En+

Building Envelope System

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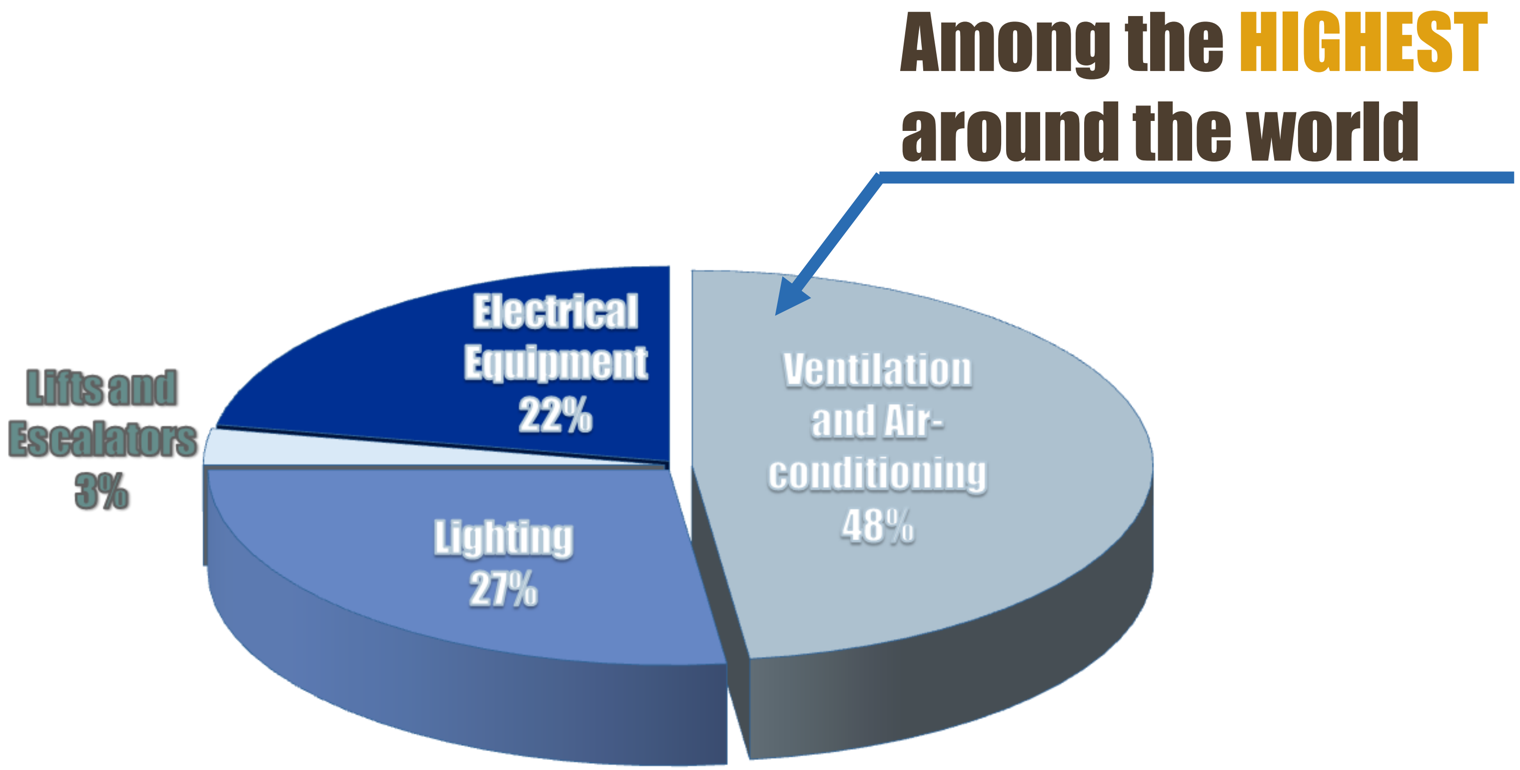
RUSAL

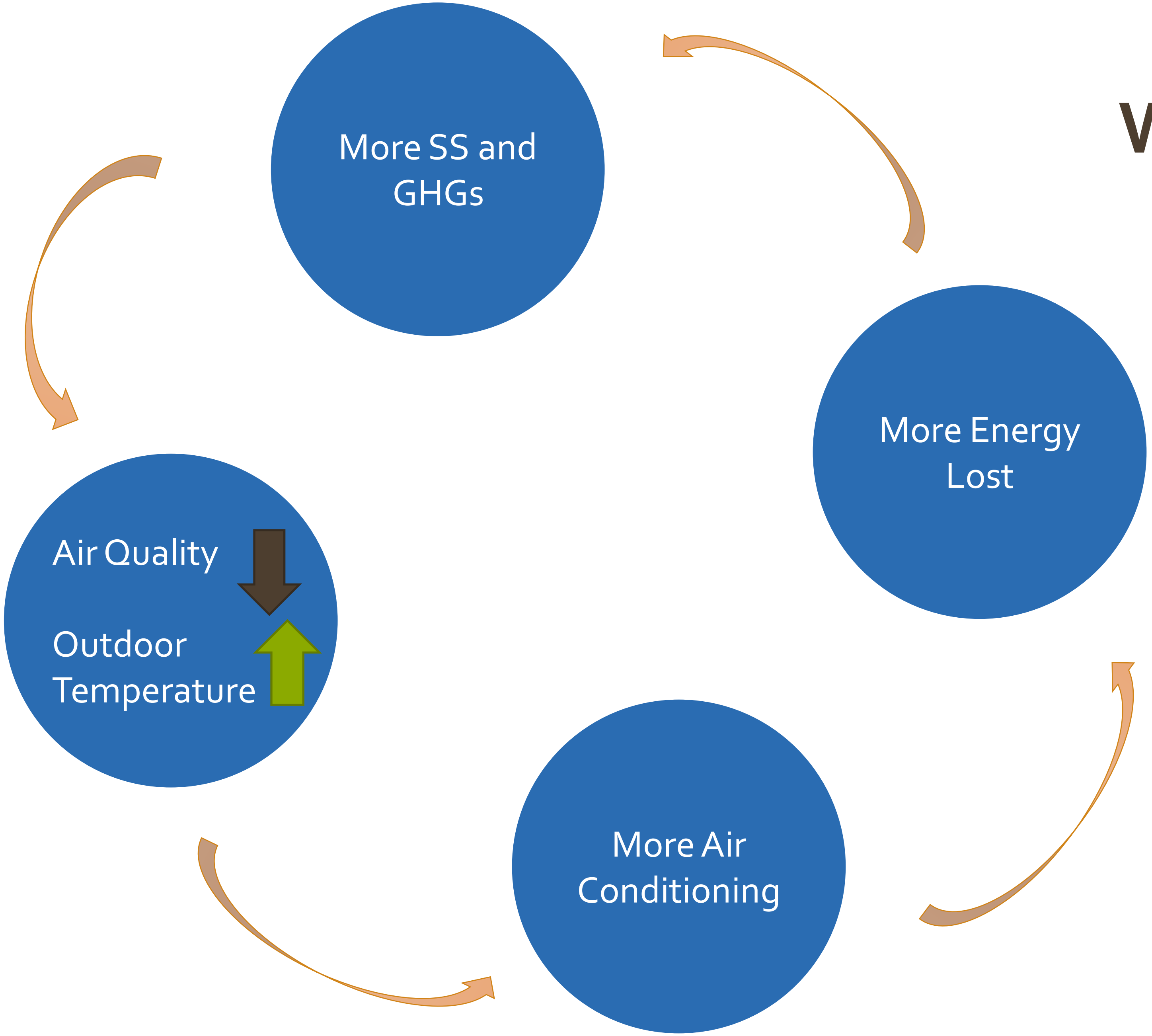
Built Environment in Hong Kong

- Buildings consumed nearly **90%** of total electricity in Hong Kong
- Only 40%-50% for U.S. and European Union
- Dependency on **air-conditioning** for cooling and human comfort

Built Environment in Hong Kong



Why?



More SS and GHGs
More Energy Lost
More Air Conditioning
Air Quality
Outdoor Temperature

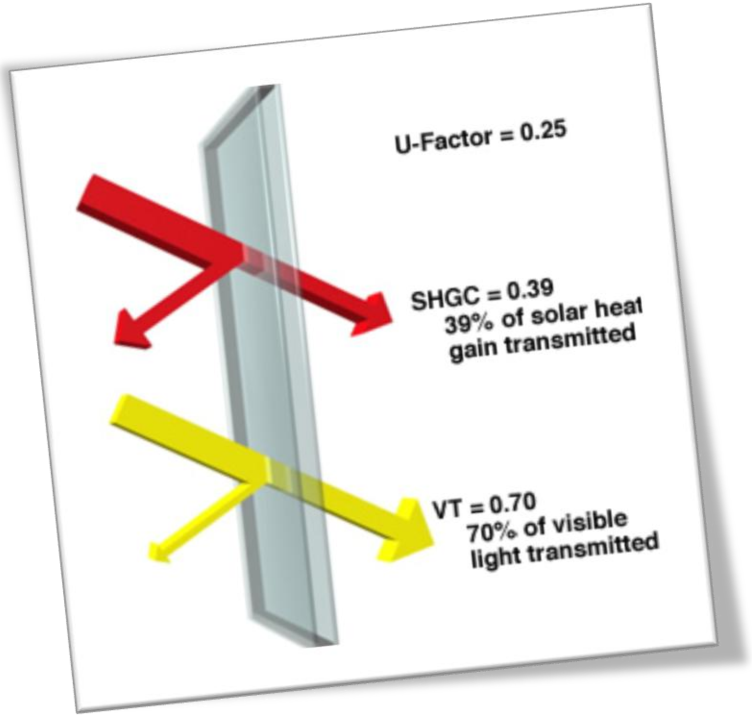
Energy Efficiency of Thermal Envelope Systems

- A number of outer skin design approaches are available to improve the thermal insulation of a building

- In general, we can divide TE systems into to sub-systems
  - Glass system
  - Opaque system (Metal Panels + Independent insulation layer)

Energy Efficiency of Thermal Envelope Systems

- A number of outer skin design approaches are available to improve the thermal insulation of a building
  - Dual Glazing Panels (Conduction)
  - Low-e (low-emissivity) Glass (Radiation + Lighting)
  - Silver Reflective Coating (Radiation)
  - Aluminium/Metal Panels (Radiation)
  - Polyurethane Insulated Panels (Conduction)
  - Gypsum Board Insulated Walls (Conduction)



Problems of existing BE designs

- **Existing BE design**

  A. **Insulated Glass Panels with non-insulated frames**

  B. **Non-insulated aluminum panels (Small)**

  C. **Polyurethane Insulation layer installed separately**

  D. **Extensive use of waterproof sealants (Insufficient strength in aluminum panels)**

Problems of existing BE designs

Researchers demonstrated that the actual thermal energy efficiency of existing BE designs are only around **25%** of its design value

Energy Efficiency of Thermal Envelope Systems

- **Heat Gain Through Walls and Glazing**
  - **The Overall Thermal Transfer Value (OTTV)**

$$OTTV_W = \frac{(A_W \times U \times \alpha \times TD_{EQ_W}) + (Af_W \times SC \times ESM \times SF)}{Ao_W}$$

