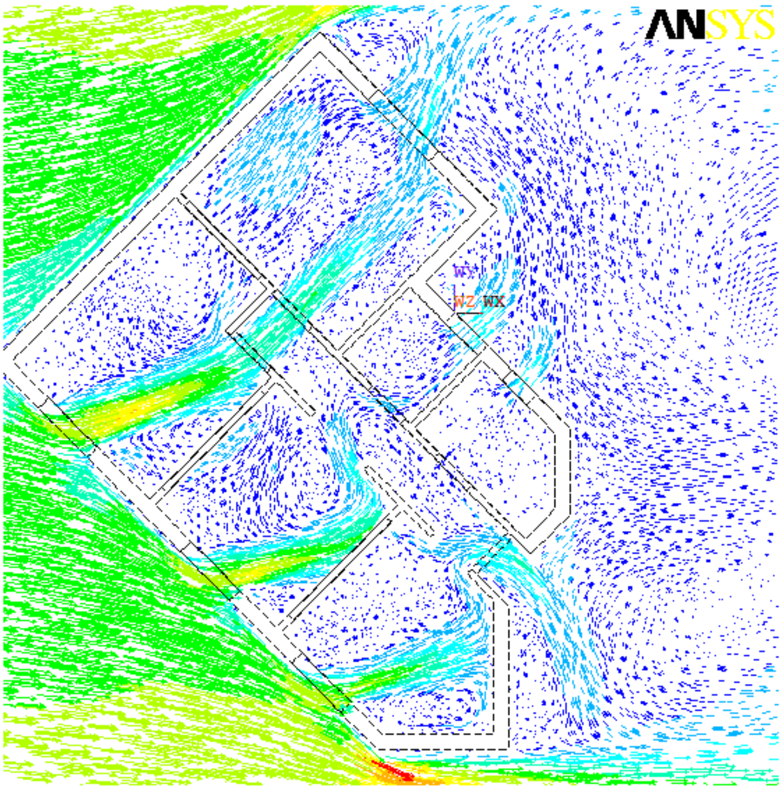
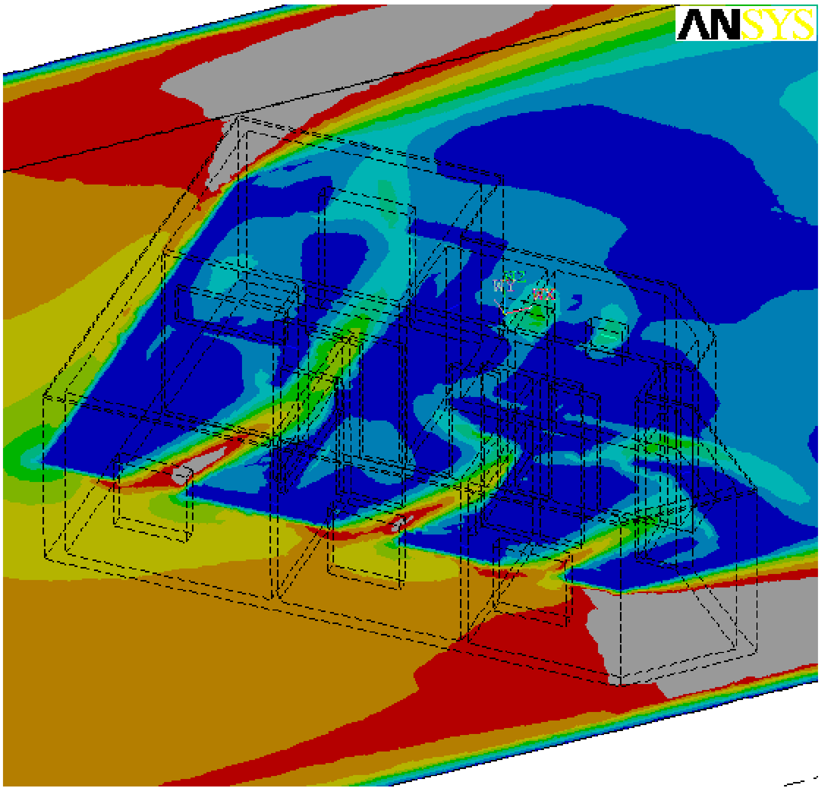


Fig.116 Plan that shows air speed and flow direction and turbulences calculated by ANSYS



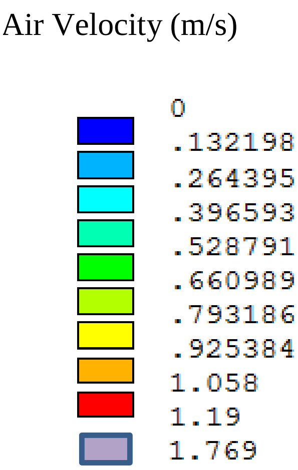


Fig. 117 3D model that shows air speed calculated by ANSYS

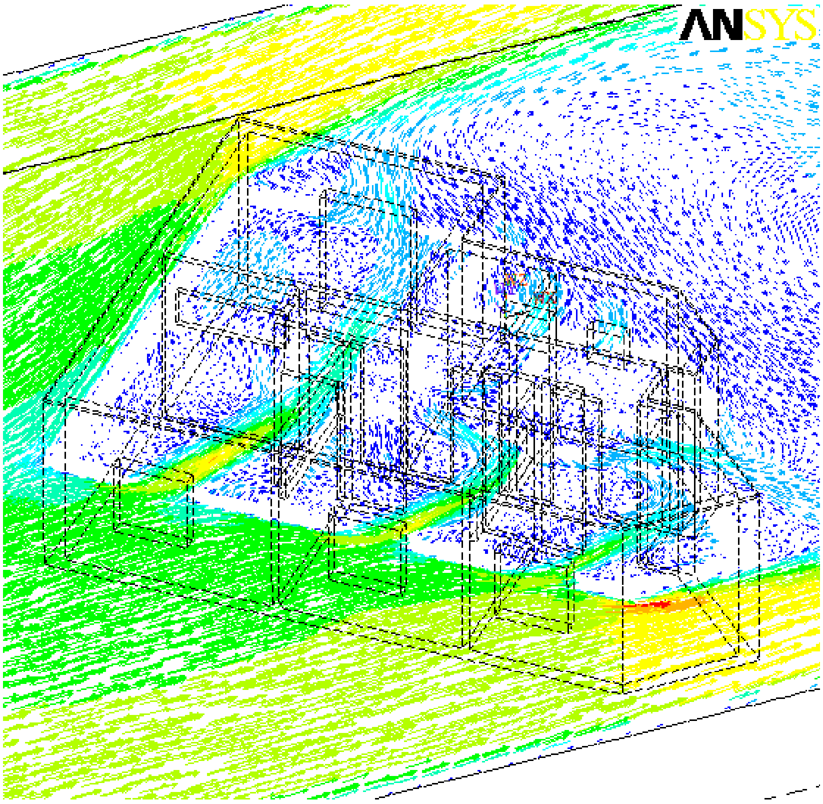


Fig. 118 3D model that shows air speed and flow direction and turbulences calculated by ANSYS

1.6 Calculating Air Change Rate and comparing it to Egyptian Ventilation Code

After running the ANSYS simulation on a $63m^2$ apartment that was designed for Youth Housing, and reviewing its results, the average air flow was calculated in order to calculate the Air change rate per hour and compare it to the Egyptian Code for Ventilation.
So first we have to explain the calculation method for the Air change rate.

Air Change Rate - Imperial Units

Air change rate - air changes per hour - can be expressed in imperial Units as:

"n = 60 q / V"

Where

"n = air changes per hour (1/h)"

"q = fresh air flow through the room (Cubic Feet per Minute, cfm)"

"V = volume of the room (Cubic Feet)" [38]

Air Change Rate - SI Units

Air change rate can be expressed in Standard Unit (SI) as:

"n = 3600 q / V"

Where

"n = air changes per hour"

"q = fresh air flow through the room (m^3/s)"

"V = volume of the room (m^3)" [38]

This table shows 68 nodes on inlet windows in the leeward direction where average air flow rate was calculated and since incoming airflow is equal to out coming air flow that was already measured during the first experiment where the SMP sheet was placed in a model and it measured 1m/s, then this figure (1 m/s) was entered in the simulation to calculate the average airflow figure and the result was 0.62 m/s.

Table 8 shows the nodes on the window where the air velocity was measured and their average was taken.

	VX	VY VZ	VSUM
1	0.37153	-0.181852	0.40149
2	0.39739	-0.205176	0.43659
3	0.42694	-0.239151	0.47808
4	0.24004	-0.092147	0.25457
5	0.61194	-0.31509	0.65134
6	0.86462	-0.33593	0.89722
7	0.97171	-0.31589	0.99725
8	0.92091	-0.147292	0.92758
9	0.668	-0.080389	0.67095
10	0.64344	-0.080564	0.6461
11	0.64477	-0.150407	0.65352
12	0.62037	-0.23863	0.64299
13	0.58618	-0.19179 0.58707E-01	0.61955
14	0.76529	-0.22599 0.74597E-01	0.80144
15	0.83627	-0.22270 0.23932E-01	0.86575
16	0.84198	-0.122042	0.84668
17	0.71156	-0.297003	0.75843
18	0.64772	-0.293403	0.69957
19	0.61285	-0.29604	0.66472
20	0.90657	-0.286468	0.93968
21	0.95496	-0.172406	0.96708
22	0.86122	-0.206968	0.87677
23	0.84704	-0.311937	0.88346
24	0.84566	-0.379801	0.90854
25	0.83957	-0.321134	0.88723
26	0.81848	-0.331879	0.86955
27	0.904	-0.299401	0.94115
28	0.88049	-0.314708	0.92074
29	0.3984	-0.15429 0.68647E-01	0.43272
30	0.53357	0.67508E-01-0.13540	0.55461
31	0.53684	0.15382 0.22342E-01	0.55889
32	0.34301	-0.213755	0.37729
33	- 0.69986E-	01 0.14330E-01-0.12827	0.14682
34	- 0.82409E-	01-0.10236 -0.10063	0.16552