Conduction of opaque system

Radiation and Conduction of glass system

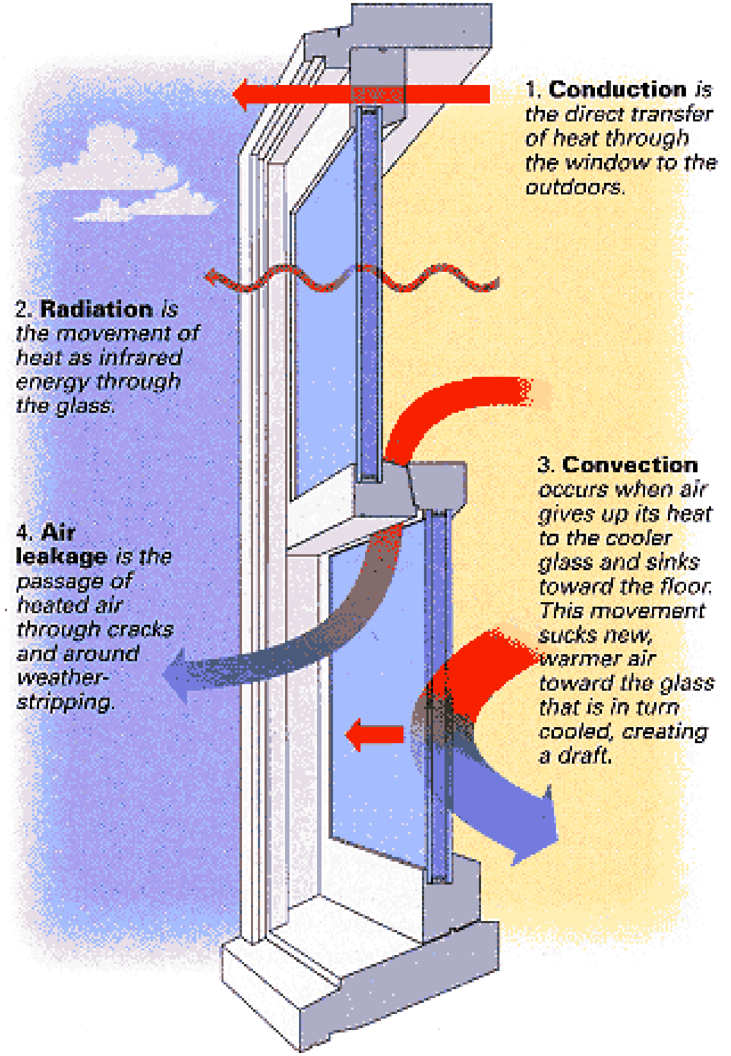
Energy Efficiency of Thermal Envelope Systems

- **Conduction**
  - Direct molecular interaction
  - Via a substance (Conductivity)

- **Radiation**
  - Wave (energy)
  - Most cladding materials have emissivities above 0.9
  - Metal surface reflects most thermal radiation

- **Convection**
  - Via air (fluid) flow

- **Infiltration**
  - Air leakage



Energy Efficiency of Thermal Envelope Systems

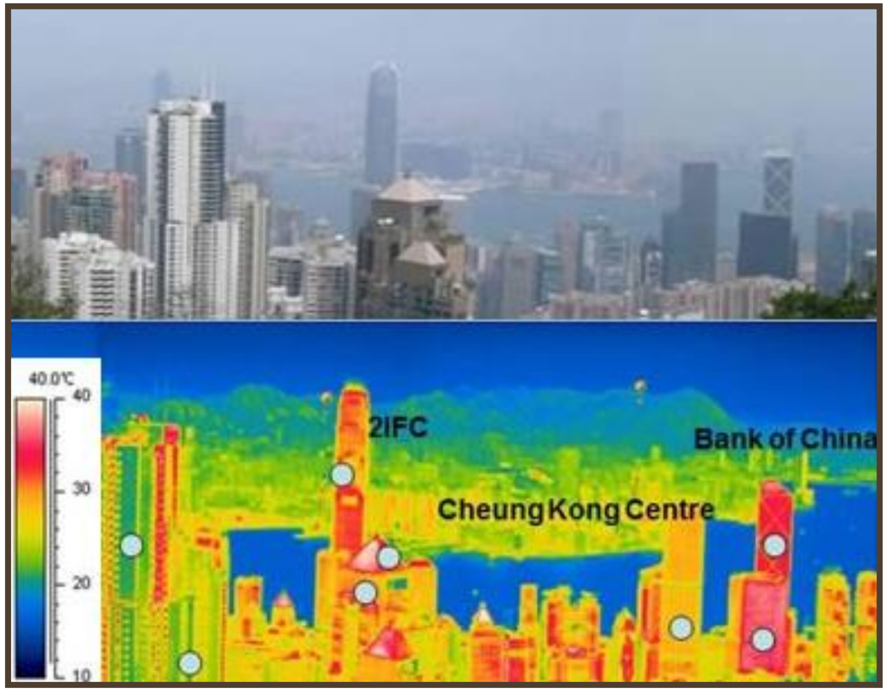
The plate-plate and plate-frame connections will inevitably generate pathways for air leakage especially when **the material is deformed** due to wind pressure or temperature change.

This infiltration issue leads to **35%-45%**

extra heating/cooling requirement and cost in residential buildings and account for 15% heating/cooling load in office buildings, according to field measurement by different researchers and organizations

Energy Efficiency of Thermal Envelope Systems

Heat transfer appears to be greatest along the perimeter of all thermgrams.
This is because the conductivity of the framing material is often high



Problems of existing BE designs

1. Heat lost from non-insulated window frames and sealants
   - Conduction + Convection

2. Air leakage due to damage of sealants and deformation of window frames/ panels
   - Infiltration

3. Damage/ deterioration of unprotected insulation layer
   - Durability of unprotected insulation material < 5 years
   - Conduction + Convection

Thermal efficiency of the *En*+ composite panels. Approaches and solutions

Sustainable Solution of BES

- ✓ Stiff and Strong
- ✓ Light
- ✓ Green
- ✓ High U-value
- ✓ Durable

→ Material Level

→ System Level

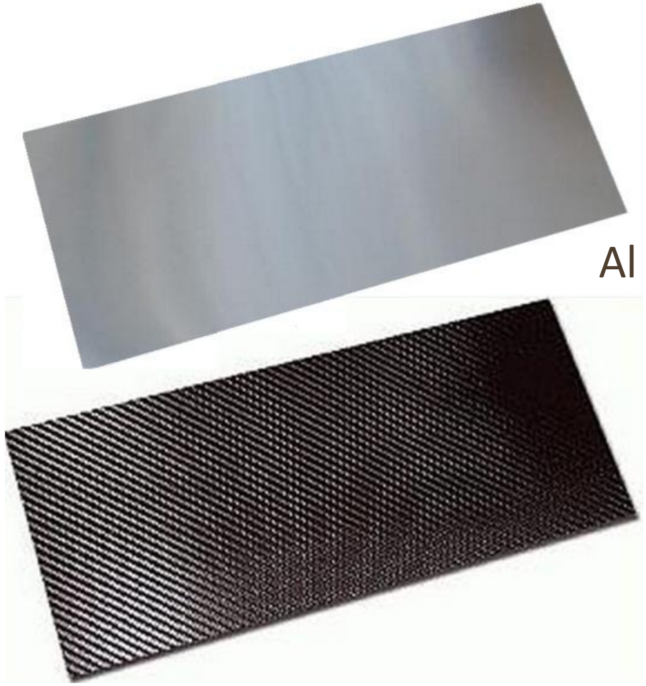
✓ Inexpensive

Material Level - FRA

Fiber Reinforced Aluminum (FRA)

Fiber Reinforced Aluminum (FRA)

Fiber Reinforced Aluminum (FRA)

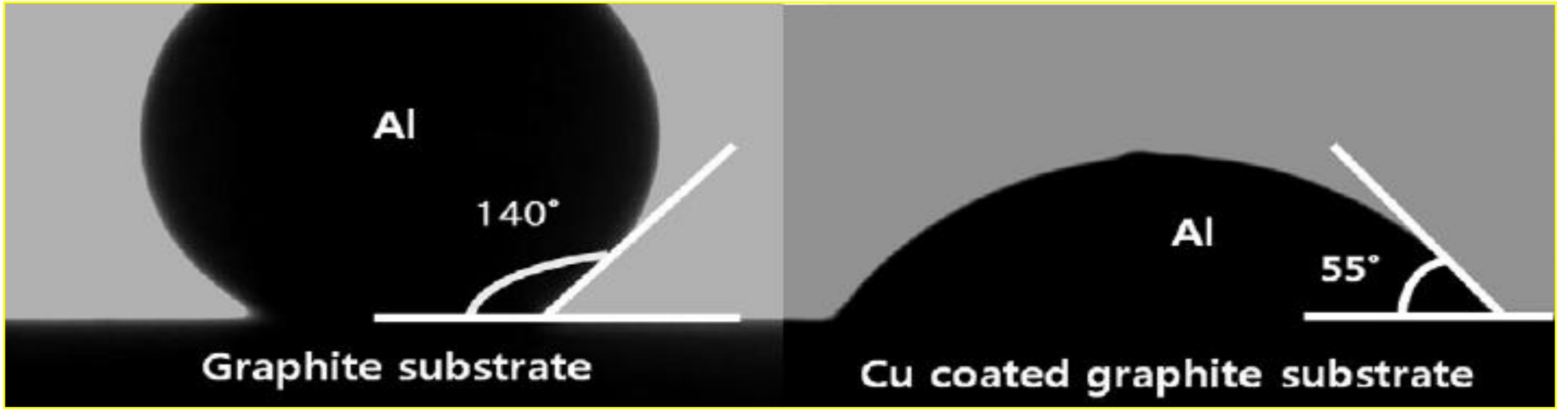


Al alloy

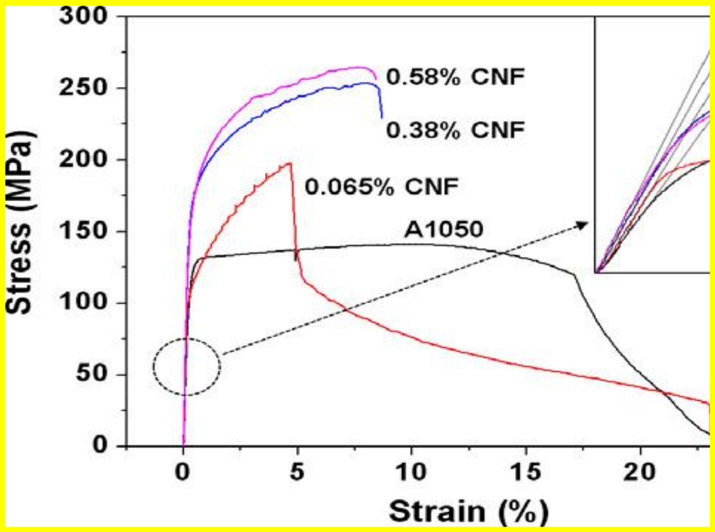
FRP

Epoxy

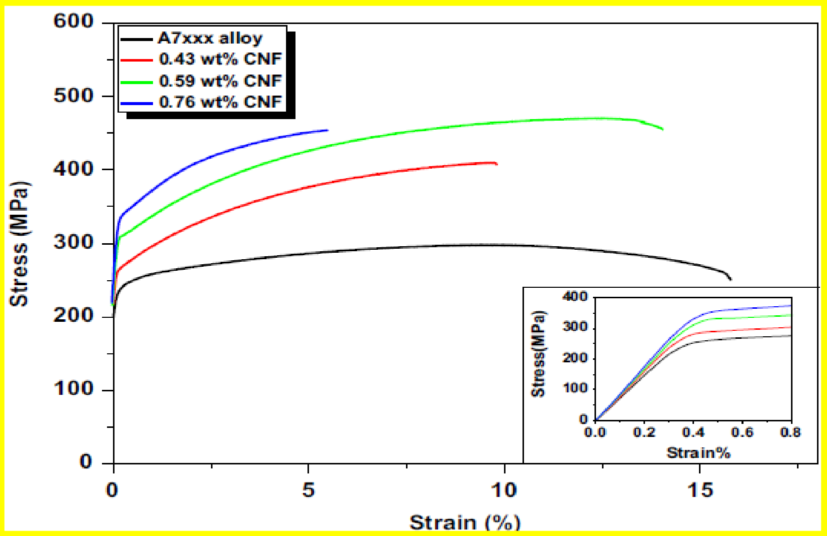
Poor molten Al wetting of carbon



[Se-Il Oh a, Jun-Young Lim a, Yu-Chan Kim at al.]



A 1050



A 7XXX

Chemically vapor deposited CNF.