35	-0.17172	-0.090447	0.18355
36	-0.155	0.58848E-02-0.12258E-01	0.1556
37	0.87141	0.21237 -0.26039E-01	0.89729
38	0.71495	0.10508 -0.11299	0.73141
39	0.41713	0.90818E-01-0.15797	0.4552
40	0.32447E-	01 0.12643 -0.17976	0.22216
41	1.067	0.28411 0.21791E-01	1.1044
42	0.9548	0.21859 -0.37378E-01	0.98021
43	0.96969	0.23223 -0.10648	1.0028
44	0.91331	0.19050 -0.13624	0.94286
45	0.76956	0.10815 -0.77950E-01	0.78103
46	0.66152	0.21555E-01 0.49387E-01	0.66372
47	0.35606	-0.89170E-02 0.63042E-01	0.36171
48	0.13084	0.42677E-02 0.33288E-01	0.13507
49	0.19188	-0.113273	0.2178
50	- 0.17288E-	01-0.49424E-01- 0.40378E-01	6.61E-02
51	0.37085E-	01-0.46385E-01- 0.20570E-01	6.28E-02
52	0.83523	0.45219E-01-0.31260E-01	0.83704
53	0.58325	-0.093275	0.58796
54	0.74382	0.54141E-01-0.50097E-01	0.74747
55	0.74809	0.20160E-01-0.51323E-01	0.75012
56	0.47483	-0.065778	0.47839
57	0.32878	-0.12838	0.34139
58	0.24463	-0.072026	0.2505
59	0.60797	-0.085513	0.61106
60	0.60804	-0.061577	0.6096
61	0.99319	0.31375 -0.20410	1.0614
62	- 0.20808E-	02 0.29168E-01 0.28733E- 01	4.10E-02
63	0.90641	0.52059 0.13077	1.0534
64	0.37090E-	01 0.26426E-01-0.77911E- 01	9.02E-02
65	0.57817	-0.38989E-01 0.94606E-01	0.58715
66	0.65577	-0.19758	0.67547
67	0.75328	0.20927 -0.52694E-01	0.78358
68	0.46066	-0.12125 0.12726E-01	0.47652
SUM	39.26687	-7.137312	42.28994
AVG	0.569085	-0.103439	0.621911

If we applied the average air flow in the previous equation, the outcome will be as follows:

TOTAL WINDOW area (A_w)	= No. of windows xWxH (m^2)	= 3.24
APARTMENT Area (A_{room})	= Total apartment area (m^2)	= 63
ROOM HEIGHT (h)	= 3 m	
ROOM VOLUME (Vroom)	= Room area x Room Height (m3)	= 189
INLET AIR VELOCITY (Vair)	= 0.6 m/s	
VOLUMETRIC FLOW RATE (q)	= (inlet Air vel. x Window area) m^3/s	= 1.944
AIR CHANGE PER HOUR (ACH)	= n=ACH= 3600 x q / V_{room}	= 37 [38]

According to the Egyptian Code for Ventilation which states the following:

Location of opened window	Time of window opening		Minimum rate for recommended ventilation	
	Day	Night	Air change rate (ACH)(hour $^{-1}$)	Acceptable ventilation (watt/m^2 hr)
One side only	Closed	Closed	1	0.3
	Opened	Closed	3	1.0
	Opened	Opened	10	3.3
More than one side	Closed	Closed	2	0.6
	Opened	Closed	10	3.3
	Opened	Opened	30	10.0

Table 9 Natural Ventilation rates in unairconditioned residential buildings.

Window location	Air change rate (ACH)(hour $^{-1}$)
Window and door closed	0-0.5
Window tilted and curtains closed	0.3-1.5
Window tilted and curtains opened	0.8-4.0
Window half opened	5-10
Window opened	9-15
Window opened and door opened and across each other	Almost 40

Table 10 Natural Ventilation rates with changing window location. [39]

In our case, in both tables, it is the last row that applies, where windows or openings are located in more than one side, and it is opened, and across each other, so the minimum air change per hour is 30 and 40, and if we compare it to the calculated Air change of the above apartment which is 37 (hr^{-1}), then we can conclude that the apartment with the SMP windows achieved the minimum requirement for natural ventilation and exceeded.

1.7 Egyptian Green Building Code for Innovation and Added Value

In the Egyptian Green Building Code for Innovation and Added value there are 13 fields of innovation and the Material is one of the fields, and the code states the following:

"The innovative building material can be natural or a new industrialized that was not known or repurposing non building materials in construction elements (cans- bottles). Recycling wasted materials result in greater efficiency.
Materials that are locally available can be used innovatively, Repurposing innovatively of previously used building materials or elements such as doors, lintels with the purpose of reducing and recycling wasted materials."
And since the Shape Memory Polymer is a new industrialized material that is being introduced into the Architecture field, then it deserves the 5 credit points for innovation.[40]

The SMP sheets could be used within the structure through different applications either in exterior or interior applications, the following part explore various ideas for proposed applications.

1.8 Proposed Architecture Applications

After reviewing the results of the experiments held on different samples and selecting a sample to place in a model and monitoring the wind speed, then the selected SMP sample started opening until it reached 90 degrees, accompanied by running ANSYS simulation with the wind speed flowing through the SMP sample in an apartment case study, the researcher thought of the structure that would hold the SMP sheets within the building elements, and the researcher chose the honeycomb structure to act as the supporting structure. The SMP sheets could be shaped into hexagonal shape to fit into the honeycomb structure.

Honeycomb structures:

Honeycomb structures occur often in nature, as the hexagonal structure is the most densely packed structure in two dimensional space. Technical honeycomb structures are made of plastic, ceramics, paper and metal. Processing includes: the cutting of hexagonal sheets and subsequent gluing, insertion of strips of glue between the sheets and subsequent stretching, or the use of moulds, especially when plastic is used. Honeycombs are used for the core of sandwich panels and composite designs. Due to their large surface area, they are suited for use in cooling machines and catalysers. They are also used as the surface layer of tyres and packaging.

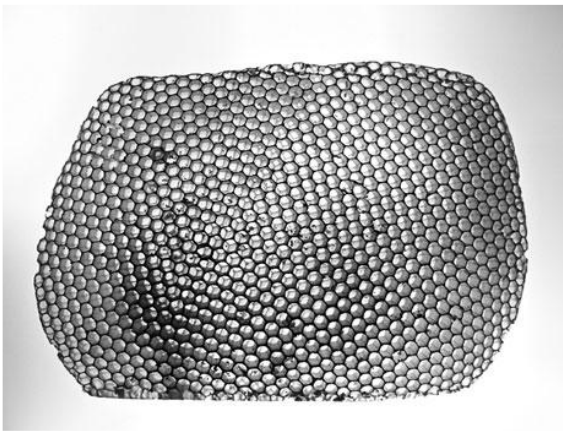


Fig. 119 Honeycomb structure found in nature.

The use of self-organised buckling to structure material enables industry to use thinner material, and thus eke out resources. Materials used include metal, paper and plastics. The product has spread into all kinds of applications: in architecture, roof and facade products of the Rheinzink company are structured in this way. Vault structured material is also used for ventilation technology, lamps, washing machines, in the car and packaging industries. Apart from the constructive aspect, the structure has the advantage of having its low weight uniformly distributed. [14]

The reasons for choosing honeycomb structures to act as a support for SMP sheets are as previously mentioned could be breifed as follows :
1. Minimal amount of used material
2. Minimal weight
3. Minimal material cost
4. Minimal density
5. High compression properties
6. High shear properties

Besides being a shape inspired by nature which acheives the goal of biomimicry.

SMP sheets could be shaped in different shapes and sizes and could be programmed to react to a wide range of temperature,it could also be treated to be subjected to exterior climatic conditions and so therefore could be placed in facedes of buildings and canopies.

1.8.1. Exterior Application:

As in the figure shown, a high rise building covered with a mesh of honeycomb structure, this structure, as proposed by the researcher, could act as a support for SMP sheets that would fit into these hollow cells and perform the same function of windows.
Or could be placed in a large shading canopy.

Fig.120 Office tower in Seoul by Korean studio Archium.
(Arch Daily, 2014, http://www.archdaily.com/office/archium)

Fig.121 Fed Square Cloud canopy, Melbourne. (Archi Channel, 2013, http://www.archichannel.com/project/fed-square-cloud-canopy/)

1.8.2. Interior Applications

The honeycomb structure was adopted within interior design too and the following pictures are products used in interior architectural elements such as partitions, doors, and openings and could be used in different colors too.
SMP sheets could replace the facing sheet.
These products are manufactured by a swedish company known as "Design Composite". [40]

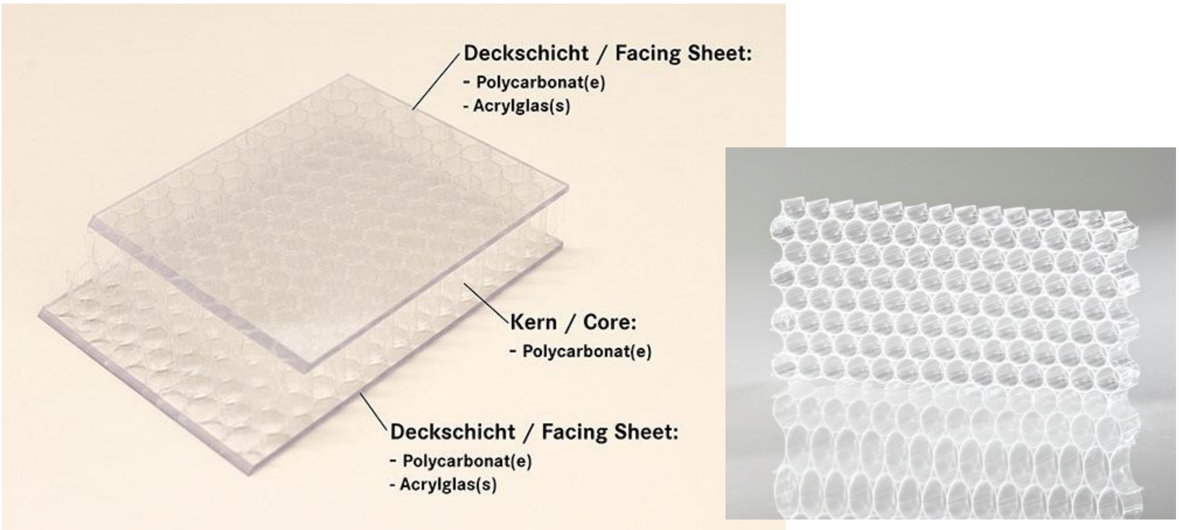


Fig. 122 Translucent hexagonal honeycomb sandwich panel. (Design Composite, 2015, http://www.design-composite.com/index.php/en/anwendungen/architecture-design)