Russian Federation is flaring 40 to 50 bcm of APG annually, equivalent to 80-100 million tons of CO_2 emissions and wasting of more than $5 billion per year

Associated petroleum gas

$C_nH_{2n+2} = nC+(n+1)H_2$

Energy saving

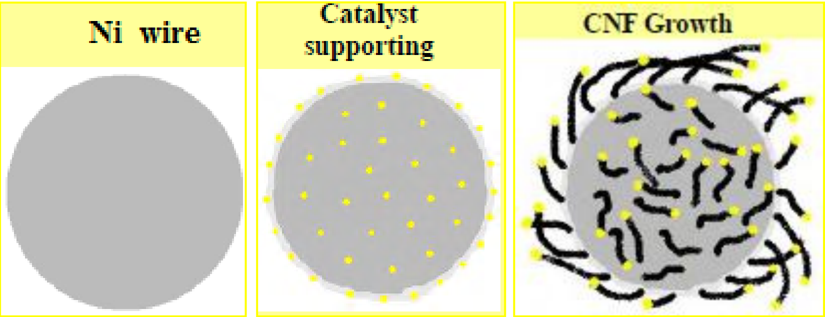
Cl-containing wastes

$C_2H_4Cl_2 = 2C + H_2 + 2HCl$

Environment protection

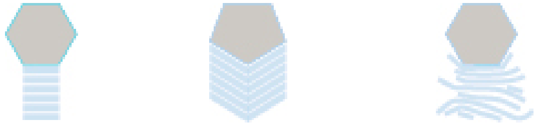
Chemical Vapor Deposition on Ni catalyst (600 °C, 3 h)

C_2H_6 (3.5 Vol.%)
C_3H_8 (81.5 Vol.%)
C_4H_{10} (15.0 Vol.%)

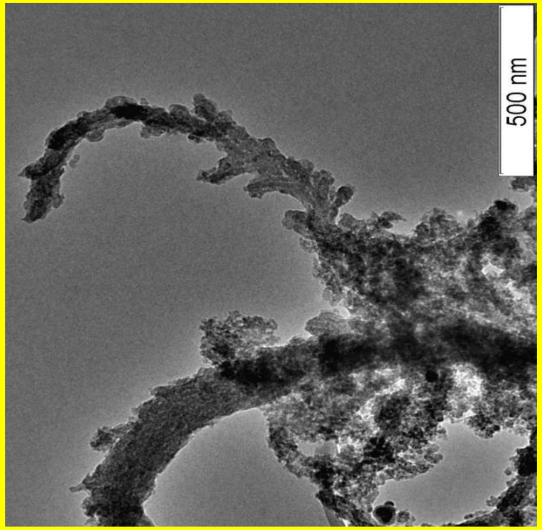


Chemically vapor deposited CNF.

Fishbone carbon nanofibers (CNFs) with 16 wt.% Ni

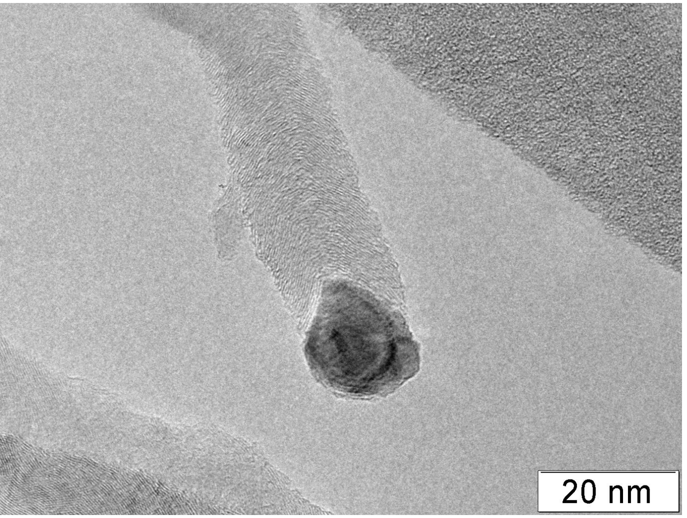


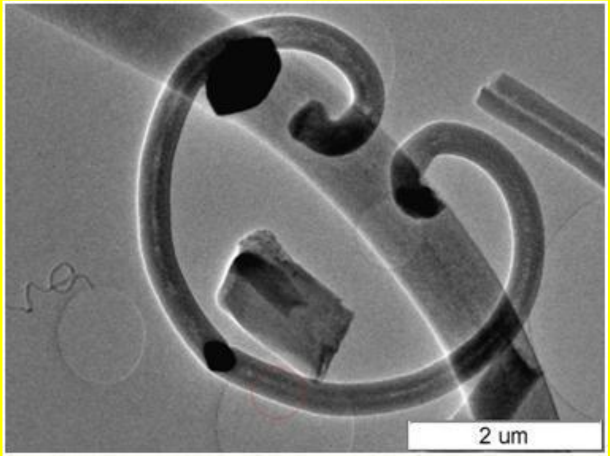
CNF diameter – 50-250 nm	50-250 нм			
CNF length	up to 0,5 мм			
CNF morphology		**"Pile of books"**	**"Fish bone"**	**Disordered "feathery"**
"Bulk density, g/cm^3		≤ 0,45	≤ 0,65	≤ 0,32
Pore volume, cm^3/g		≥ 0,25	≥ 0,30	≥ 0,65
S_{sp}, m^2/g		≥ 90	≥ 70	≥ 320

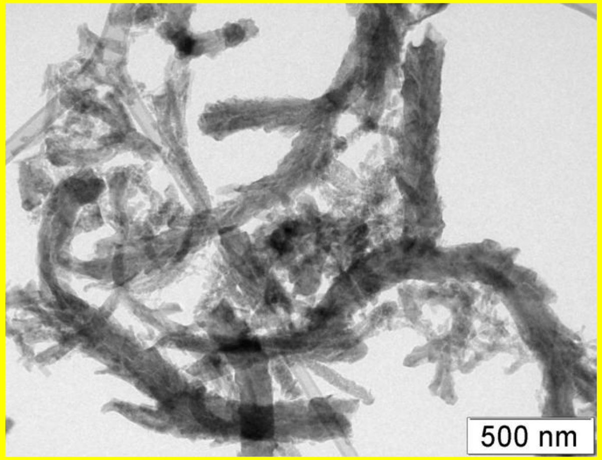


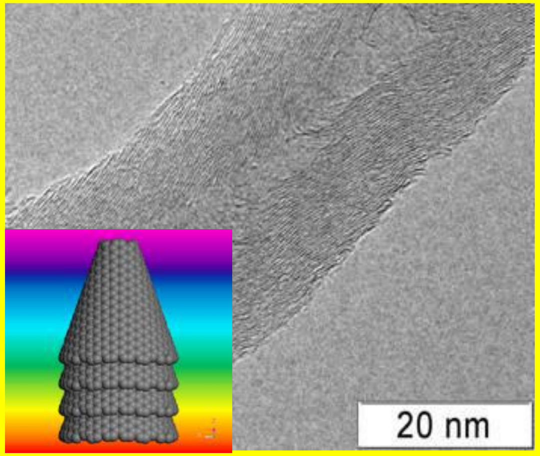
Unique structure

Nano composition of **Carbon** & **Nickel**







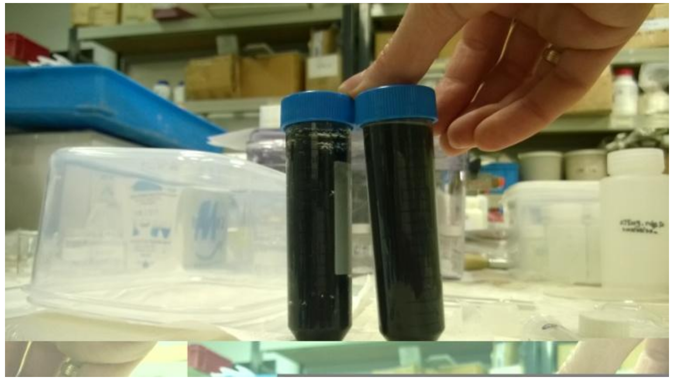


Chemically vapor deposited CNF.

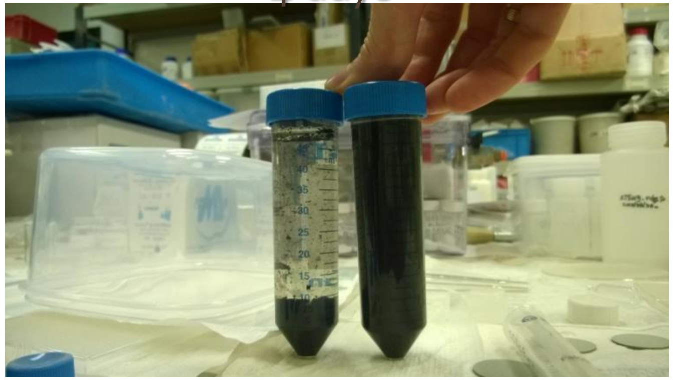
Carbon water suspension decay

CNF (Russia)   MWNT (Traditional)

4 sec



4 days



H_2O (1 g/cm^3)   C (1.8-2.1 g/cm^3)

Sintering Process

- The homogeneous powder was compacted at 200 MPa followed by sintering in **nitrogen** at 870 K for 2 h (min 99.95%, H_2O < 50 ppm, O_2 < 50 ppm)

$$3Al + Ni = Al_3Ni, \Delta H_{870K} = -157 \text{ kJ/mol}$$

- The sintering is mainly enhanced by contribution of highly exothermic reaction with N2

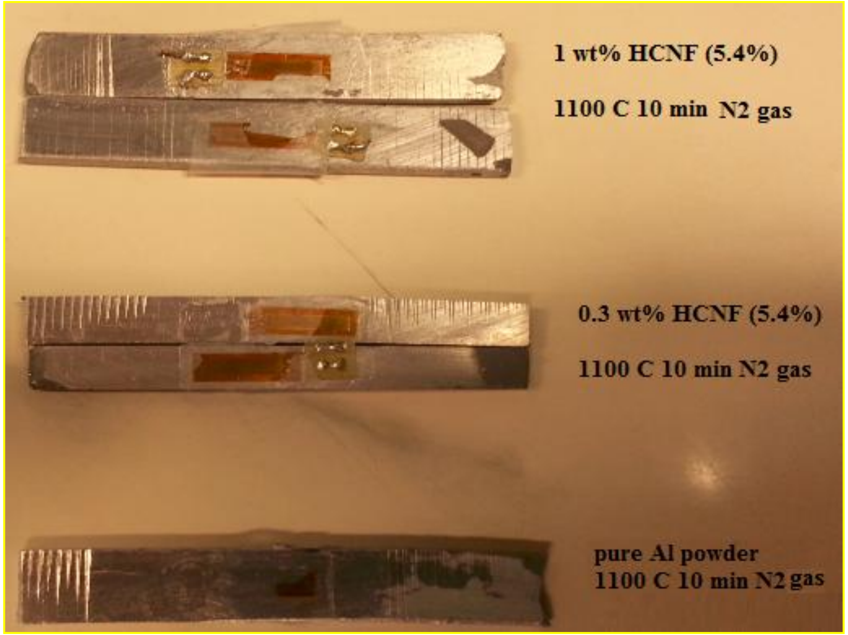
$$2Al + N_2 = 2AlN, \Delta H_{870K} = -318 \text{ kJ/mol}$$

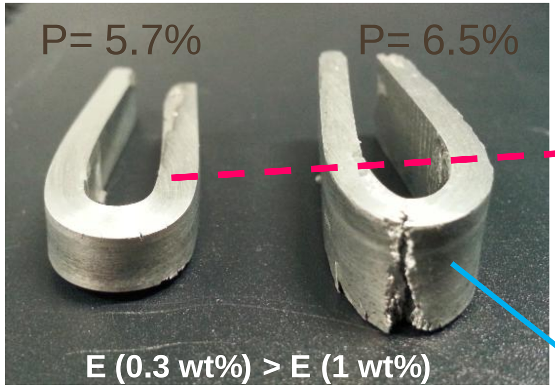
- Extra heat brings to local melting and good spreading of aluminium within pores due to molten Al wets AlN
- CNF & Nitrogen can also reduce alumina layer

$$2Al_2O_3 + 2N_2 = 4AlN + 3O_2 \qquad Al_2O_3 + 3C + N_2 = 2AlN + 3CO$$

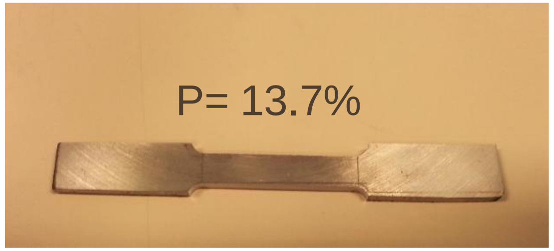
Fiber Reinforced Aluminum (FRA)