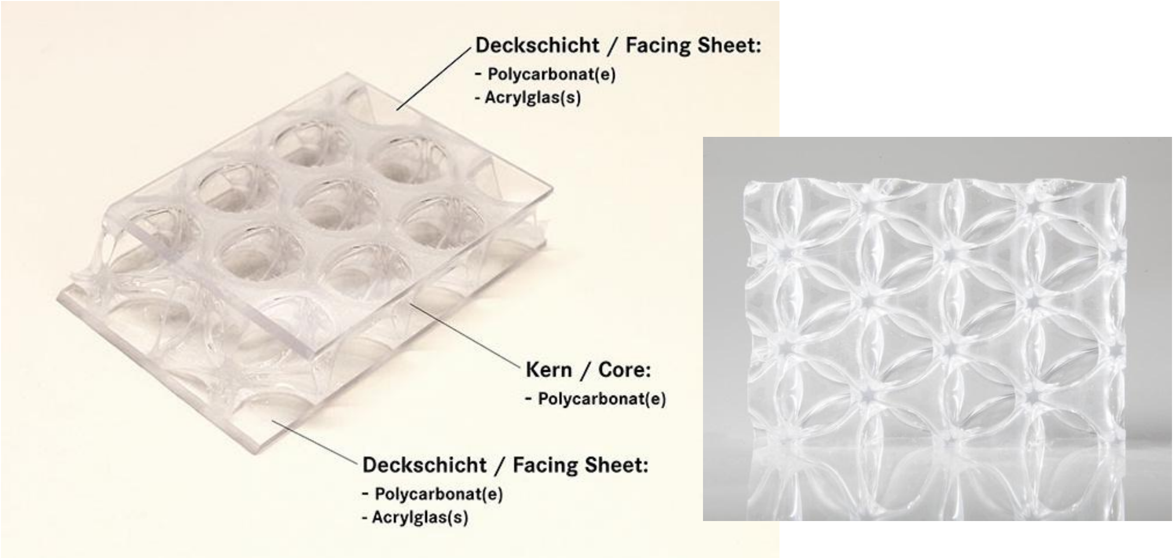
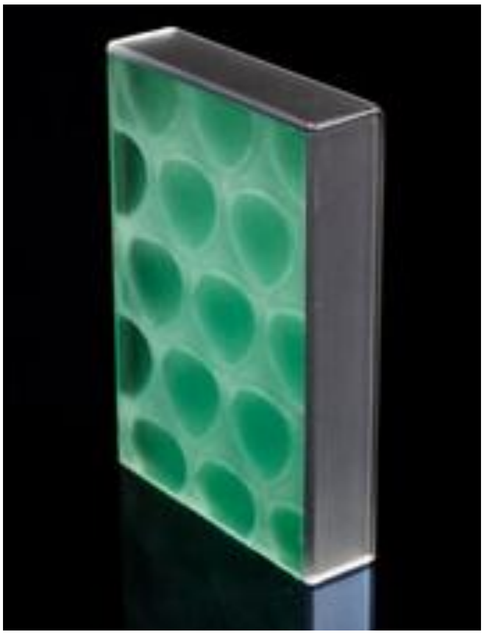
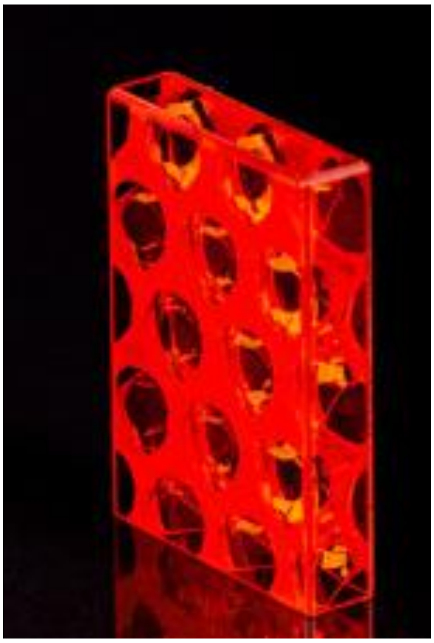
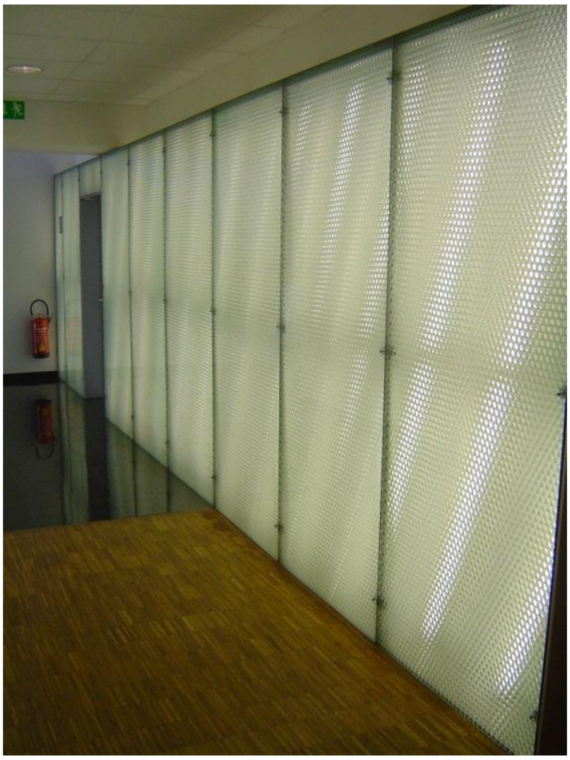
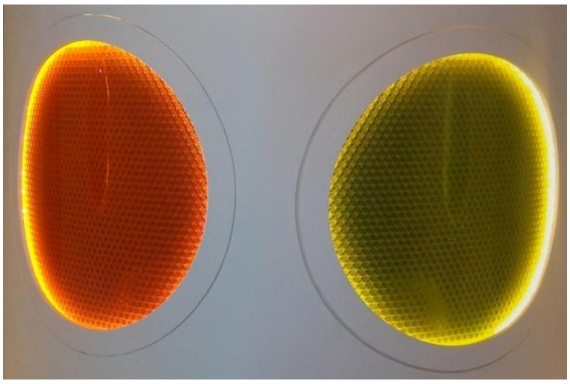


Fig. 123 Translucent Tricore honeycomb sandwich panel. *(Ibid)*









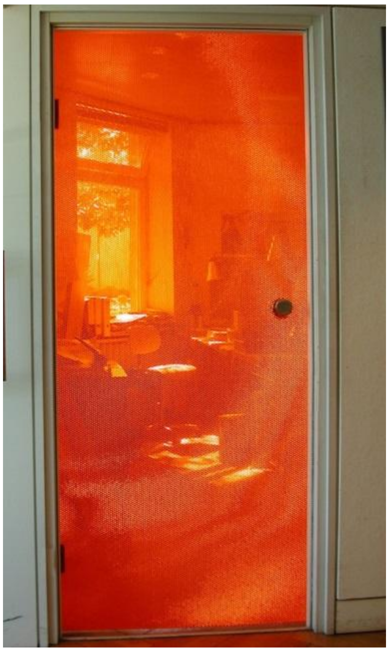


Fig. 124 Show a lot of possible interior applications through doors, partitions and internal windows. *(Ibid)*

2. CONCLUSION AND RECOMENDATIONS

This thesis discussed three main topics to reach its conclusion, and those three topics were: Global warming and climate change- Biomimicry in architecture- Smart materials.
The researcher reviewed the phenomena of global warming, its causes, and consequences on climate change and its devastating effect on our beautiful planet and on our existence as humans and other living creatures, and unfortunately these consequences are actually happening right now, not in the far or near future, so unless we start taking real actions to minimize these negative effects then the deterioration and the damage of the planet will be faster than we can predict.

So the researcher took the approach of learning from nature since it was able to survive more than 3.8 years of evolution, nature with its plants, animals and microbes gained a lot of experience, and has learned: what works; what is appropriate; what lasts.

Learning from nature or mimicking nature is the biomimetic approach, and it's a new field that architects started giving attention to after biomorphism.
In Biomimicry, architects work with biologists and chemists to try to extract from nature techniques and ideas that could be utilized in architecture and they succeeded in six main disciplines:
-Structures
-Materials
-Waste management
-Water management
-Thermal environment control
-Energy production
All six disciplines were discussed thoroughly with examples, to help architects understand biomimetic architecture and its advantages in architectural design and of course its positive impact on nature.

After reviewing the biomimetic architecture approach and disciplines the researcher chose to focus on material discipline from the six discipline of biomimicry, and the way to biomimic materials in architectural is by using Smart building materials.
And because the building envelope and the internal walls have a great effect on the internal temperature of the building, we reach the conclusion that using conventional materials that don't respond to the surrounding stimulus as temperature, light or humidity, is no longer acceptable in buildings with the increase on energy demand and its negative effect on climate change.
Buildings need to function as the human skin does and interact naturally and automatically without any human interference, we can achieve that by using smart materials in architecture combined with biomimetic design, this could contribute a lot to energy efficient design in architecture.
The researcher reviewed different smart materials and discussed its history, theory, applications, advantages and disadvantages and they were:
-Phase change materials
-Hydrogel
-Thermo Bimetals
-Shape memory polymers
-Shape memory alloys

The researcher chose to work with Shape Memory Polymers for several reasons that were discussed.
Lab experiments were conducted on three different samples of SMP sheets in order to reach a sample of SMP sheet with the right thickness and can bend when exposed to hot air at a certain temperature.
After several trials, the researcher reached the desired sample and built a simple model to place in it the selected SMP sheet in order to measure the air flow when the sheet bended and opened due to exposure to air heated to 37 ^{o}C.
Wind velocity was measured successfully and was applied to a simulation called ANSYS to simulate the air flow direction, velocity and turbulences.
Using ANSYS simulation, the researcher conducted another run on an apartment 63 m^2 in area to calculate the average air flow velocity to calculate the Air Change per Hour and compare it to the Egyptian ventilation code rates.
Results were very satisfying and complying to the code which opens a wide range of applications through a lot of elements in the building such as:
-Windows in internal and external walls
-Solar chimneys
-Openings in domes
-Skylights

And by using it, the material becomes the system, and performs the same thermoregulating function as the skin performs to the body and a decrease in electrical consumption is achieved because natural ventilation will increase and therefore the reliability on air conditioning is minimized.
The researcher recommends adopting Two Way Shape memory polymer sheets which act as a temperature actuator in the building envelope in order to avoid retaining its flat shape mechanically since the Two Way Shape memory polymers retains its shape and react to temperature on its own.
The researcher also proposed the honeycomb structure as a supporting structure for the SMP sheets which can be applied exteriorly and interiorly.