The homogeneous powder was compacted at 200 MPa followed by sintering in **nitrogen** at 870 K for 2 h (min 99.95%, H_2O < 50 ppm, O_2 < 50 ppm)



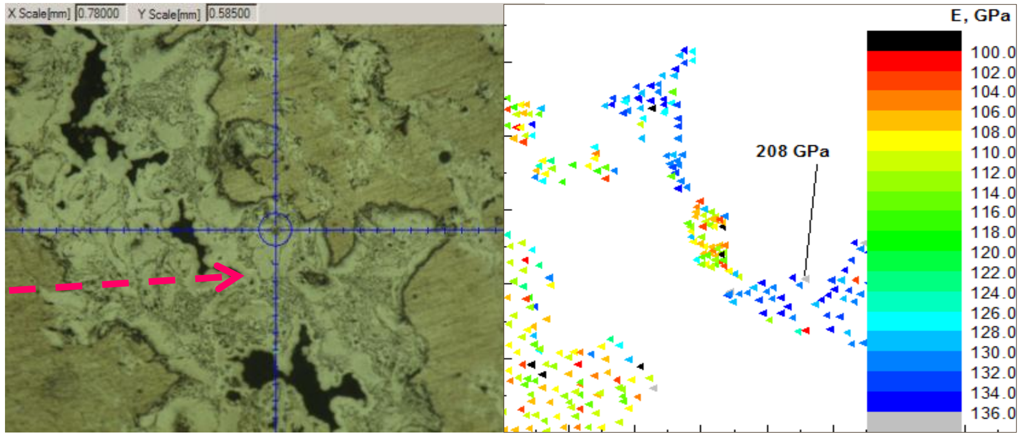


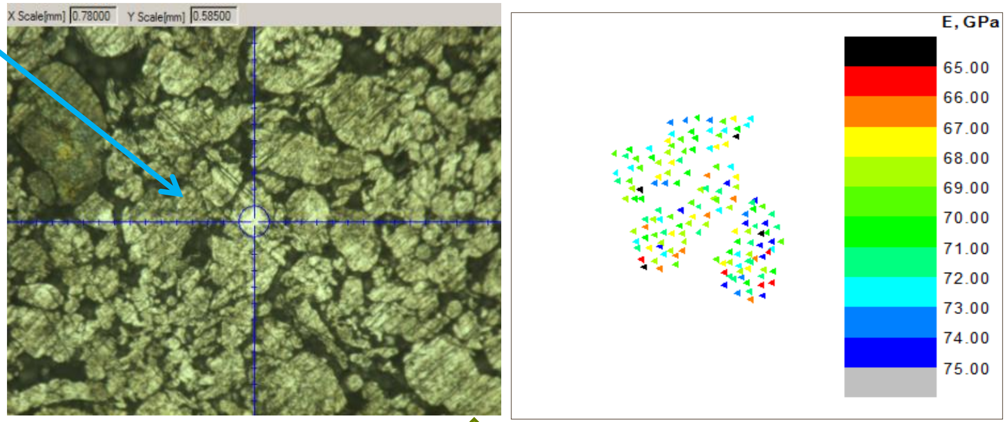
Quickly pre-molten at 1100C



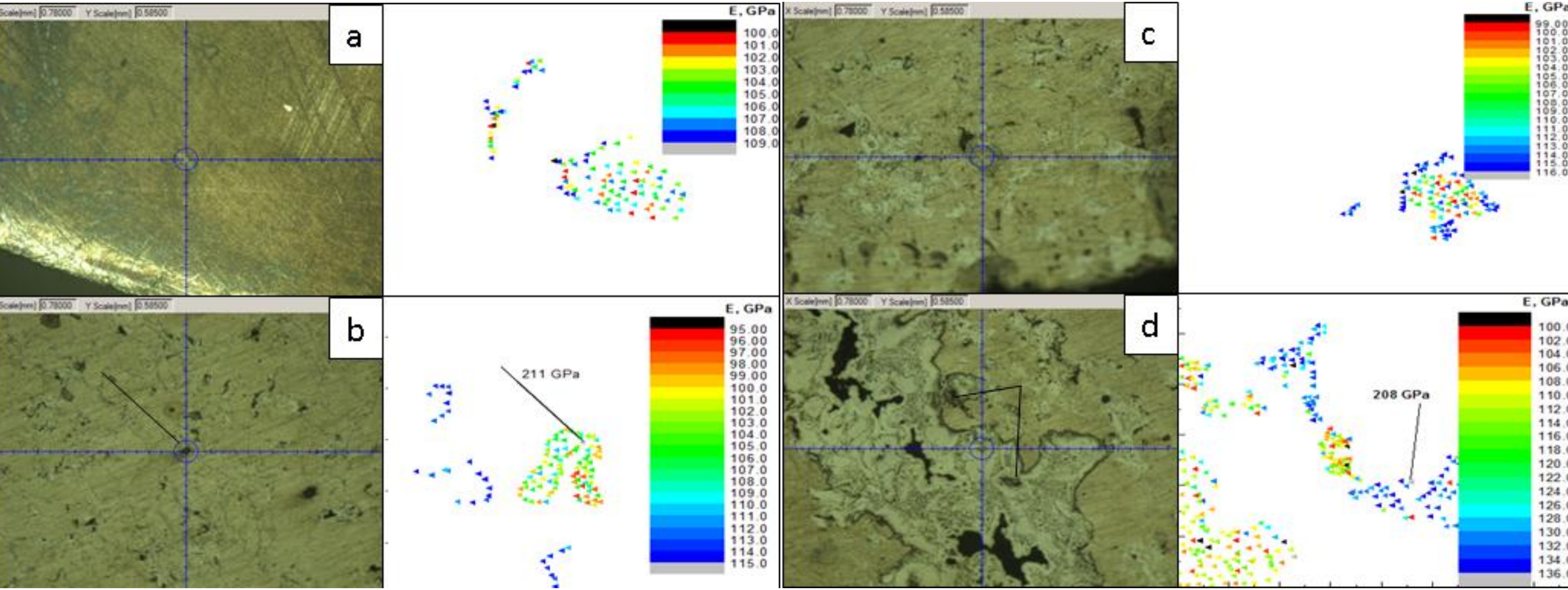
2h in vacuum at 600C

Nanoindentation result



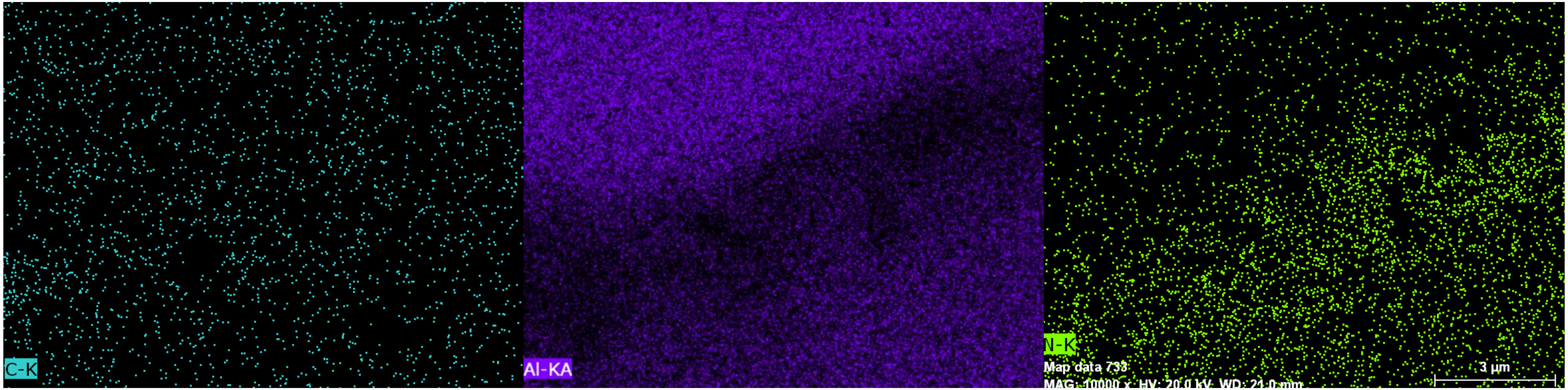


E 100%



a
b
c
d
X Scale[mm] 0.78000 Y Scale[mm] 0.58500
E, GPa
100.0
101.0
102.0
103.0
104.0
105.0
106.0
107.0
108.0
109.0
E, GPa
95.00
96.00
97.00
98.00
99.00
100.0
101.0
102.0
103.0
104.0
105.0
106.0
107.0
108.0
109.0
110.0
111.0
112.0
113.0
114.0
115.0
211 GPa
208 GPa

energy dispersive x-ray spectroscopy analysis

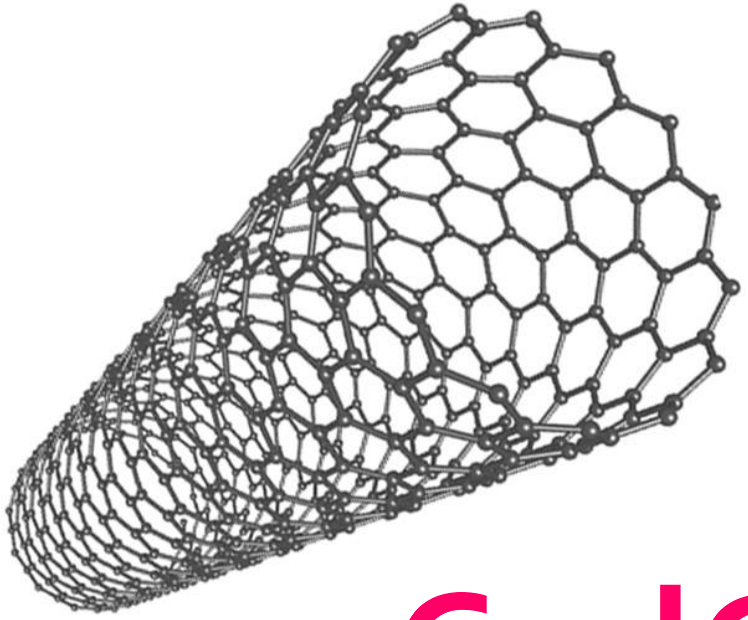


SEM EDS mapping (×10,000) of typical Al - interphase area

The interfacial bonding mechanism was governed by amount of CNFs and the AlN composition

Material	Al	Al_2O_3	Al_4C_3	AlN	Al_3Ni
E, GPa	69	300	50-60	332	176-215

Fiber Reinforced Aluminum (FRA)



Carbon Nanotube (CNT)

CCVD-CNT

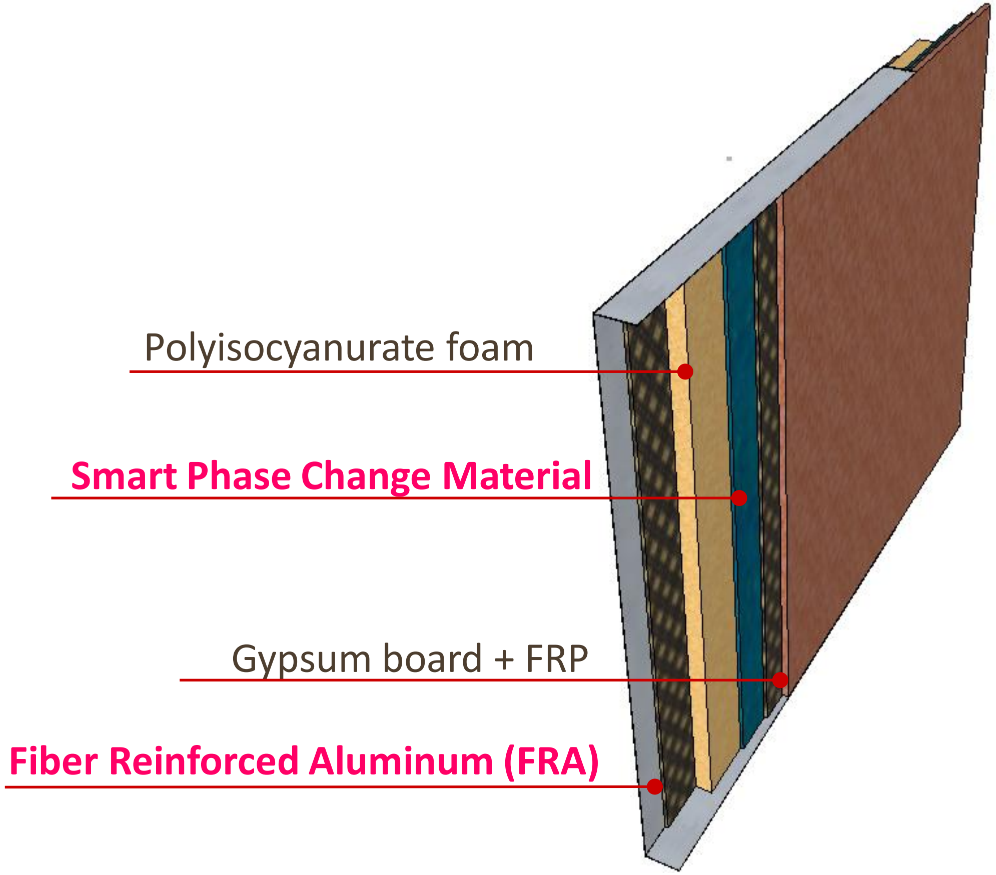
USD$250/kg

USD$90/kg

System Level

RUSAL/HKUST SMART Building Envelope Composite

Type:	Systemized
Transparency:	Opaque / window
Dimensions:	3×3 m plus
Smartness:	Available
Metallic frame	Not required
Improvement	Layered
Destination	Sidewall, roof



The product (*En+*) development

Introduced ideas

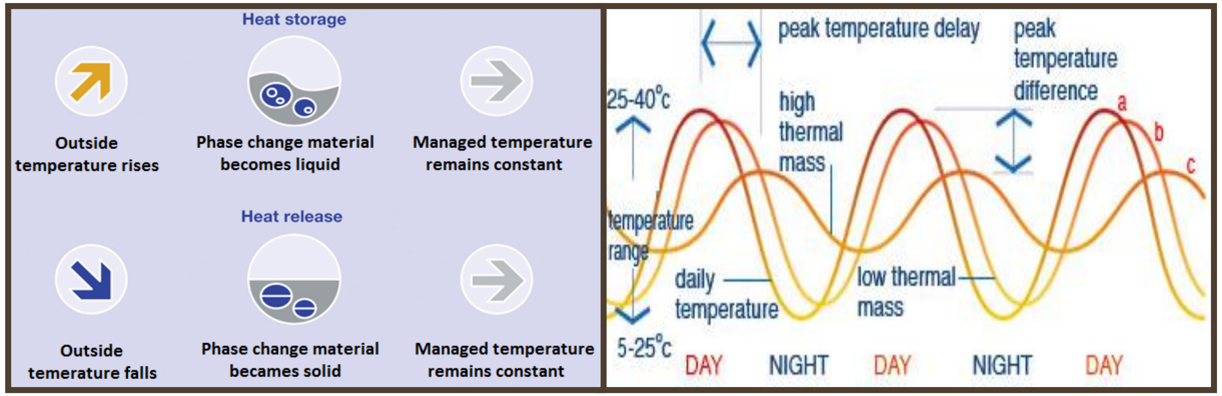
PCMs compensate all the lightweight insulator’s low thermal mass

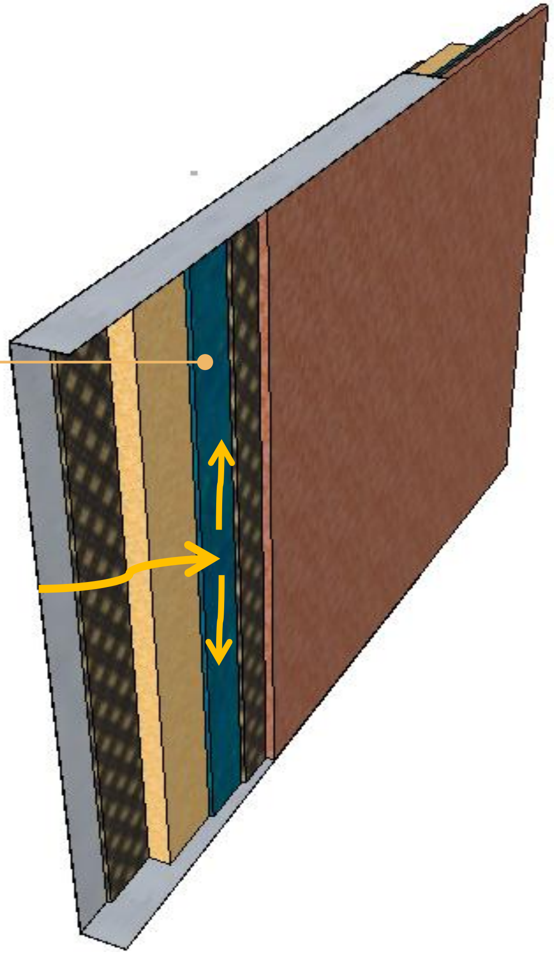
Living comfort

Owing to PCM with high thermal mass, cooling energy consumption is cut down

Peak thermal load is retained by:

Aluminium enveloped phase change material (Rubitherm RT27)





Computed/Validated

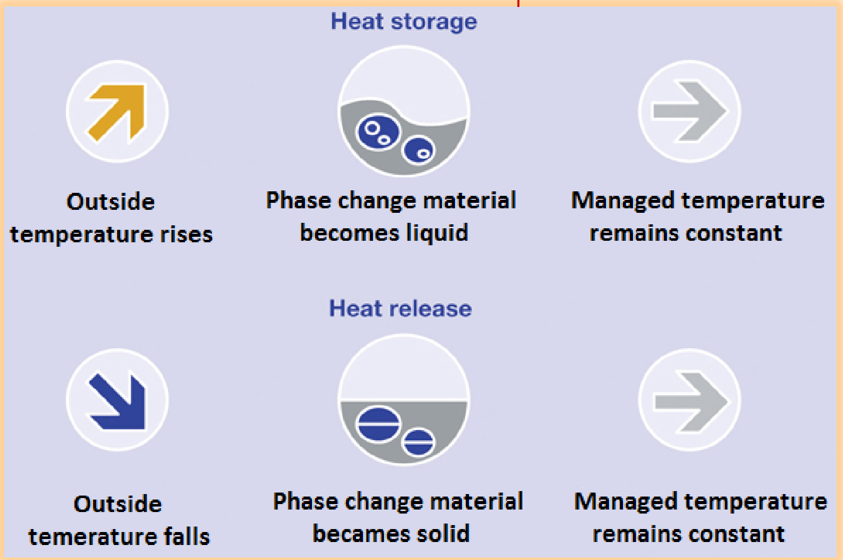
Peak load delay - 3-5 h

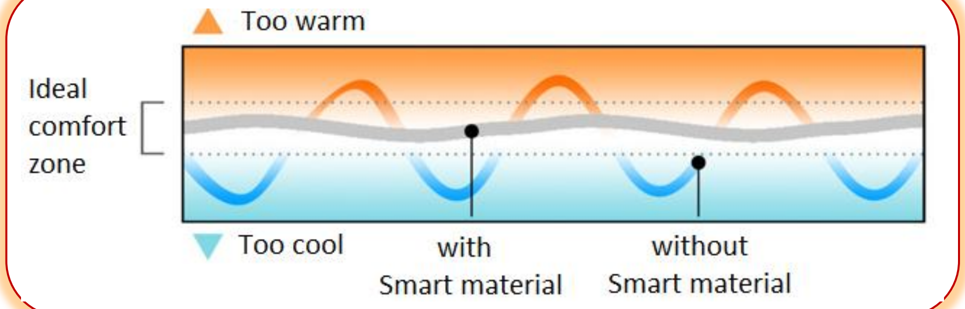
Peak. load drop - 46-55%

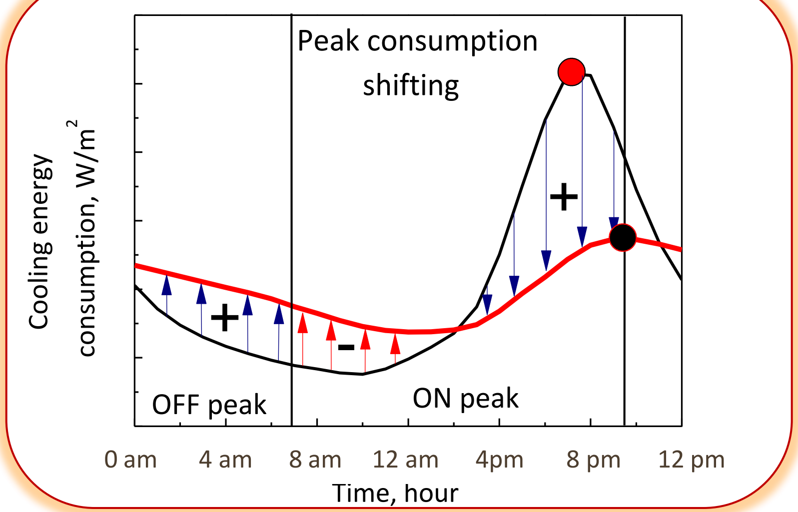
Living comfort

Smart Al container with phase change material inside

Principle of operation **Results in**

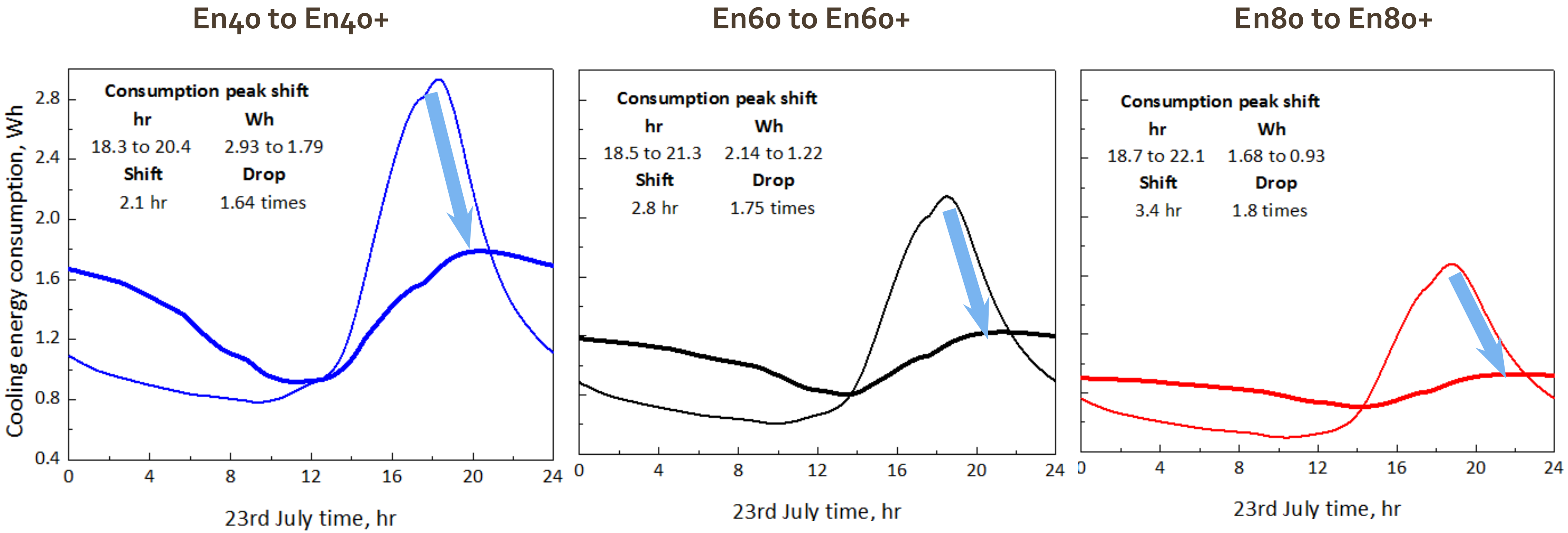






2.5mm PCM

The PCM optimization allows us to level the cooling energy consumption properly



The considered case is when Troom=22°C, PCM thickness = 2.5 mm, PCM displacement =0.6 (Qon=min)