3. Other ideas derived from combination of biomimicry and smart materials:

1. Thermo Bimetal discs could be designed to react at temperatures between 25 ^{o}C and 35 ^{o}C and could be placed in exterior walls to act as openings to enhance natural ventilation.

2. From the Namibian desert beetle, one has learned how it could capture water from fog, and this could be very useful for our projects here in Egypt due to the scarcity of water and the efforts made to save in water consumption.
So by learning techniques for capturing water from fog, this water could be utililsed in different projects such as:

- Washing off dust from facades containing TiO_2 coatings which mimic the lotus leaf effect, these coatings exist in the form of paints or glazing.
- Feeding Hydrogel either in the form of membranes or ceramics, after its water content evaporates, with water again.
- Providing amount of water that could be used in capillary tubes planted in building structures to enhance evaporation and cools off the building.

There a lot more ideas that could be inspired from nature if we really give it more thought and studies and those just few thoughts that would help open the door for more to come, in hope to participate even for a little to save this planet from the destruction made by human that won’t pass peacefully without bad consequences on the whole humanity.

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المراجع العربيه:

٣٩. اللجنه الدائمه لإعداد الكود المصرى للتهويه فى المبانى، ٢٠١٠ ، " الكود المصرى للتهويه فى المبانى"، المركز القومى لبحوث الإسكان و البناء ، مصر

الملخص

يواجه العالم كله خطر حقيقي ومشكلة مستمرة بدأت بالفعل منذ عقود، ولكن لا تزال حتى الآن فى تزايد مستمر، هذه المشكلة هي "الاحتباس الحراري" و الذى يرتبط بارتفاع حرارة الأرض و ينتج عن ذلك قائمة من العواقب الوخيمة التى سوف تصيب كوكبنا.

الاحتباس الحراري يأتى نتيجه لتكون طبقة من الغازات تمنع خروج الحراره خارج الأرض و انما تردها للأرض ثانية مما يزيد من حرارتها، وأحد الموارد الرئيسية لهذه الغازات وخصوصا ثاني أكسيد الكربون هو حرق الوقود الأحفوري لتوليد الكهرباء.

بجانب تلك الآثار السلبية على الصعيد العالمي، نحن في مصر نواجه بالفعل مشكلة كبيرة مع الكهرباء التي لم نكن على استعداد لها، و قد تم بالفعل الكثير من الإجراءات لحل و تجاوز هذه المشكلة ولكن لا نزال بحاجة إلى الاعتماد على حلول أكثر استدامة.

و كمهندسه معماريه، من بين المهندسين المعماريين الآخرين ونتحمل مسؤولية تصميم مباني ذات كفاءه عاليه فى استخدام الطاقة، قد وجدت أن أفضل معلم لنتعلم منه كيفية تصميم هذه المباني هو معلمنا العظيم "الطبيعة"، مما أدى هذا البحث إلى دراسة علم "محاكاة الطبيعة" ومحاولة ترجمتها إلى العناصر المعمارية .

قدمت الباحثه ستة مبادئ مختلفة تتأسس عليها "محاكاة الطبيعة" فى مجال العمارة ، و تم اختيار المواد الذكية لتكون النقطه البحثيه التي من شأنها تعزيز كفاءة استهلاك الكهرباء بالإضافة إلى مبادئ التصميم مستوحى أيضا من الطبيعة.

بعد سرد "محاكاة الطبيعة" فى مجال العمارة والتعلم من مبادئها، ناقشت الباحثه أنواع مختلفة من المواد الذكية واختارت المواد الأكثر ملاءمة للعمل بها، وكانت نوع من البوليمرات التى تستطيع تذكر شكلها الأصلى و وقع هذا الإختيار على هذه الماده بعينها نظرا لمزاياها العديدة.

كما عززت الباحثه البحث بأمثله من المشاريع التي يمكن أن تؤخذ كنماذج يمكن التعلم منها كما و انها اتخذت كدليل أو موجه إلى النتيجة النهائية والهدف المنشود تحقيقه فى البحث.

استخدمت الباحثه عينات مختلفة من المواد المختارة للدراسة فى التجارب المعملية الى أن نجحت للوصول أخيرا للعينة التي استطاعت ان تتجاوب مع درجات حرارة معينة دون استخدام أية وسيلة ميكانيكية أو كهربائية.