- **Numerical model and simulation parameters**
- Energy PLUS 7.2 Software

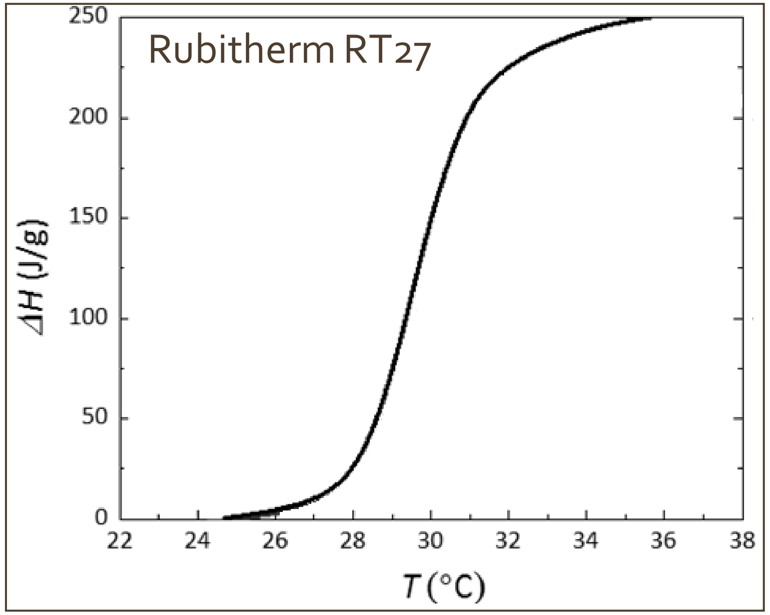
IDEAL CASE : Heat flux through the envelope = cooling energy consumption
Heat balance algorithm: Conductive finite difference method
Crank-Nickolson scheme (2nd order):

$$c_p d\Delta x\left(\frac{T_i^{j+1}-T_i^{j}}{\Delta t}\right)=\frac{1}{2}\left[k_w\left(\frac{T_{i+1}^{j+1}-T_i^{j+1}}{\Delta x}\right)+k_E\left(\frac{T_{i-1}^{j+1}-T_i^{j+1}}{\Delta x}\right)+k_w\left(\frac{T_{i+1}^{j1}-T_i^{j}}{\Delta x}\right)+k_E\left(\frac{T_{i-1}^{j}-T_i^{j}}{\Delta x}\right)\right]$$

$$c_p=\frac{H_i^{j+1}-H_i^{j}}{T_i^{j+1}-T_i^{j}}$$

T is a nodal temperature,
Δt is a calculation time step, 60 per min
Δx is a finite difference layer thickness
Δx_{Al} = 3 mm, Δx_{BFRP} = 1.2 mm,
Δx_{PIR45} = 1.43 mm, Δx_{PCM} = 0.63 mm,
Δx_{gypsum} = 1.2 mm.

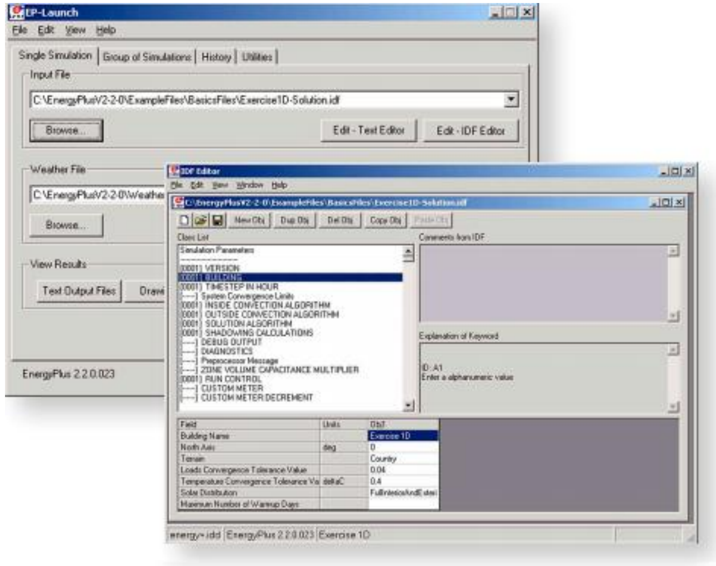
Studied PCMs (paraffin type)
Rubitherm RT27 (PRC-Germany)



Enthalpy-temperature dependence

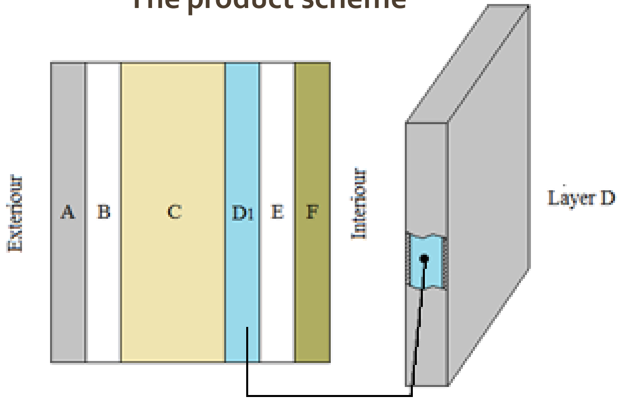
Implementation instrument

EnergyPlus | www.energyplus.gov



EnergyPlus is one of the most robust simulation tools available in the world today for fully integrated heating, ventilation, and air conditioning (HVAC) simulations.

The product scheme



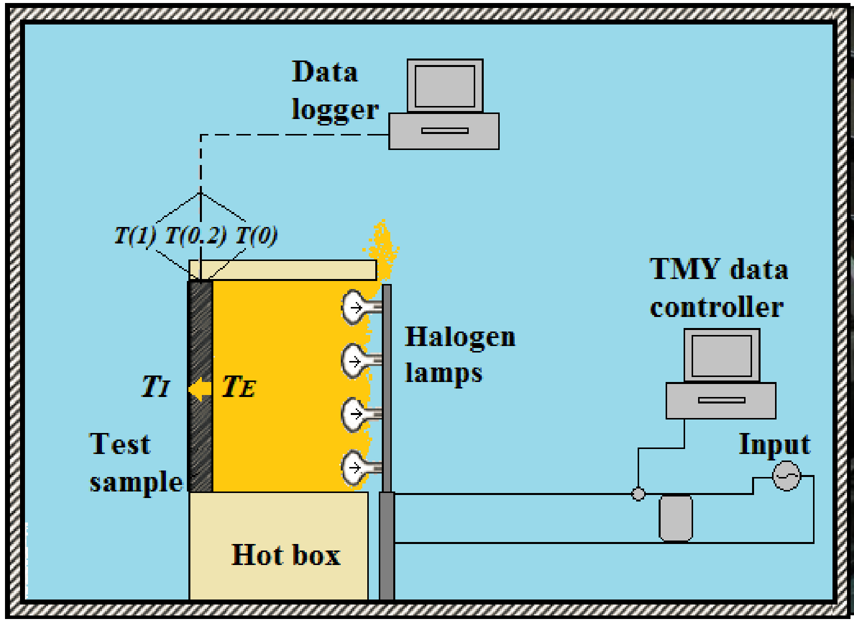
EnergyPlus gives a reliable and sharp estimate for a layered and large-scale envelope

EnergyPlus processed a thoroughly examined properties of commercially bought materials

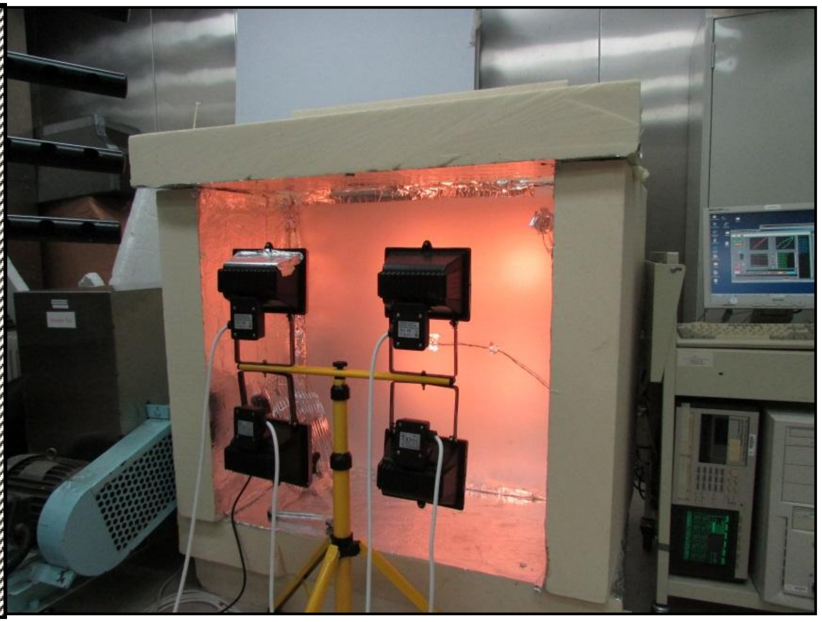
	Material	*thickness* mm	*conductivity* W/m·K	*heat capacity* J/kg·K	*density* kg/m^3
A	Aluminium	0.5-5	201	880	2700
B	Ext. BFRP	2	0.35	750	1660
C	PIR45	40-80	0.033	1320	45
D	RT27Ch	2.5	0.2	3495	849
E	Int. BFRP	2	0.35	750	1660
F	Gypsum	12	0.16	1150	640

- **Validation of the numerical scheme:**
- Validation set up: An environmental chamber at the Jockey Club Controlled Environment Test Facility in the Department of Mechanical Engineering of HKUST

Test schematic

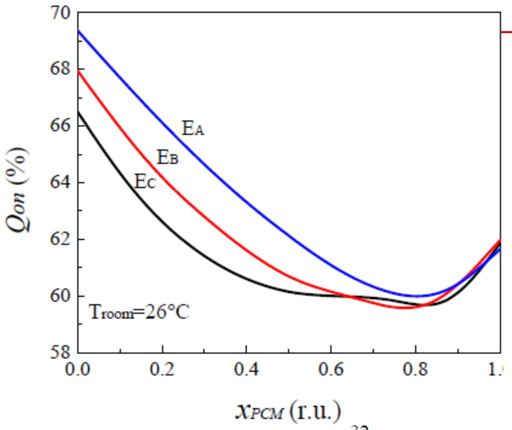


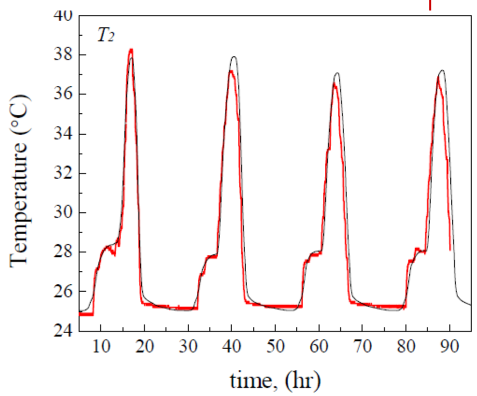
Test view

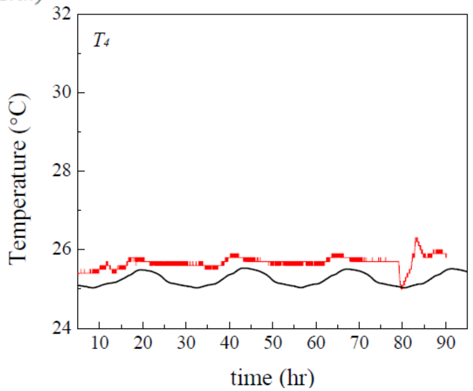


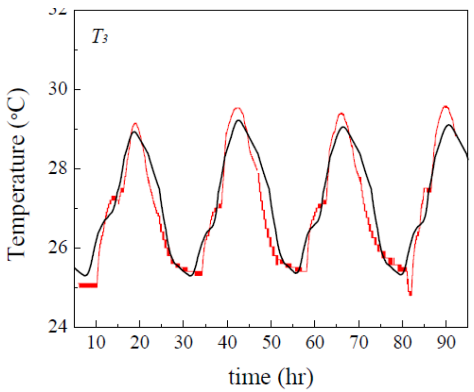
Thermal efficiency and comfort

A series of large scale tests	**has been carried out**
The numerical model	**has been validated**
Thickness of PIR foam	**has been optimized**
Optimal PCM parameters	**has been defined**







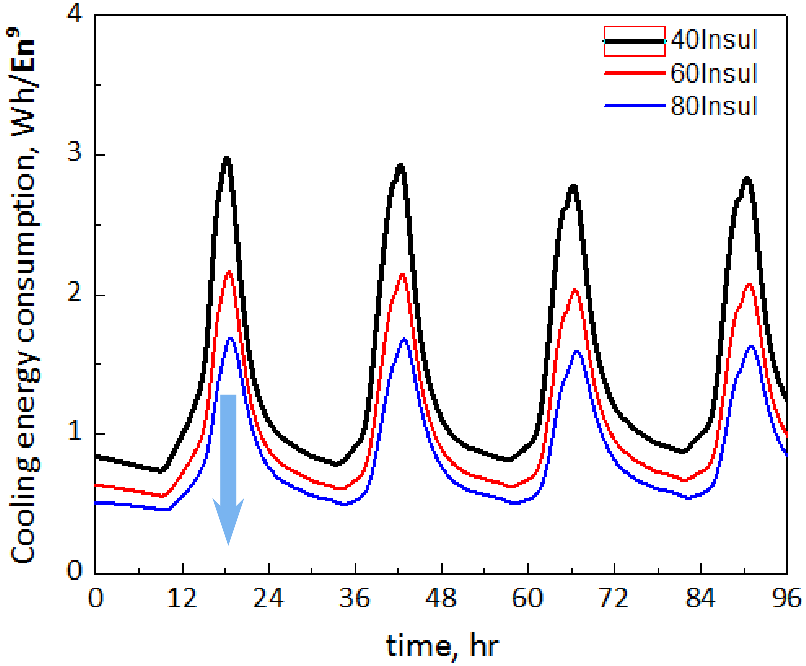


Implementation instrument

EnergyPlus | www.energyplus.gov

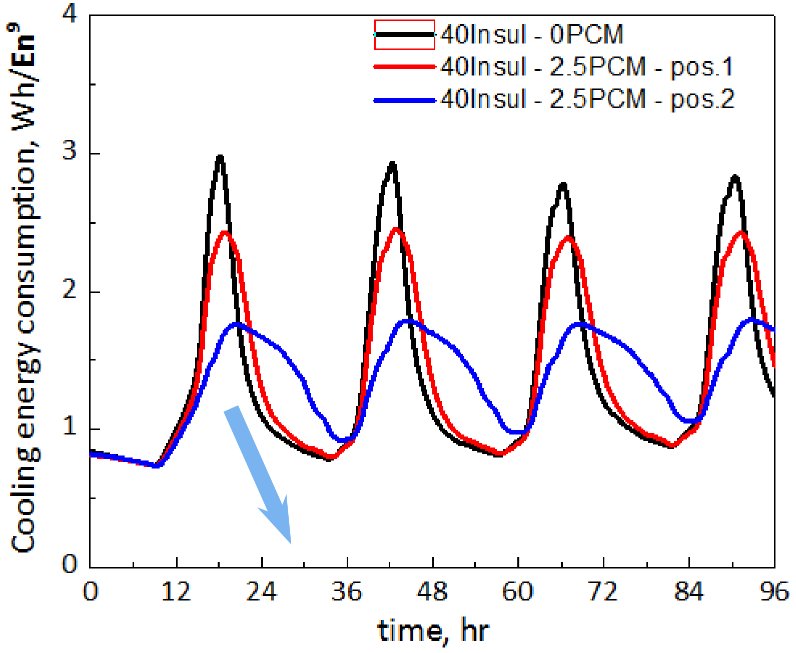
The validated scheme was applied for simulation of large-scale (9m²) envelope for the 22July-25July period. The enveloped smart office (west side) holding 22°C during the hot season in Hong Kong

Insulation effect
Whole consumption drop



Thanks to insulator efficiency,
a further thickening is not so justifiably

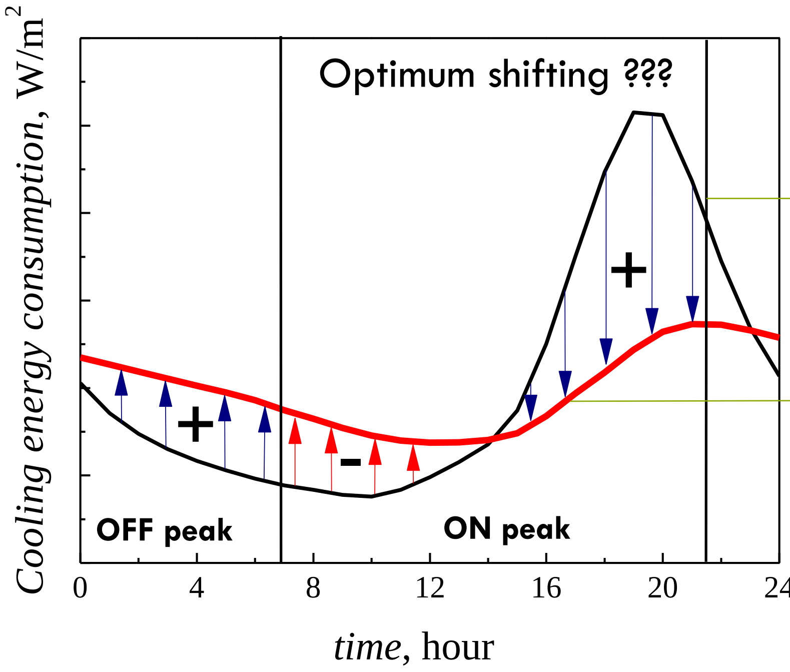
Phase Change Material effect
Day consumption drop, Night consumption grow



Even PCM is used its position inside
insulator matters significantly

- As the core thermal resistance is rather high, the optimization problem is then simplified
- Optimization method:

$$Q^{on} = \frac{\sum_{\tau} Q^{on}}{\sum_{\tau} Q^{on} + \sum_{\tau} Q^{off}} \cdot 100\%$$



$\sum Q^{on}$ and $\sum Q^{off}$ refer to the total on-peak and off-peak energy demanded by the HVAC to maintain a desired room temperature

A PCM location (or ***x*** value) respects to a particular energy distribution or ***Qon*** value

An optimal $\boldsymbol{x_{opt}}$ respects to the minimal ratio of on-peak to off-peak energy consumption

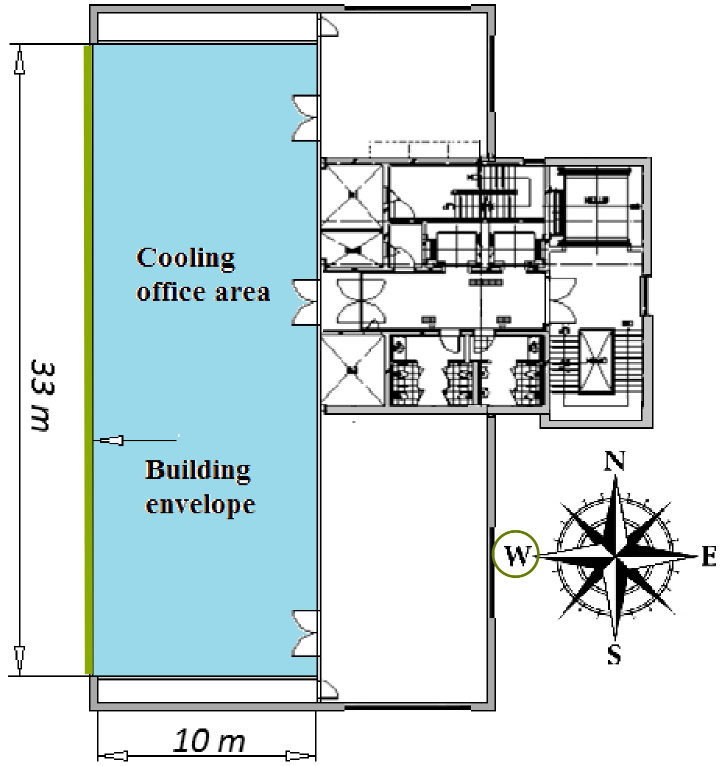
- Numerical model and simulation parameters

Typically, the annual-averaged solar radiation in Hong Kong is follows:
North – 116, East – 167, South – 203 and West – 211 kWh/(m^2day)
Envelope is westerly oriented

Studied case: when a building includes a closed area which is under HVAC control.

Total envelope length : 33 m/storey

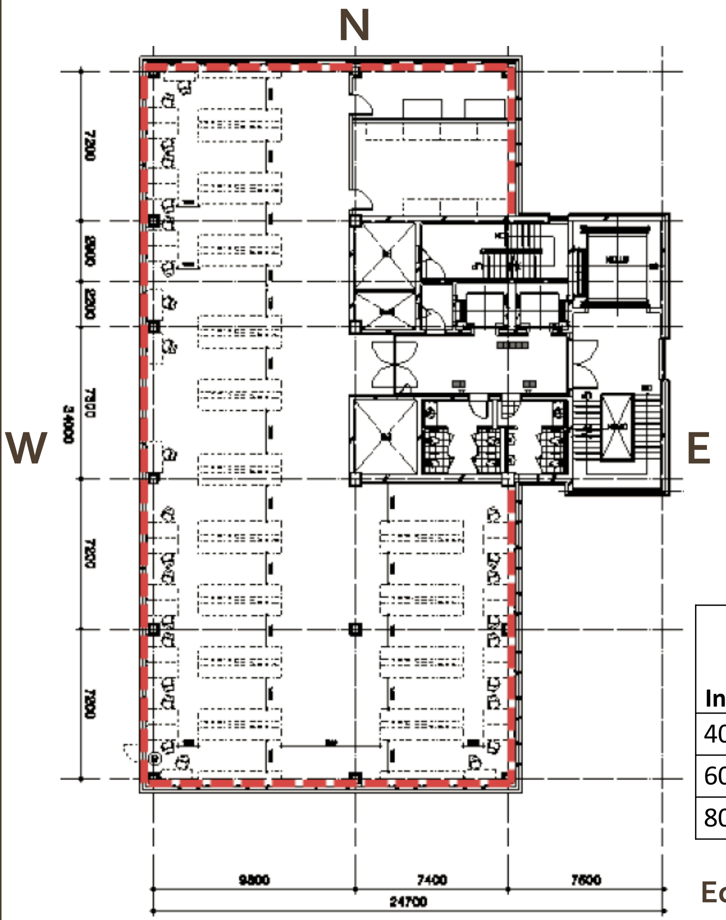
Building height : 50 storeys



Thermo solutions

Implementation instrument

EnergyPlus | www.energyplus.gov



Long-term summer season calculations:

The typical 50 storey building was considered as smart offices accommodated with hot season temperature control:
Case 1 - 22°C, Case 2 - 26°C.

PCM is optimally inserted into the insulator. HVAC COP=200%

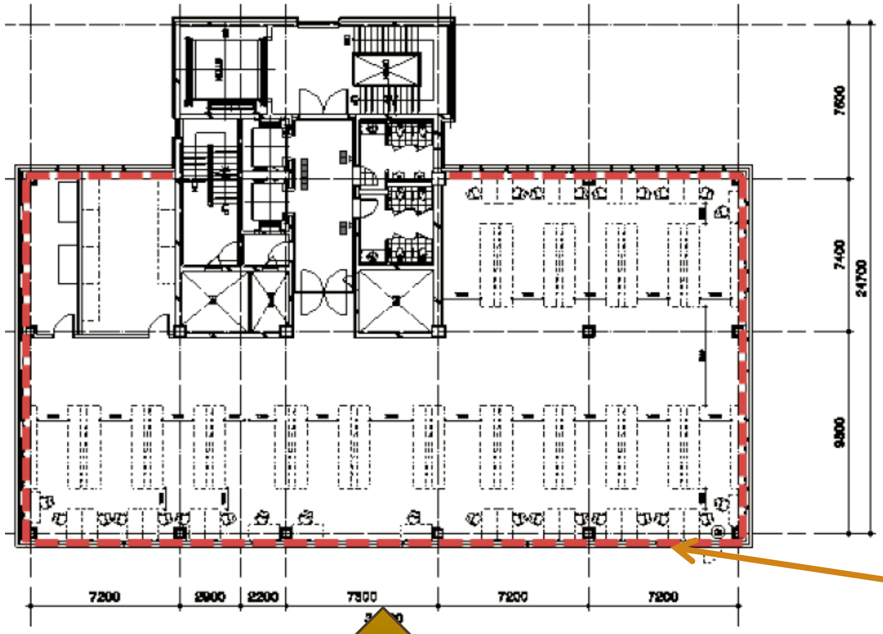
The validated scheme was applied for simulation of large-scale (9m²) envelope for 1May-31Oct. Period

panels only covered the studied building season economy

Insulat	**economy concrete to panel,** MWh/1bd		**economy PCM add effect,** MWh/1bd		**economy concrete to panel, kUSD**/1bd		**economy, PCM add kUSD**/1bd, PCM	
	22 ºC	26 ºC	22 ºC	26 ºC	22 ºC	26 ºC	22 ºC	26 ºC
40 mm	101.8	66.7	7.6	6.7	24.4	16.0	1.8	1.6
60 mm	115.5	76.3	5.0	4.3	27.7	18.3	1.2	1.0
80 mm	123.6	82.0	3.5	2.9	29.7	19.7	0.8	0.7

Economy results : The major season savings are given by insulation effect,
PCM profits when insulation has min. thickness

Thermal efficiency of panel with PCM



Solar radiation

How much can we save?