تم ادخال نتائج التجارب المعمليه فى برامج محاكاه لمقارنتها مع معايير الكود المصرى للتهوية الطبيعية فى المبانى ، وكانت النتيجة مرضية جدا و واعدة ويمكن أن تسهم في ترشيد استهلاك الكهرباء وبالتالي يساعد في تخفيف مشكلة الكهرباء التى نواجهه في مصر بشكل خاص، و من

خلال خفض استهلاك الكهرباء، و انخفاض معدل حرق الوقود الأحفوري سيكون له تأثير إيجابي بشكل عام على الصعيد العالمي.

البحث تم تقسيمه للأبواب التاليه:

الباب الاول :

وهى المقدمه و قد ناقشت فيه الباحثة المنهج البحثى من خلال طرح السؤال البحثى و الفرضيه و الهدف من البحث و المنهجيه المتبعه فى البحث للوصول للهدف السابق تحديده.

الباب الثانى :

وعرضت فيه الباحثة الخلفيه النظريه و ذلك من خلال ثلاثة اجزاء:

الجزء الأول: و هو عرض لمفهوم محاكاة الطبيعه و تطبيقها فى مجال العماره و ذلك من خلال ست تخصصات أو أفرع رئيسيه و هم:

١. كفاءة الهيكل الإنشائى

٢. المواد و تصنيعها

٣. ادارة المخلفات

٤. ادارة المياه من خلال تجميعها و تخزينها

٥. التحكم الحرارى للبيئه

٦. انتاج الطاقه

و بعد عرض هذه التخصصات بأمثلة لتطبيقها فى العماره ، اختارت الباحثه تخصص المواد لمحاكاته من خلال دراسة مواد البناء الذكيه.

الجزء الثانى : و هو تعريف لمواد البناء الذكيه و تقسيمها و أنواعها و هى كالتالى:

١.الجل الذكيه Smart Gels

٢. المواد ذات المراحل المتغيره Phase Change Materials

٣. المعادن الحراريه المزدوجه Thermo Bimetals

٤.البوليمرات ذات الذاكرهShape Memory Polymers

٥.المعادن ذات الذاكره Shape Memory Alloys

و بعد عرض المواد و شرحها من خلال تطورها و خواصها الفيزيائيه و تطبيقاتها، اختارت الباحثه دراسة ال Shape Memory Polymers أو اللدائن التى عندها قابلية تذكر شكلها الأصلى و ذلك لأسباب كثيره منها قابلية تشكيلها و سعرها المنخفض مقارنة بباقى المواد و قابلية تطبيقها فى عناصر معماريه كثيره و أسباب اخرى تم شرحها بالتفصيل فى هذا الجزء.

الجزء الثالث: و هو عرض لأهم المشاريع و الأبحاث التى استخدمت و طبقت مفهوم محاكاة الطبيعه و المواد الذكيه و استطاعت دمجهم فى مشاريع يمكن الإستفاده و التعلم منها.

٣ – الباب الثالث :

فى هذا الباب درست الباحثه Shape Memory Polymers أو اللدائن التى عندها قابلية تذكر شكلها الأصلى من خلال اجراء تجارب معمليه على ثلاثة عينات تم اختيار عينه منهم و تم ادخالها على نموذج لمحاكاتها من خلال برنامج ANSYS ثم تم مقارنة النتائج بالكود المصرى للتهويه الطبيعيه و جاءت النتائج مطابقه لمعدلات تغيير الهواء بالكود

اسم المهندس : **ماريان عزمى نسيم**

تاريخ الميلاد : **١٩٧٧/٦/٢٧**

الجنسيه : **مصريه**

تاريخ التسجيل : **٢٠١١/٩**

تاريخ المنح :

القسم : **الهندسه المعماريه**

الدرجه : **دكتوراه الفلسفه**

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عنوان الرساله : **محاكاة الطبيعه كمدخل لتصميم مبانى ذات كفاءه عاليه فى استخدام الطاقه**

الكلمات الداله : **التغير المناخى ، الإحتباس الحرارى ، محاكاة الطبيعه ، المواد الذكيه ،اللدائن التى تتذكر شكلها**

ملخص الرساله :

الرساله اتخذت مدخل جديد لتناول مشكلة الإحتباس الحرارى و ذلك عن طريق التعلم من الطبيعه من خلال محاكاتها و ترجمة هذه المحاكاه الى عناصر معماريه. الباحثه اختارت دراسة المواد الذكيه لأنها مواد تستشعر و تتجاوب مع البئه المحيطه بها و هو الحال فى الطبيعه. بعد عرض مواد ذكيه مختلفه، اختارت الباحثه دراسة اللدائن التى عندها قابلية تذكر شكلها و التى تتجاوب مع المحفز الحرارى. و من خلال تجارب عديده و برامج محاكاه، توصلت للدائن قابله لتذكر شكلها قابله للتحرك بحيث تسمح لدخول الهواء بالقدر المطابق لكود التهويه المصرى و عرضت اقتراحات لتطبيقه و استخدامه فى عناصر معماريه كالفتحات الداخليه.

محاكاة الطبيعه كمدخل لتصميم مبانى ذات كفاءه

عاليه فى استخدام الطاقه

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فى
الهندسه المعماريه

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٢٠١٦

محاكاة الطبيعه كمدخل لتصميم مبانى ذات كفاءه

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محاكاة الطبيعه كمدخل لتصميم مبانى ذات كفاءه

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