Typical HK building of 50 storey.
Run from May to November.

Installation of only 11 panels per storey

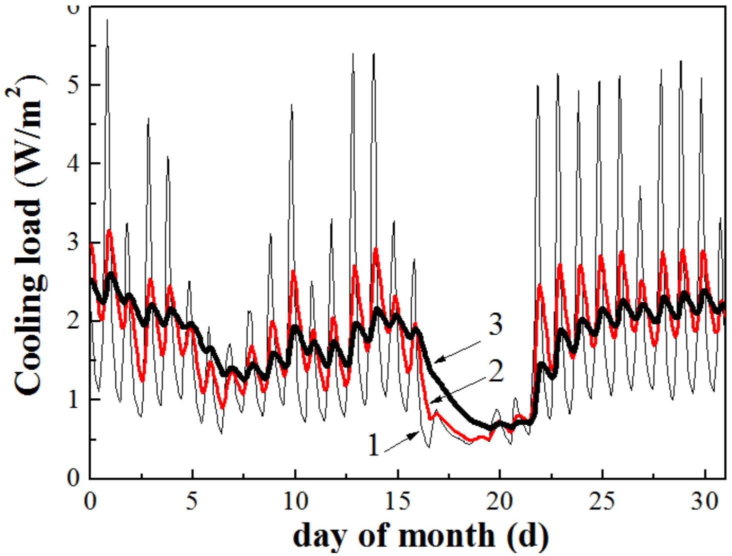
Envelope	*Layer, mm*						**Economy of power used** , *USD*	
	Al	*FRP*	*Insul.*	*PCM*	*FRP*	*Gyps.*	*22 ℃*	*26 ℃*
E_A	3	2	40	2.5	2	12	**4261**	**2820**
E_B	3	2	60	2.5	2	12	**2268**	**1504**
E_C	3	2	80	2.5	2	12	**1253**	**835**

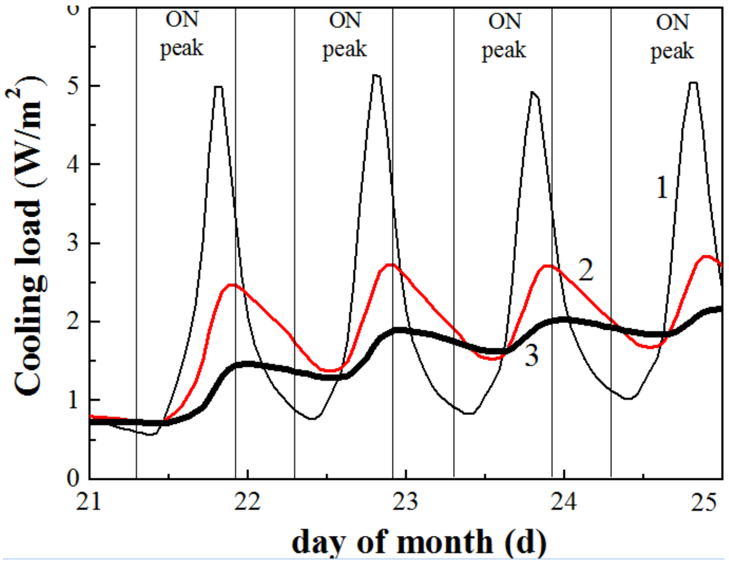
That is not all

Thermal efficiency of panel with PCM

Effect of PCM in the envelope Ec (80 mm of insulation), July weather

1. No PCM, **2.** 2.5 mm of Rubitherm RT27, **3.** 10 mm of Rubitherm RT27





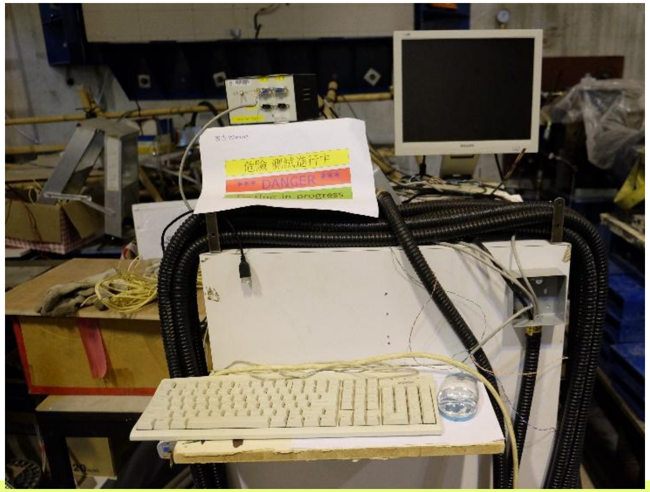
		Max load delay	Max. load drop
1.	no PCM	0 h, 0 min	0 %
2.	2.5 mm (*optim.*)	2 hr, 53 min	46 %
3.	10 mm	5 hr, 2 min	55 %

1. Max. load delay – uniform energy consumption
2. Max. load drop – A/C power cut down

HK GREEN HOUSE STRATEGY

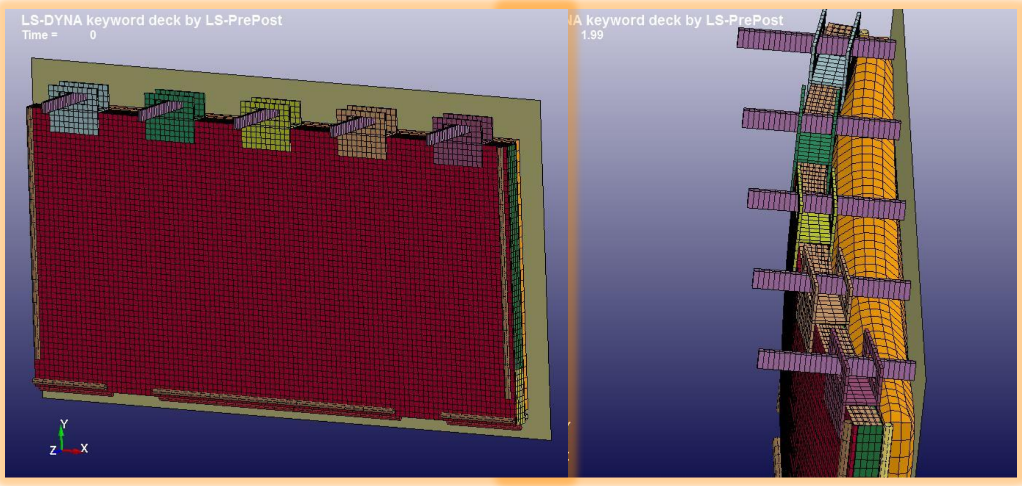
Large scale testing of mechanical properties of the composite panel

Air bag system



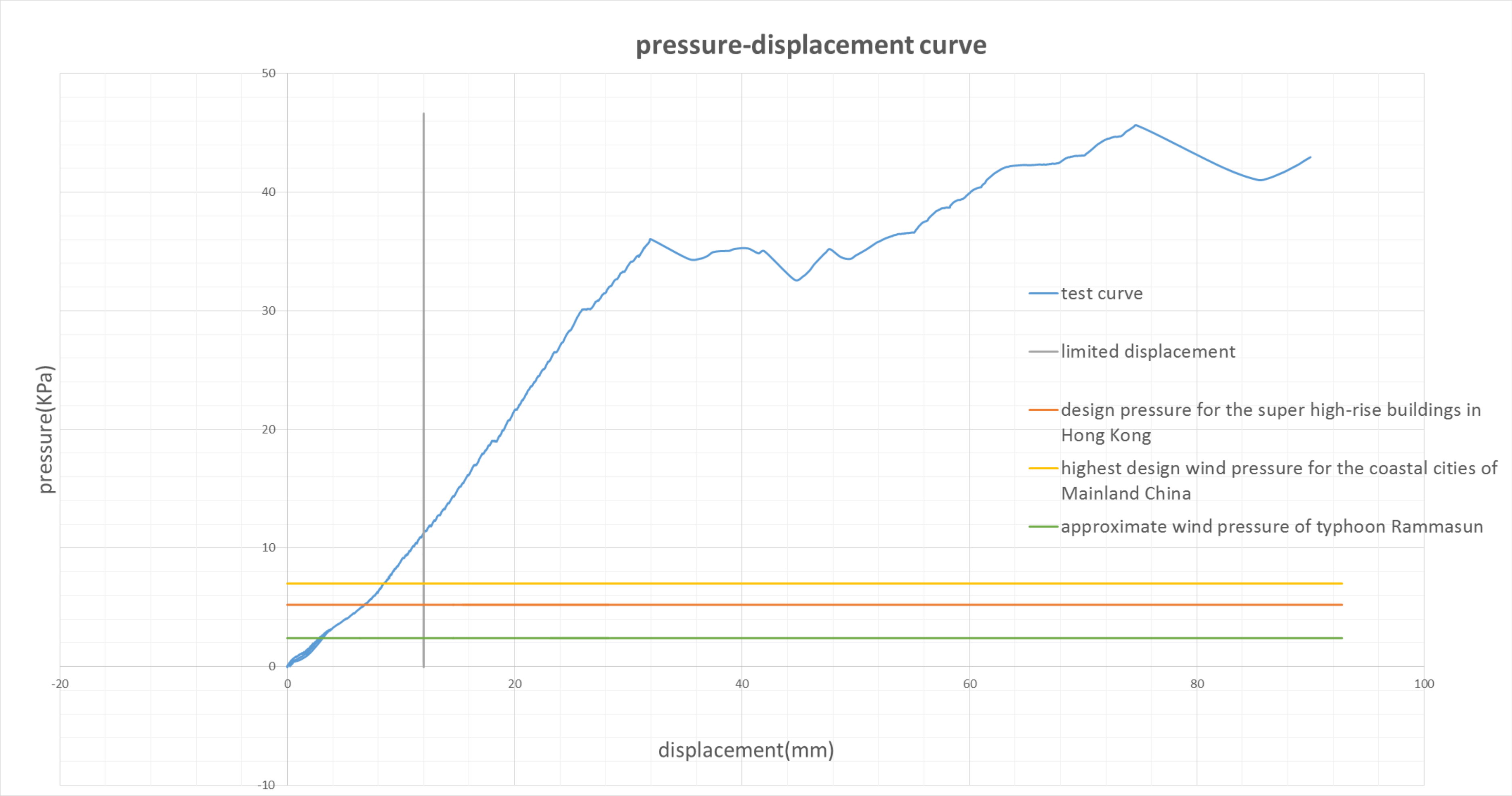
of the panel – half scale model

A series of large scale tests **has been carried out**



Post failure behavior of the panel

Results of the large scale panel testing



Stiffness ↑ 60%

able to take the most severe wind pressure

eliminate air leakage

Weight 40%

reduce transportation cost

Reduce construction cost

Durability ↑ 30%*

reduce maintenance cost

50% Energy Saving

Payback period < 30 years

Reduce chiller size

extra saving for off peak cooling